Appendix C
Demonstration Model

Connecticut River Partnership
Demonstration hydrologic/dam operations models

Overview

The Nature Conservancy, together with partners, has identified an altered flow regime as one of the primary threats to all of our conservation targets in the Connecticut River Watershed. To help abate this threat, we are working to restore the flow, form and other dynamics of the river to a more natural state, in ways that will improve aquatic biodiversity throughout the watershed. To accomplish our goal requires a sophisticated understanding of how water currently flows in the Connecticut River and its tributaries, and how the operations of 65 large dams in the basin work together to influence the current hydrologic regime. We plan to gain this understanding through the development of a basin-wide hydrologic model that can be used to evaluate dam operations throughout the basin and through the development of hydraulic models for specific river reaches of interest. We will pair this hydrologic model with ecological information to assess alternative dam operations that will fulfill human needs, including flood control and hydropower generation, as well as the needs of aquatic and floodplain species and communities throughout critical stages of their life cycle. Our ultimate goal is to better incorporate environmental flow recommendations into dam operations while still providing for human needs.

The first step toward construction of this basin-wide hydrologic model is the completion of a demonstration project for a small portion of the basin. The goal of the demonstration project was to test technologies that may be valuable in analyzing the entire watershed at a much smaller scale. Through this testing, the capabilities of individual tools were better understood, enabling a more educated selection of tools for the larger study. This work was done by the Connecticut River Technical Team, which consists of members of the U.S. Army Corps of Engineers (New England District and the Hydrologic Engineering Center), The Nature Conservancy, the U.S. Geological Survey (USGS), and Tufts University.

Demonstration project objectives:

1. Examine model technologies, cost, and data needs
2. Evaluate the ability of the models to capture current dam operations and assess alternative operations scenarios
3. Assess potential application of the selected models (unimpaired flows, rule-based dam operations model, goal-based optimization model) to the entire Connecticut River basin and compare with alternative models

Demonstration Project Area

The demonstration project focused on the Connecticut River watershed between North Walpole, New Hampshire, and Montague City, Massachusetts. This section includes a stretch of the Connecticut River mainstem and four of its tributaries - the West, Ashuelot, Millers, and Deerfield Rivers. Six reservoirs were included in the model. Vernon and Turners Falls Reservoirs are located on the Connecticut River mainstem and are operated primarily for hydropower. The Ball Mountain and Townshend projects are located on the West River. The Surry Mountain and Otter Brook projects are located on the Ashuelot River. The tributary reservoirs are owned by the U.S. Army Corps of Engineers and are operated primarily to reduce flooding along the mainstem of the Connecticut River.

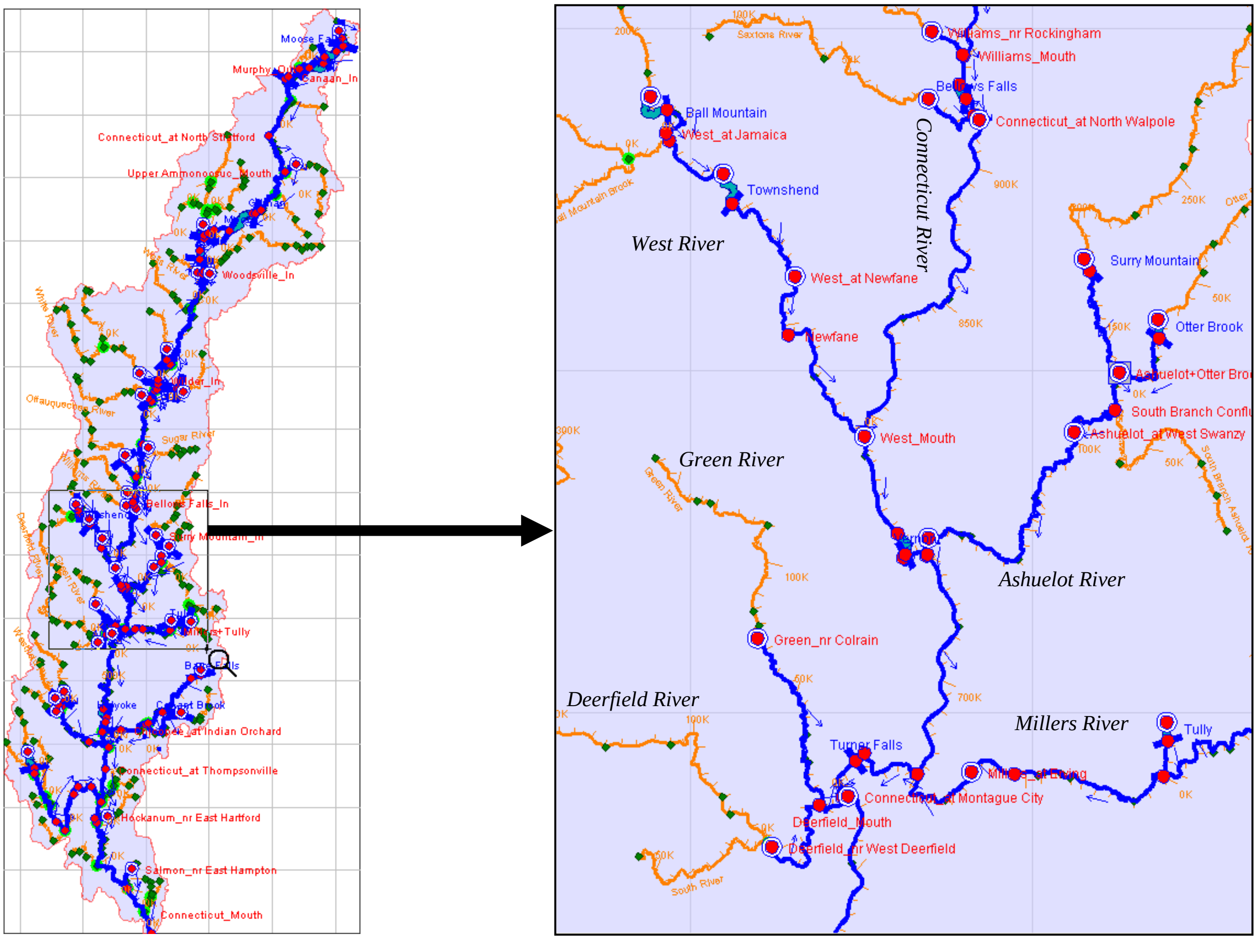

Figure 1. Map of the Connecticut River Basin and the demonstration project area. The map depicts reservoirs (labeled in blue) and stream gages (labeled in red) included in the HEC-ResSim and HEC-ResFloodOpt models. Operations for reservoirs on the West (Ball Mountain and Townshend) and Ashuelot Rivers (Surry Mountain and Otter Brook) were included in the model; all other reservoirs did not contain any operations logic and were modeled as simply passing all inflow.

Input hydrology

The first step in creating a hydrologic model is creating a hydrologic foundation, or a dataset of baseline (unregulated) and current (regulated) daily river flow data for the project area. For the West and Ashuelot Rivers, natural flows were computed by teasing out the influence of reservoirs on river flows using a water-balance approach. This was a time intensive process that used available gage data as well as historical reservoir levels and outflows. This method was appropriate for the volume of data needed to establish a hydrologic foundation over a 20-year period of record for the West and Ashuelot Rivers. However, the level of effort that would be required to produce similar estimates for the entire Connecticut Basin is daunting and, at this time, cost prohibitive. Because of these constraints, baseline flows have not been calculated for other tributaries in the demonstration project area, or for any portion of the Connecticut River mainstem.

Because of the issues identified above, we sought an alternative method for calculating inputs to the model. We currently are cooperating with the U.S. Geological Survey to develop the Sustainable Yield Estimator (SYE) as a method for estimating baseline flows for the entire Connecticut River Basin. The SYE is an interactive, point-and-click tool, built upon a geographic-information system, to estimate streamflow at any location on a perennial stream (2 to 300 mi^2) in the watershed. This method estimates a daily time series of unaltered flows at a given site from a set of equations that relate basin characteristics to properties of flow-duration curves and the structure of the ordered flows to estimate other points along a flow duration curve. From this synthesized flow-duration curve, daily streamflows at the ungaged site are determined for a given day by the percent exceedence of flow on that day at an index gage(s) for the period-of-record (POR) or the period-of-interest (POI). This tool will be used to provide daily estimates of baseline flow as input boundary conditions to the reservoir operations models that will be developed for the entire basin.

This tool was initially completed for the state of Massachusetts and is currently under development for the state of Connecticut. The methodology will be extended to include index gages in the northern portion of the basin. Additional analysis will be completed to quantify the uncertainty in the SYE-estimated streamflows; in particular, SYE-estimated and observed flood-frequency statistics will be compared to determine uncertainty associated with the SYE-estimated flood flows.

In cooperation with the U.S. Army Corps of Engineers and Tufts University, SYE-estimated streamflows will be routed through the reservoir-operations models already being developed for the Connecticut River Basin. Because the SYE-estimated inflows cannot be applied to basins larger than 300 mi^2, larger basins will be subdivided into smaller basins and routed through the reservoir-operations models to obtain streamflow estimates for basins larger than 300 mi^2.

In cooperation with the University of Massachusetts-Amherst, the SYE methodology will be extended to incorporate the effects of climate change. Streamflow records and flow-duration curves at the index gages will be extended using downscaled climate-model results from selected climate-change scenarios.

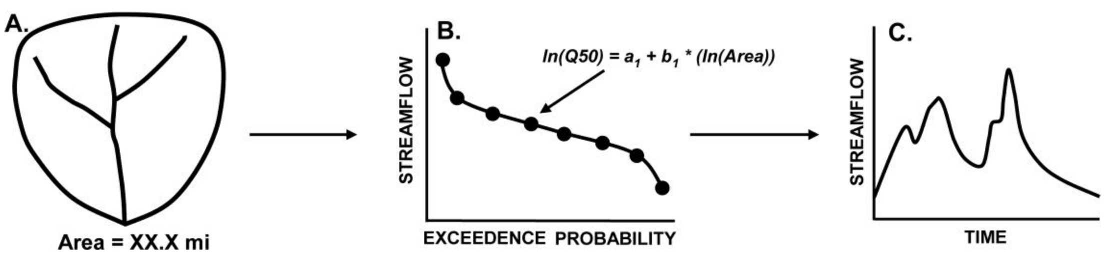

Figure 2. Overview of the sustainable-Yield Estimator methodology. Unimpacted daily

streamflow at an ungaged location is estimated by: (1) calculating the basin characteristics at the ungaged location (panel A), (2) solving regression equations that relate measurable basin characteristics to flows at selected flow-duration-curve exceedence probabilities (panel B), (3) interpolating between flows at the selected flow-duration-curve exceedence probabilities to obtain a continuous flow-duration curve (panel B), and (4) transforming the estimated flow-duration curve into a time series of streamflow by use of an index gage (panel C).

Reservoir Operations Models

Reservoir operations models simulate the storage and release of waters in systems of reservoirs. These models are typically either rule-based simulation 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 to make simulated releases agree with how the reservoirs are actually operated. When the model is producing reasonable results, 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 make decisions 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 (start at an optimized operation and change from there). Optimized operations can be modified and used as input to rule-based models to examine alternative management scenarios. Using rule-based and optimization models in tandem can be a very effective way to consider changes in operations. By maximizing net benefits, optimization models are helpful in suggesting new ideas for operations, which can then be expressed and simulated in rule-based models as that tool typically offers a closer reflection of existing operations (for Corps reservoirs). Figure 3 shows a comparison of the rule based and optimization models tested in this demonstration project.

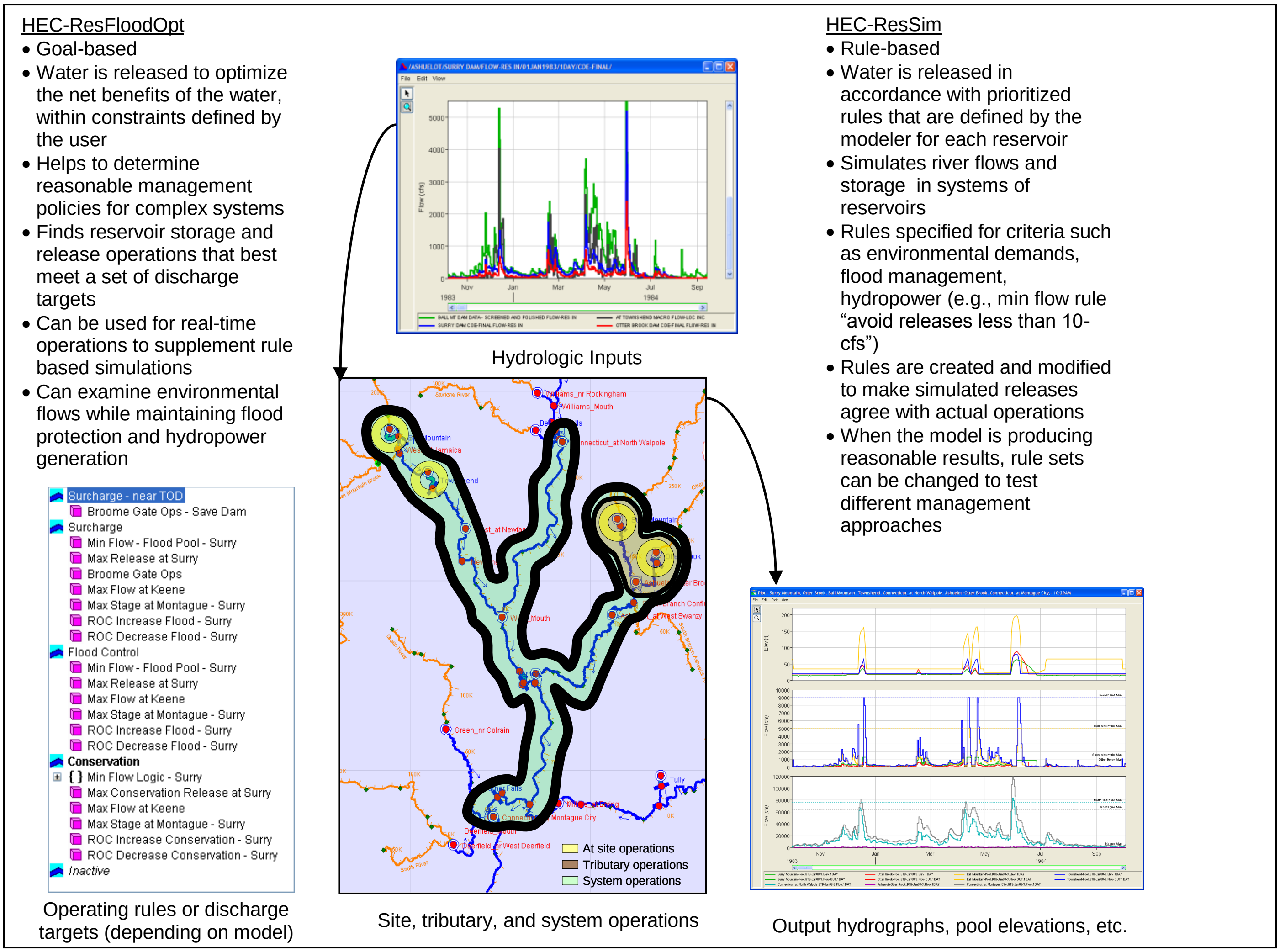

Figure 3. Comparison of the reservoir operations models assessed in the Connecticut River Basins technologies demonstration project.

Rule-based operations model – HEC ResSim

HEC-ResSim is a rule-based reservoir operations model produced by the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers. The purpose of ResSim is to help engineers and planners perform water resources studies that involve simulating the behavior of reservoirs and to help reservoir operators plan releases in real-time during day-to-day and emergency operations.

For the demonstration project, a set of rules was developed to simulate "By the Book" operations. Simulated operations were based on operation policies obtained from the New England District website. These guidelines were summarized as "Standard Operating Procedures" and "Outflow Guidance" for each of the tributary reservoirs on the West and Ashuelot Rivers. Vernon and Turners Falls were not assigned any operations logic. Those reservoirs are in the model, but, for now, simply pass all inflow.

Simulation results showed that the ResSim model was very good at simulating the “By the Book” operating policies. Flood risk management rules, which limit high flows and stages at Keene, North Walpole, Montague, and just below the four Corps dams, as well as instream low flow rules, which are based on season and inflows to the Corps projects, were met during simulations. Figure 4 shows simulation results for the four Corps reservoirs and operating locations at Keene, North Walpole and Montague City.

ResSim simulates water management alternatives through the use of different sets of rules and information about the physical layout and characteristics of reservoirs. It has standard plotting tools that allow point-and-click visual comparisons of alternatives and well as customizable plots and tables for post-processing results.

Without knowing the full scope of operations for the Connecticut, it is impossible to say with certainty that HEC-ResSim is directly applicable to the entire Connecticut River Basin. However, the software certainly performed well for the demonstration area and water managers from NAE have confirmed that operations at those Corps reservoirs are representative of Corps operations throughout the basin. This helps instill confidence that ResSim would be capable of simulating a larger reservoir network for “By the Book’ and alternative operating scenarios.

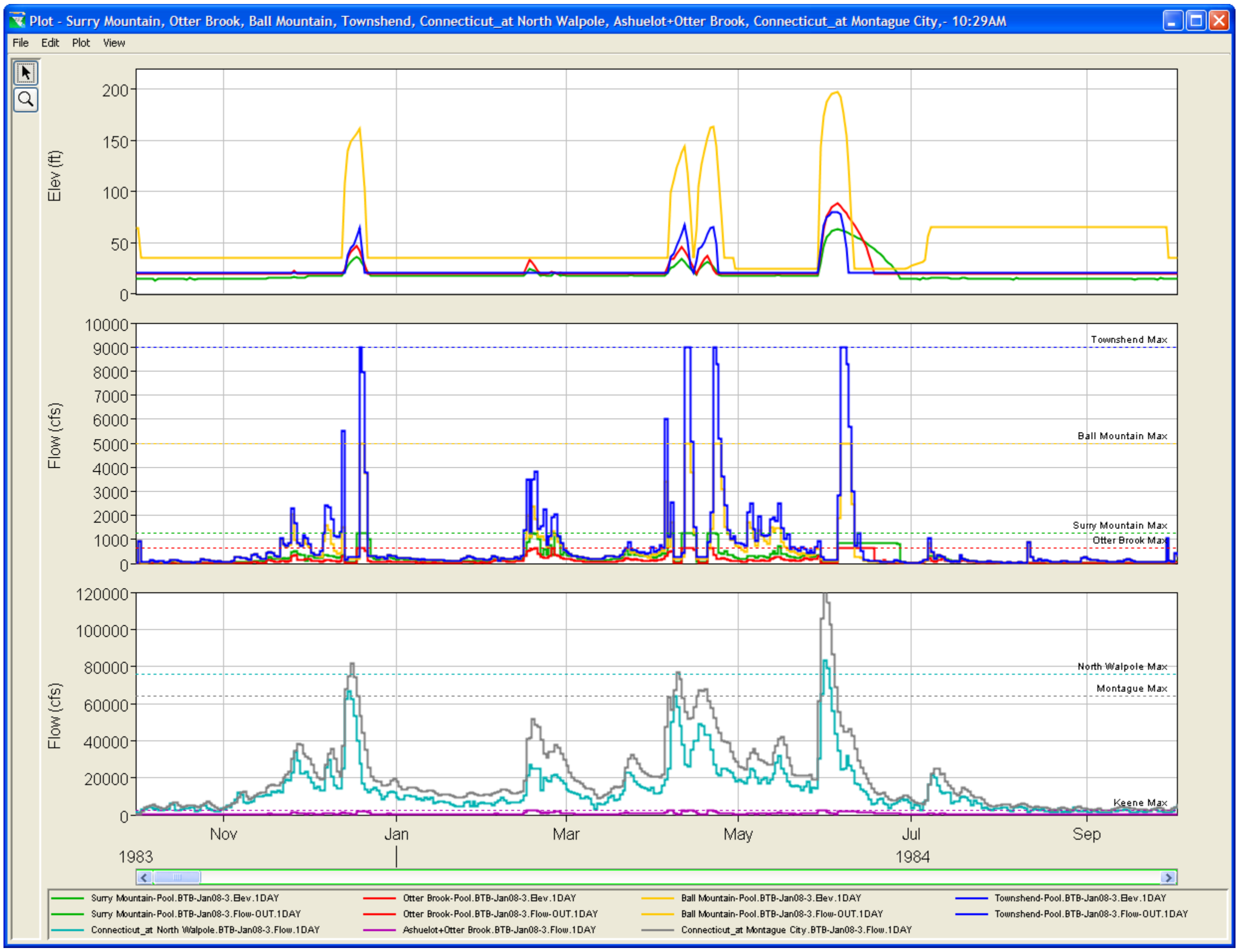

Figure 4. Sample output from HEC-ResSim, a rule-based reservoir operations model. Data show simulated reservoir releases from four reservoirs, which are operated in part to hold high flows below maximum limits (see dotted lines) at the dams and other operating points.

Goal-based optimization model – HEC ResFloodOpt

HEC –ResFloodOpt (hereafter referred to as FloodOpt), is a goal-based, linear programming model that simulates releases from reservoirs in order to minimize user-defined penalties that accrue when river flows violate operational guidelines. It can function at variable time steps even as small as one hour. The input and output are done via text files except for the stream flow time series, which are done using HEC-DSS (Data Storage System) files.

For the demonstration project, daily flood risk management operations were examined for April 3-6, 1987 (4 time periods) to determine if the model could simulate a reservoir operating schedule based on existing low and high flow limits in the basin. Due to lack of hydropower data, hydropower operations were not considered.

It was found that FloodOpt did have some utility for simulating optimal releases from reservoirs, but it was also found that the software's input and output management was antiquated and cumbersome. FloodOpt also requires a license for an internal solver that performs the optimization computations. Due to these limitations, it was judged that FloodOpt is not a desirable tool for application to the entire basin and even though HEC is planning to update the software, necessary improvements are unlikely to be ready for use within the current study schedule. Other optimization software packages, including commercial tools, are being considered.

Alternative scenarios of dam operations

The hydrologic models developed for the entire Connecticut River basin will be used to model current operations of all large dams in the watershed as well as alternative future scenarios of dam operations. The goal of examining alternative scenarios is to evaluate operational changes that are needed to produce measureable environmental benefits while still meeting the human needs of flood control, hydropower generation, and water supply. Flow scenarios will often take the form of flow restoration goals and will help to inform recommendations for flow restoration. These scenarios will initially be evaluated at current climate and land use conditions in the basin. In addition, we will evaluate scenarios that incorporate changes in water availability as a result of climate change.

Although we were not able to examine alternative scenarios of dam operations within the context of the demonstration project, our experience with the models has provided greater insight into how we may address scenario comparisons in the whole-basin model.

Expanding to the Connecticut River Basin

As described above, construction of the demonstration project has provided information on which technologies (input hydrology, reservoir operations model, optimization model) are best to use for an application to the entire Connecticut River basin. We envision that this whole-basin model will provide estimates of baseline flows, current flows, and flows for each alternative scenario of dam operations and water management for points of interest throughout the basin, including each of the 65 large dams and sites of conservation interest (e.g., floodplain sites, locations of rare species, aquatic communities representative of different river types, etc.). We intend that this model will be useful to recommend flow restoration targets and changes to dam operations throughout the basin. In addition, we plan to work closely with water managers and natural resource agency staff in all four states to craft alternative scenarios of water management that address ecological needs, as well as the needs and interests of a wide range of stakeholders.

The demonstration project results, including cost, ease of use, temporal and logistical constraints, and model performance, have been used to guide the selection of technologies that we will apply at the scale of the entire Connecticut River basin. We will develop input hydrology using the Sustainable Yield Estimator. This method has already been applied to the state of Massachusetts, and is now being expanded to include the states of Connecticut, New Hampshire, and Vermont, with the boundaries of the Connecticut River watershed. Because HEC-ResSim performed well as a rule-based operations model in simulations of reservoir operations and four USACE flood control dams we plan to apply the model at the whole-basin scale. In contrast to HEC-ResSim, HEC-ResFloodOpt did not perform well in our demonstration project, most due to problems with the software's input and output management. Because of those issues, we will not apply the model at the whole-basin scale, but instead have contracted with the Department of Civil Engineering at University of Massachusetts, Amherst to develop a goal-based, linear programming model that will allow us to explore optimal water management scenarios under a series of user-defined constraints and penalties. This optimization model will use input hydrology developed by SYE and will provide optimized operating rules and resulting mean daily flows as output data.

Future schedule

We have five general areas of work moving forward with the creation of a hydrologic model for the Connecticut River basin: (1) developing input hydrology using SYE, both for current conditions and under climate change scenarios, (2) development of the rule-based dam operations model using HEC-ResSim, (3) development of the goal-based dam operations model, (4) creation of ecosystem models that reflect flow needs for aquatic and riparian species and natural communities, and that will inform flow restoration scenarios, and (5) involving stakeholders to help provide input data for dam operations and ecosystem models, evaluate model results, develop alternative scenarios for evaluation, and eventually use model results to support changes in dam operations and water management.

Work in all five areas has begun. USGS is currently developing the SYE input hydrology for the watershed and partners with University of Massachusetts will adapt the SYE data to reflect climate change scenarios. The Hydrologic Engineering Center (USACE) will construct the rule-based dam operations model (HEC-ResSim). University of Massachusetts is under contract to construct the goal-based optimization model, as well as work with stakeholders to collect dam operations data needed as input to both models. The Nature Conservancy's Connecticut River Program is creating ecosystem models and collecting information on flow needs of aquatic and riparian species and natural communities. Massachusetts Institute of Technology is under contract to identify and involve stakeholders throughout the process. The project will be ongoing for the next three years and is expected to be completed in the fall of 2012.