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**SUSTAINABLE WATER MANAGEMENT USING ENVIRONMENTAL FLOWS IN  
THE CONNECTICUT RIVER**

A Masters Project Presented

by

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May 2013

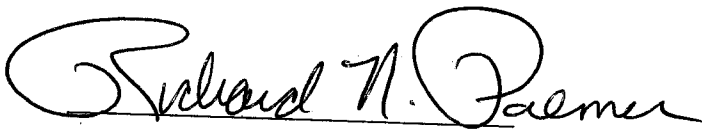
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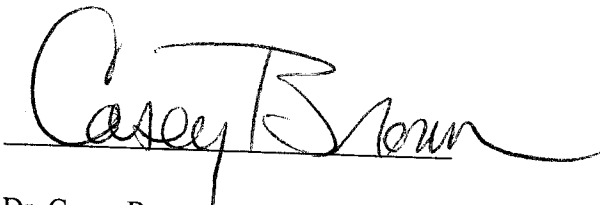
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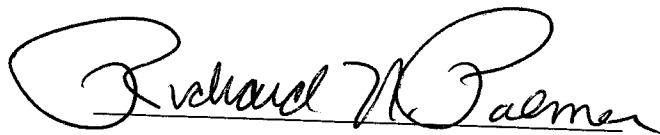
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*It is one thing to find fault with an existing system. It is another thing altogether, a more difficult task, to replace it with another approach that is better.*

-Nelson Mandela, 16 November 2000  
(speaking of water resource management)

## **1. ABSTRACT**

There is significant evidence demonstrating that altering river flows downstream of impoundments harms native aquatic ecosystems and decreases the ability of native species to thrive and survive. Innovative water management practices are needed to improve the health of native aquatic species and their surrounding ecosystems while maintaining the benefits from historic operating policies at these facilities. The impacts of individual reservoir operations on ecosystem health are often masked by the compounding influence of multiple upstream impoundments, making it difficult to analyze an individual facility's impact within the larger system. This study presents an optimization model that investigates the value of coordinated reservoir management practices for ecological benefits in a dynamic system with several major reservoirs operating for hydropower production. An application of this model is presented for five hydropower facilities along the Connecticut River using The Connecticut River Environmental Assessment Model (CREAM). The Connecticut River Basin is the largest river basin in New England and one of the most impounded rivers in the United States. Five hydropower facilities along the Connecticut River are undergoing Federal Energy Regulatory Commission (FERC) re-licensing. These facilities respond to both seasonal and hourly power demands. CREAM includes the five facilities undergoing this re-licensing process. This process provides an opportunity to explore and alter the operations of these facilities utilizing coordinated reservoir management practices that investigate a variety of operating objectives. This study provides an opportunity to contribute to the long history of using optimization models to explore tradeoff between different operational objectives of hydropower facilities. This

research explores the various emerging environmental concerns in the hydrologic regime while addressing historical operating objectives for management of hydropower reservoirs in the Connecticut River. Results suggest that coordinated operational changes to current hydropower reservoirs can restore some aspects of the natural hydrologic regime necessary for ecosystem persistence without considerable losses to current economic benefits.

## **2. INTRODUCTION**

Human water demands must be balanced with the needs of natural ecosystems associated with the river but tensions in water resources allocation are intensifying (Petts, 2009). Hydropower reservoirs often make releases that respond to seasonal, daily, and sub-daily energy prices.

Although any change to natural hydrology may be detrimental, rapid changing sub-daily flow release patterns are harmful to many aquatic species and ecosystems that rely on the natural flow of the river. Alternations to the natural hydrologic regime have led to both direct ecological and indirect geomorphic responses that have degraded the health of riverine ecosystems and depreciated the services they provide (Poff, et al., 1997) (Bunn & Arthington, 2002).

Instream flow requirements are normally considered as a seasonal target assuring a minimum level of streamflow is provided. Recent literature has emphasized that instream flow needs are far more complex than providing an aquatic baseflow requirement. These baseflow release requirements have largely ignored the ecological need for natural variability in streamflow, including variations in magnitude, timing, duration, frequency, and rate of change (Poff, et al., 1997). Despite the shortfalls of static instream flows, they are still utilized and compose the vast majority of environmental requirements imposed on reservoir systems. Traditional hydropower facilities have minimum flow releases that must be met throughout the year. These types of

requirements are used, in part, because their effects on reservoir performance are easily analyzed using existing water resource systems analysis techniques (Petts, 2009). These requirements fail to address key hydrologic regime components necessary for ecosystem health.

The ecological integrity of riverine ecosystems depends on their natural dynamic character, and there is considerable interest in characterizing the natural flow regimes of streams prior to significant human alteration of their watersheds (Richter, Baumgartner, Powell, & Braun, 1996) (Poff, et al., 1997). Native flora and fauna in streams and associated riparian zones are adapted to various features of the natural flow regime, and human alteration of flow regimes often impairs these biological communities (Poff, et al., 1997). A river's flow regime is recognized as a master variable that drives variation in many other components of a river ecosystem, e.g., fish populations, floodplain forest composition, nutrient cycling, in both direct and indirect ways. The species richness and productivity characteristic of freshwater ecosystems is strongly dependent upon, and attributable to, the natural hydrologic conditions (Richter, Matthews, Harrison, & Wigington, 2003)

The potential energy used in hydropower operations is a common pool resource with public discretion as to its end use. Hydropower provides a quick source of reliable energy due to its ability to transform potential energy from stored water into kinetic energy, and ultimately electricity, on very short notice, often within seconds, and thus adds significant flexibility to an energy supply portfolio (Viers, 2011) However, despite these benefits, a river impoundment can impose many environmental constraints on a natural system. As a result of dams and other anthropogenic regulation on river systems, the magnitude, frequency, and duration of low flows and low flows change, the range of flow magnitudes is altered, timing of high flows is shifted, and ramping rates are increased (Graf, 2001). The onset of operation of a dam generally results



in sudden changes in the hydrologic regime of a stream (Baker, Richards, Loftus, & Kramer, 2004). Hydropower operation is associated with a number of serious environmental problems: water diversion, interruption of fish migration, hydropeaking, reservoir flushing, and inundation of landscapes and alteration of natural ecosystem attributes (Truffer, et al., 2003) Restoration of more natural streamflow regimes is considered by many to be an essential component of aquatic life restoration efforts in streams (Richter, Baumgartner, Powell, & Braun, 1996). The restoration of riverine ecosystems below reservoir impoundments requires new operational rules that can help reintroduce components of natural flow variation. Upcoming FERC re-licensing provides an opportunity for these facilities operations to be collectively studied and altered to account for these emerging ecological objectives. This paper presents the development of a linear programming model of this integrated system of reservoirs that can explore the tradeoffs between traditional reservoir hydropower management objectives and the maintenance of ecologically acceptable streamflow variability.

There is an existing, well-established set of tools for evaluating reservoir operations' impact on different water use objectives (Loucks, van Beek, Stedinger, Dijkman, & Villars, 2005).

Optimization modeling is a popular approach to analyzing the operations in these systems for competing objectives. Despite extensive research on optimization modeling within multi-objective reservoir systems, much of the literature ignores environmental flows, and those studies that do consider instream flows generally account for them using fixed minimum flow constraints that do not allow for flexibility in tradeoffs between environmental and human needs (Homa, et al., 2005) (Jager & Smith, 2008). There are also some studies utilizing simulation modeling to establish these tradeoffs (Shiau & Wu, 2007). Simulation tools cannot establish the same optimal tradeoffs possible with optimization models. This study focuses on optimization

approaches for balancing water allocation between ecosystem and societal uses, with an emphasis on the maintenance of natural streamflow regime.

Because this study's purpose is to explore coordinated release rules within a reservoir system for the maintenance of natural streamflow variability, a linear programming optimization approach is adopted. Using a linear model allows very large and complex problems to be solved however, all relationships between variables must be continuous and related through addition, subtraction, equality and inequality. Linearization separates the model from reality; however, it is necessary to linearize components of the model to reach an optimal solution. Hydropower production, for example, is influenced by both volume of flow released and the head above the hydropower turbine. To linearize this, the optimization models used in this thesis assumes that head remains constant.

Model objectives are expressions of system performance that can either be maximized or minimized in the optimization framework. One or more objectives make up the objective function, the guiding statement of an optimization model. The components of the objective function provide a quantitative measurement of system performance. Vogel et. al. 2007 reviewed the water resources optimization literature and found studies that have explored tradeoffs between ecological and human water needs in multiple objective reservoir management.

Decision variables such as reservoir release and storages are values the model optimizes. The model assigns values to different decision variables to optimize the objective function. Model constraints limit the value of decision variables to reflect physical and operational limits for different variables such as reservoir maximum capacity, and minimum flow constraints that must

be met. Variables in the optimization model must satisfy constraints. If there is no solution that satisfies the constraints, the model is infeasible. Yeh (1985) describes typical reservoir constraints including mass balance continuity, maximum and minimum storages, maximum and minimum releases, penstock limitations, hydropower generation license limits, and contractual obligations.

Sale et al. 1982 was one of the earliest studies to examine tradeoffs of river system objectives using optimization modeling techniques (Sale, Brill, & Herricks, 1982). Their study employed linear programming to determine optimal release schedules required to maximize the minimum weighted usable area index for fisheries health in a river in Illinois. Others embedded a habitat capacity model within a linear program of a reservoir system to determine new minimum flow requirements for different seasons and hydrologic year types (Cardwell, Jager, & Sale, 1996) Neither of these studies, however, investigated dynamic streamflow targets.

Some recommend a holistic approach to management that uses appropriate understanding of the natural system to maximize both ecological benefits and benefits associated with energy production (Jager & Smith, 2008). As part of a larger study of the Connecticut River sponsored by the Nature Conservancy and the US Army Corps of Engineers, two workshops were held with aquatic scientists and biologists familiar with species and eco-systems unique to the Connecticut River. These workshops provided an opportunity for the aquatic scientists and biologists to specify appropriate flow regime characteristics for different ecological species of their specialty.

A review of the water resources optimization literature found a handful of studies that have explored tradeoffs between ecological and human water needs in multi-objective reservoir management (Vogel, et al., 2007). Because the purpose of this study is the exploration of

coordinated release rules of five facilities within a vast and complex basin for the maintenance of natural unimpacted streamflows, a linear programming optimization approach is considered. The two optimization objectives in CREAM are 1) maximizing hydropower value produced through the five facilities and 2) reproducing unimpacted natural streamflows at ecological locations of interest with some flexibility on allowable deviation from unimpacted flow. This study presents the development and preliminary results for CREAM within the Connecticut River. The model is designed to explore tradeoffs between hydropower based water use objective and the maintenance of environmental flow targets.

## **2.1. SUSTAINABLE RIVER MANAGEMENT**

The beneficiaries of environmental flow protection are numerous, arguably extending to the whole of society. Environmental flow requirements should be viewed not as a use or allocation of water, but as a necessary and desirable outcome of sustainable water management. The existence of adequate environmental flows is an indicator that water resources are being managed for long-term sustainability (Richter B. , 2010) There is no rule-of-thumb for defining the amount of water that should remain in a river to satisfy environmental flow needs. Scientists have advanced in their ability to predict ecological consequences as a result of hydrologic alteration, how much water should remain as environmental flow in a river are societal decisions involving tradeoffs of human values and benefits. The fundamental ecological principle for the sustainable management of riverine ecosystems is the need to sustain flow characteristics that mimic the natural, climatically driven characteristics of flow. This includes the important role of floods as well as instream flows. The natural flow regime shapes the evolution of aquatic biota and ecological processes and every river has a characteristic flow regime and an associated biotic community (Petts, 2009) The development of instream flows for this model have been

established with the underlying assumption that attempting to bring the flow regime closer to the estimated unimpacted natural condition would be sustainable and beneficial to all users of water.

Sustainability in water management will require that human impacts on the natural variability of water chemistry and hydrologic processes are constrained within specific limits, as agreed to by water managers and stakeholders. This model will provide valuable insight to stakeholders involved in the decision making process for the Connecticut River.

## **2.2. CONNECTICUT RIVER PROJECT OVERVIEW**

This research supports Connecticut River Watershed Project, a collaborative project of the U.S. Army Corps of Engineers (USACE), The Nature Conservancy (TNC), the University of Massachusetts Amherst (UMass), and the U.S. Geological Survey (USGS). The Connecticut River Watershed Project will identify management modifications for influential dams in the Connecticut River Basin to increase environmental benefits while maintaining existing human uses such as water supply, flood control, and hydropower generation. The overall process for modeling the five hydropower facilities in CREAM will occur in the years prior to the 2018 Federal Energy Regulatory Commission (FERC) re-licensing of five major hydropower facilities along the mainstem of the Connecticut River. Through the Federal Power Act, the US FERC is the sole issuer of licenses for nonfederal hydroelectric operations. Since 2005, licenses often undergo an Integrated Licensing Process, which provides opportunity for affected parties to recommend issues for consultative investigation and possible mitigation, such as the impacts on downstream ecosystems.

A basin-wide daily optimization model, sub-daily re-licensed facilities optimization model, a basin wide daily simulation model, and a sub-daily re-licensed facilities simulation model will be

constructed for this project. The optimization models will determine possible environmental and hydropower benefits, explore coordinated release decisions, and explore optimal operating decisions for specific objectives.

The focus of this paper is on the construction of CREAM, a sub-daily optimization model of the five hydropower facilities on the mainstem of the Connecticut River that are undergoing the FERC re-licensing process. The sub-daily optimization model allows water managers and key stakeholders to evaluate environmental and economic outcomes based on different coordinated management scenarios. These models will be increasingly important during the re-licensing process to allow stakeholders and operators to understand the coordinated operational adjustments that can be made to benefit existing hydropower operational objectives and emerging environmental concerns. The focus of the CREAM is to analyze how sub-daily operations at five hydropower facilities impacts the natural flow regime of the Connecticut River. Zimmerman et. al. (2009) identify risk of hydrologic alteration from sub-daily flow variation for Connecticut River tributaries and Mainstem. The portion of river where the facilities are located are classified as ‘Severely Impacted’ with sub-daily flow variation outside the range expected for unregulated rivers.

The five facilities undergoing relicensing are modeled in both the full-basin daily optimization and simulation models, but also in the finer timestep hourly optimization and simulation models. The hourly time steps used in these models will provide insight into how hydropower operations at these facilities can have an impact on the natural hydrology of the Connecticut River. For applications such as hydropower generation, a daily timestep may not be sufficient to model the desired system operations since hydropower reservoirs commonly make releases based on energy prices, which fluctuate on a sub-daily basis (Adamec 2011). CREAM utilizes an hourly

timestep to investigate the sub-daily variations in flow regimes that are important for hydropower production and natural ecosystem health.

A unique component of this project is direct stakeholder interaction. With the implementation of a set of specified environmental flows at designated *eco-nodes* at different locations throughout the basin, an interactive discussion with a variety of aquatic scientists and biologists occurred. Several workshops provided the scientists and biologists an opportunity to discuss the methods used in the optimization model dealing with meeting specific species requirements. This unique component of the project provides more validity to the results of the model.

### **3. BACKGROUND**

#### **3.1. INTRODUCTION TO RE-LICENSING**

The Integrated Licensing Process is intended to streamline the Federal Energy Regulatory Commission (FERC) licensing process by providing a predictable, efficient, and timely licensing process that continues to ensure adequate resource protections. The process includes a process plan and schedule for each project, guidelines and options for the effective participation, communication protocols, and access to documents generated in the process. The five facilities in this study all are being relicensed together, with the new licenses set to expire in 2018.

FERC licenses last between 30 and 50 years. Because of their longevity, forecasting the future conditions and operational requirements under which the facility will operate is important for the length of the license. This provides a unique opportunity to promote long term changes in the hydrologic regime of the Connecticut River for years to come.

### **3.2. OPERATORS AND OTHER STAKEHOLDERS**

The five facilities undergoing relicensing are owned by two companies, TransCanada and GDF Suez FirstLight. These two companies operate the facilities for hydropower and are owned by large multi-national energy conglomerates. The main objective of these companies is to maximize hydropower value, or profit generated through the production of hydropower through its facilities.

The Nature Conservancy (TNC) is undertaking the coordination of the Connecticut River Project with the purpose of determining how management of various dams and water systems can be modified for environmental benefits while maintaining traditional operating objectives. The Nature Conservancy aims to

- Increase diversity and abundance of conservation targets
- Restore timing and magnitude of high flow events to increase floodplain inundation and restore channel processes
- Reduce within-day flow variability to improve quality and quantity of aquatic habitat and
- Seek ways to ameliorate effects of large water withdrawals and maintain healthy ecosystems

### **3.3. SYSTEM PHYSICAL DESCRIPTION**

The Connecticut River Basin is the largest and most highly developed river system in New England. Draining a total of 11,985 square miles, the river flows southward for 410 river miles from its headwaters in the Connecticut Lakes in northern New Hampshire and Canada to the Long Island Sound passing the states of New Hampshire, Vermont, Massachusetts, and



Connecticut. The basin contains thousands of dams along its mainstem and tributaries, many of which are relic low-head hydro projects developed for power production during the Industrial Revolution.

Hydropower reservoirs are characterized into three categories: Hydropower reservoirs with storage, Run of River hydropower facilities, and Pumped Storage facilities. Hydropower Storage reservoirs have large long term storage that can be released at different seasons or over several seasons. Run of River facilities have limited storage and operate such that daily inflow is roughly equal to daily outflow. There is very little active storage in these facilities. Pumped Storage facilities operate separate reservoirs connected via a pipeline. Water is pumped to an upper storage reservoir during off-peak energy prices and returned to generate power during peak load times. (WURBS 1991). The hourly optimization model of the Connecticut River includes 4 Run of River hydropower facilities and one Pumped Storage facility between miles one hundred twenty two and two hundred seventeen in the states of Massachusetts, Vermont and New Hampshire.

### **3.3.1. Wilder Project**

The Wilder Project is located on the Connecticut River at river mile 217.4 approximately 1.5 miles upstream of the confluence with the White River and 7 miles downstream of the confluence with the Ompompanoosuc River. The dam is a concrete gravity structure extending across the Connecticut River from Hartford, VT, to Lebanon, NH. The concrete impoundment is 59 feet high and the tailwater pool extends upstream 45 miles from the dam. The dam has a useable storage capacity of 13,350 acre-feet with a five-foot drawdown.

The powerhouse at Wilder contains three generating units with a total installed capacity of 35.6 MW. It generated an average of 153,738 MWh annually from 1982-2011. The maximum flow through the turbines is 12,700 cfs.

The project is operated as a hydropower facility. During typical hydropower generation, releases vary between the required minimum flow of 675 cfs and the facility's approximate full hydraulic capacity of 12,700 cfs. During periods of sustained high flow, the facility's generation is continuous and peaking operations are not used. Wilder is operated in coordination with the other TransCanada projects on the Connecticut River.

### **3.3.2. Bellows Falls Project**

The Bellows Falls Project is located on the Connecticut River at river mile 173.7, approximately 1 mile upstream of the confluence with the Saxtons River and 3 miles downstream of the confluence with the Williams River at the upper end of a sharp bend of the Connecticut River in Bellows Falls, VT. The dam is a concrete gravity structure extending across the Connecticut River from the town of Rockingham, CT to the town of Walpole, NH. The concrete impoundment is 30 feet high. The tailwater pool extends upstream 26 miles from the dam and has a useable storage capacity of 7,476 acre-ft with a three-foot drawdown.

The powerhouse at Bellows Falls contains three generating units with a installed capacity of 40.8 MW. That facility generated an average of 250,249 MWh annually from 2000-2011. The maximum flow through the turbines at Bellows Falls is 11,010 cfs.

The project is operated as a peaking hydropower project. During typical generating periods, downstream flows can vary between the required minimum flow of 1,083 cfs and the facility's approximate full hydraulic. During periods of sustained high flow, the project generation is

continuous and peaking operations are not utilized. Bellows Falls operations are coordinated with the other TransCanada projects on the Connecticut River.

### **3.3.3. Vernon Project**

The Vernon project is located on the Connecticut River at river mile 141.9, approximately 2 miles upstream of the confluence with the Ashuelot River and 7.4 miles downstream of the confluence with the West River. The dam is a composite overflow and non-overflow ogee type concrete gravity structure extending across the Connecticut River from Hinsdale, NH to Vernon, VT. The impoundment is 58 feet high, and the tailwater pool extends upstream for 26 miles from the dam and has a useable storage capacity of 18,300 acre-ft at an eight foot drawdown.

The powerhouse at Vernon contains ten turbine/generators with an authorized installed capacity of 32.4 MW which generated an average of 136,583 MWh annually from 2000-2011. The maximum flow through the turbines at Vernon is 17,130 cfs.

The project is operated as a peaking hydropower project. During typical generating periods, downstream flows can vary between the required minimum of 1,250 cfs and the facility's approximate full hydraulic capacity. During periods of high sustained flows, project generation is continuous and peaking operations are not used. Vernon's operations are coordinated with TransCanada's other projects on the Connecticut River.

### **3.3.4. Northfield Mountain Pumped Storage Project**

The Northfield Mountain Pumped Storage project is located approximately 5.2 miles upstream of the Turners Falls dam in the town of Northfield, MA. The upper reservoir of the Northfield Mountain project is located atop Northfield Mountain in Erving, MA, and consists of a main dam, rockfill dikes, and a concrete gravity dam. The tailrace of the project is the Turners Falls

impoundment. The upper reservoir typically operates with a 62.5 foot drawdown. Within this range, the upper reservoir has a surface area of 134 to 286 acres. The useable storage is 12,318 acre-ft. The underground powerhouse contains four reversible pump/turbines that operate at gross heads ranging from 753 to 824.5 ft. The project has an authorized FERC capacity of 1,119.2 MW. The hydraulic capacity is 15,200 cfs in pumping mode, and 20,000 cfs in generation mode.

The project is a pumped storage hydroelectric project, with a capability of using its full storage capacity for generating purposes. The project utilizes the Turners Falls impoundment as its lower reservoir. During pumping operations, water is pumped from the Turners Falls impoundment to the upper reservoir. In the summer and winter seasons, the Northfield Mountain project typically peaks twice a day, in the morning and late afternoon. During other months, the Northfield Mountain Project may be peaked one to two times per day, depending on energy demand or price. In both cases, water is typically pumped backed to the upper reservoir during the night or during low energy priced hours.

### **3.3.5. Turners Falls Project**

The Turners Falls Project is located on the Connecticut River at river mile 122 in the towns of Gill and Montague, Massachusetts. The project consists of two individual concrete gravity dams, referred to as Gill dam and Montague dam. The two dams are connected by a natural rock island known as Great Island. Montague dam height is 35 feet and the Gill dam is 55 feet high. The Turners Falls impoundment, which also serves as the lower reservoir for the Northfield Mountain project, is approximately 20 miles long extending upstream through the Connecticut River valley to the base of Vernon dam. The impoundment has a useable storage of 21,500 acre-ft. Approximately 5.7 miles of the impoundment is located in New Hampshire and Vermont.

Water is fed from the two dams through a power canal to the generating facilities located downstream of the impoundments.

The project includes two powerhouses, Station No. 1 and Cabot Station, which together have a FERC authorized installed capacity of 67.709 MW which generated an average of 320,140 MWh annually from 2000-2009. Station No. 1 contains seven turbine/generators of which five are currently operational. Cabot Station generating units consist of six turbines. The turbine and hydraulic capacity of the combined system is 18,000 cfs.

Shown below in **Table 2** is a table with basic information for each facility included in CREAM.

**Figure 1** shows the location of the five facilities within the Connecticut River Basin.

**Table 1** - Facility Information

<i>Facility Name</i>	<i>Maximum Storage (acre-ft)</i>	<i>Useable Storage (acre-ft)</i>	<i>Generating Capacity (MW)</i>	<i>Owner</i>	<i>Facility Type</i>
Wilder	104,000	13,350	35.6	TransCanada	Dam
Bellows Falls	43,000	7,476	40.8	TransCanada	Dam
Vernon	222,000	18,300	24.4	TransCanada	Dam
Northfield Mountain	17,000	12,318	1080.0	FirstLight	Pump Storage
Turners Falls	28,000	21,500	6.0	FirstLight	Dam

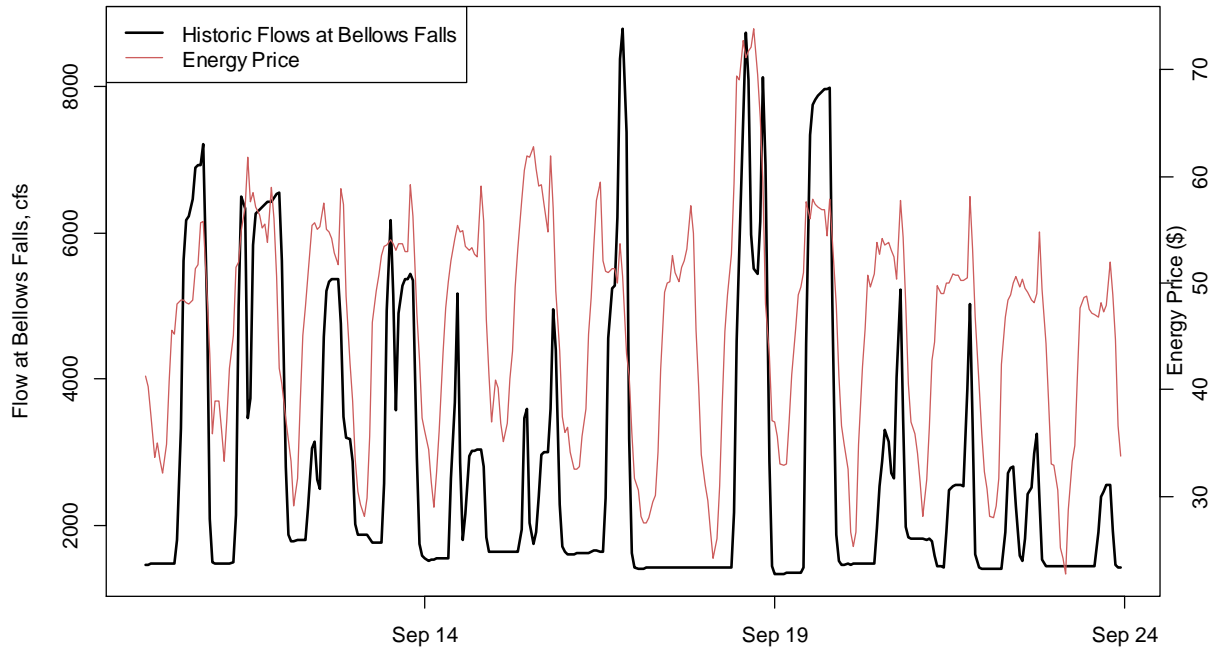


*Figure 1* - Location of the five facilities within the Connecticut River Basin. Wilder, Bellows Falls, and Vernon are located along the mainstem between the states of New Hampshire to the East and Vermont to the West. Northfield Mountain is located off the mainstem, and Turners Falls is located on the mainstem in Massachusetts.

### **3.4. CURRENT CONNECTICUT RIVER VARIABILITY**

Since the Connecticut River basin is one of the most highly regulated river systems, it is necessary to understand the existing variability in the river system at several locations. The existing conditions show how current reservoir operations are affecting the natural hydrology of the system. The USGS operates streamflow gages in the area and gage 01154500 located at North Walpole, New Hampshire, is located directly downstream of the Bellows Falls dam impoundment. This gage's location provides useful information into existing river variability.

Historic hourly gage flows were gathered for the period of record October 1990 through September 2012. **Figure 3** shows a typical month's hourly flows at this gage. There is significant variation shown every day of the month, as flows are regulated each day to meet energy demands by producing hydropower.

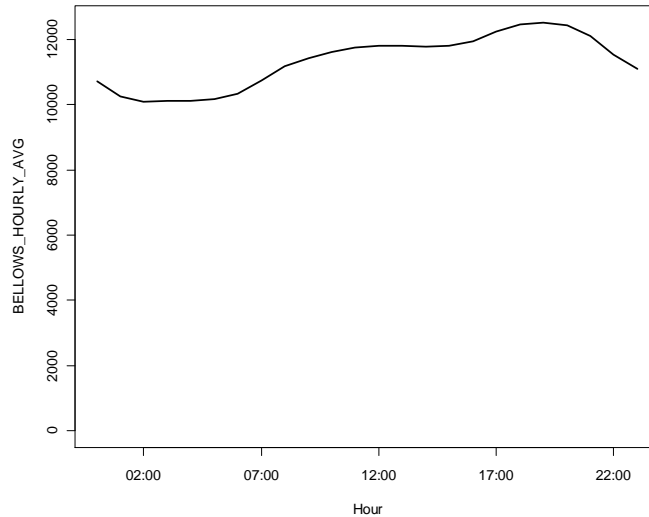


**Figure 2** - Hourly Historic Flows at USGS Gage Connecticut River at North Walpole for September 2006 showing typical sub-daily variation. Releases below Bellows Falls correspond with the USGS gage. The actual hourly energy price signal is shown in Red.

This figure shows that there is significant alteration to the natural flow of the river, and everyday, the river flow is altered by as much as 8000 cubic feet per second to meet hydropower peaking demands. The historic operations observed at Bellows Falls follow a pattern that closely resembles the actual hourly energy price signal.

The Julian Hour average flow at this gage location provides some insight into the typical daily cycle of flows in the system. **Figure 3** shows the average flow at the USGS North Walpole gage #01154500. There is average variation of nearly 2000 cfs per day over the entire period of

record. Lower flows are reported in the early morning with higher flows in the afternoon and the highest flows occurring in the evening.



**Figure 3** - Average daily flow at USGS Gage #01154500 Connecticut River at North Walpole. The flows on an average day range from 10000 cfs early in the morning (when hydropower facilities are storing water to be used for hydropower generation later in the day) to over 12000 cfs (when facilities are releasing water through turbines and producing power).

The existing conditions of the stream show that a sub-daily timestep is necessary to capture the essence of reservoir operations along the Connecticut River. For hydropower applications, a daily timestep may not be sufficient to model the desired system operations since hydropower facilities typically operate on a sub-daily timestep. Hydropower facilities operate to meet local or regional daily energy demand patterns. These operations can result in lowered flood peaks, followed by a rapidly fluctuating hydrologic pattern to the downstream river corresponding to alternating periods of power generation (Richter & Thomas, Restoring Environmental Flows by Modifying Dam Operations, 2007). These episodes of power generation are followed by periods in which dam releases may be largely or completely curtailed to allow the reservoir to refill in-between power-generation cycles. These typical operations produce a blocky or saw-blade shape on outflow hydrographs. When the dam is generating power, flow through the generating



turbines can be greater than natural, and when the dam is refilling its reservoir, flows released can be much less than natural. Studies in the past have developed approaches for assessing the effects of dam operations on sub-daily flow by characterizing sub-daily variation in river flows downstream of dams and comparing these with unregulated sites (Zimmerman, Letcher, Nislow, Lutz, & MaGilligan, 2009).

When more than one hydropower dam exists on a river, opportunities for modifying the function of any one dam will likely be increased considerably. In many rivers around the world, “cascades” of hydropower dams have been constructed. In a cascade of close reservoirs with short distances between them, the ecological health and ecosystem services provided by upstream dams may have already been so compromised that it would do little additional harm to generate more power at the upper dams. Oftentimes, the operations of these cascade dams is not fully integrated or coordinated (Richter & Thomas, Restoring Environmental Flows by Modifying Dam Operations, 2007).

A variety of indices have been developed to describe natural flow regimes and their degree of alteration. Analysis include the Indicators of Hydrological Alteration (IHA) parameters are deemed to be particularly relevant to aquatic communities (Richter, Baumgartner, Powell, & Braun, 1996). Studies on the effects of dams on sub-daily flow variation have used several metrics including flashiness indices (Zimmerman, Letcher, Nislow, Lutz, & MaGilligan, 2009).

#### **4. OPTIMIZATION FRAMEWORK**

CREAM is formulated as a linear programming optimization model. The LINGO<sup>TM</sup> software environment was used to create the model framework. This model simulates the operations of the five dams on the Connecticut River undergoing the relicensing process: Wilder Dam,

Bellows Falls Dam, Vernon Dam, Northfield Mountain Pumped Storage Project, and Turners Falls Dam. The model operates on an hourly timestep, contains constraints for maximum and minimum storage (useable storage) and releases where necessary, and provides the opportunity to optimize over objectives that enable the provision of prescribed operations for generation of revenue from hydroelectricity production. When operating over a one year period, the model results in over 700,000 constraints and over 560,000 variables. Using a powerful desktop computer (circa 2013), the model can produce an optimal solution in approximately 15 minutes. The model runs sequential years over the historic hydrologic record, and the full hydrologic record takes nearly 6 days. The model output is processed using the statistical open-source software environment “R,” which provides the ability to create and analyze the time series of system storages and releases produced.

The general structure of CREAM is to minimize the value of penalties that violate different operational objectives. The general mathematic structure of CREAM is given as

$$\min_{\mathbf{x}} Z = \sum_{t=1}^T \sum_{i=1}^N c_i \times f_{t,i}(x_{t,i})$$

subject to

$$\mathbf{Ax} \leq \mathbf{b}$$

where  $Z$  is the weighted sum of penalties incurred for the system,  $x_{t,i}$  equals the value of the  $i^{\text{th}}$  decision variable at time  $t$ ,  $f_{t,i}(x_{t,i})$  equals the loss function for the  $i^{\text{th}}$  decision variable at time  $t$ , and  $c_i$  equals the weight for the penalty on the  $i^{\text{th}}$  decision variable.

The primary decision variables include reservoir releases, reservoir storages, hydropower revenue, and flow at specific eco-node locations. The matrix  $A$  and vector  $b$  represent various constraints on the decision variables  $X$ , including continuity requirements, storage capacities, physical turbine production limits, facility license capacity, and ramping constraints, among others.

#### **4.1. INPUT HYDROLOGIC DATA**

The optimization model is run over the daily hydrologic period of record available for the basin (January 1, 1961 – December 31, 2003). Daily hydrologic inputs for each node in the model were developed from the Connecticut River UnImpacted Streamflow Estimation (CRUISE) tool (Archfield et al. 2012) produced by the United States Geologic Survey (USGS). The CRUISE tool estimates flow at a particular point in the basin in two stages. First, the flow duration curve is estimated for the location of interest. This is done using a series of regressions between flow quantiles and watershed characteristics. Next, a time series of flows from an index gage (an unregulated gage with continuous daily flows over the period of record) is transferred to the unregulated location through a flow duration curve mapping technique. The CRUISE tool was used to develop forty-three years of continuous, daily, incremental streamflow data at each of the nodes in the model. Hourly flows were then interpolated between the daily flows from CRUISE. The interpolation technique is an estimate of hourly flow that does not include any sub-daily

variation, but a natural system would not have the same amount of sub-daily variability. An interpolated method is appropriate for a natural system. These streamflow data are estimates of the natural (unregulated) flow entering a node location on any given timestep during the period of record and serve as the driving input data for the model. The period of record for the CRUISE data is October 1, 1960 through September 30, 2004.

#### **4.2. RESERVOIR PERFORMANCE OBJECTIVE**

The reservoirs in CREAM are hydropower facilities and they operate for revenue generation from the sale of electricity, which drives operations. A daily electricity price signal was developed from regional, historic locational marginal pricing (LMP) data available over the 2006 calendar year and gathered from the regional transmission organization ISO New England. The resolution of these data is hourly and these prices were averaged for each hour of the year. This same hourly price signal was repeated for each year of the simulation model, which is used to provide insight into daily fluctuation that are transparent in energy prices. Daily revenue for hydropower facilities are calculated directly in the model as the product of electricity price and the power produced from hourly discharge rates passing through facility turbines for each timestep. Total cumulative revenue for the entire run period is then maximized in the objective function.

Optimizing the system through the use of LMP energy price data develops the status quo of the system. Though many considerations are often deliberated when reservoir operators decide upon daily reservoir management strategies in these facilities, the use of solely energy price data to drive reservoir operations adequately represents the average operating procedures for all facilities. The primary purpose of CREAM is to determine how average operations could change to better preserve streamflows for ecological objectives. The use of energy price to drive

hydropower operations provides a baseline operational regime against which ecological flow needs can be traded off, providing valuable insight into how average operations could be altered to improve ecosystem functions.

### **4.3. ECOLOGICAL PERFORMANCE OBJECTIVE**

Ecological flow targets in the objective function are used to minimize deviations between modeled and natural flow for each optimized timestep. These targets apply to four eco-node locations within the five project geographic scope of CREAM along the Connecticut River. For each eco-node, a unique dynamic convex loss function is derived for each timestep that reflects the allowable flow deviation demands of ecological species during that timestep.

The eco-node locations for this study are part of a larger list of eco-nodes throughout the entire Connecticut River Basin that were identified by The Nature Conservancy (TNC). Streamflows at these locations are important for maintaining habitat and providing cues for lifecycle processes for various native species in the Connecticut River Basin, including diadromous fish, resident fish, macro-invertebrates, mussel species, and riparian floodplain vegetation, among others. On March 10-11, 2011, a 2-day workshop was held by TNC to gather the expertise of aquatic scientists, biologists, and other environmental specialists from across the watershed to determine allowable levels of flow alteration that different native species can tolerate at different periods of year. A second, 1-day workshop and several webinars were held in November 2012 to ensure that the environmental specialists approved of how the flow prescriptions were implemented in the model. *Figure 4* below shows a map of the eco-nodes implemented in CREAM. *Table 3* shows the specific eco-species targeted at each location.

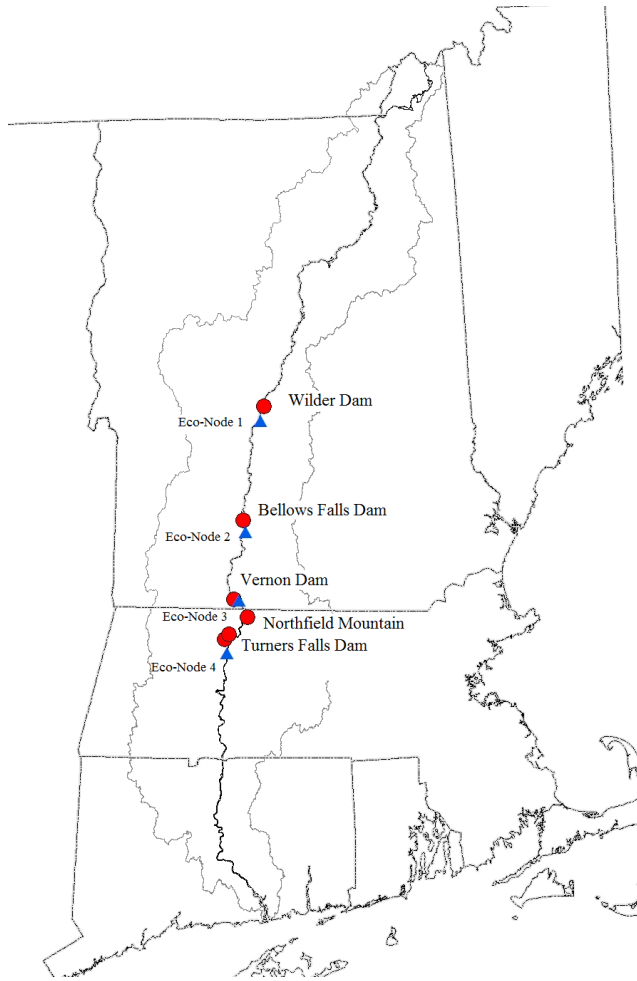


Figure 4 - Map of the Hydropower Facilities and Eco-Node locations

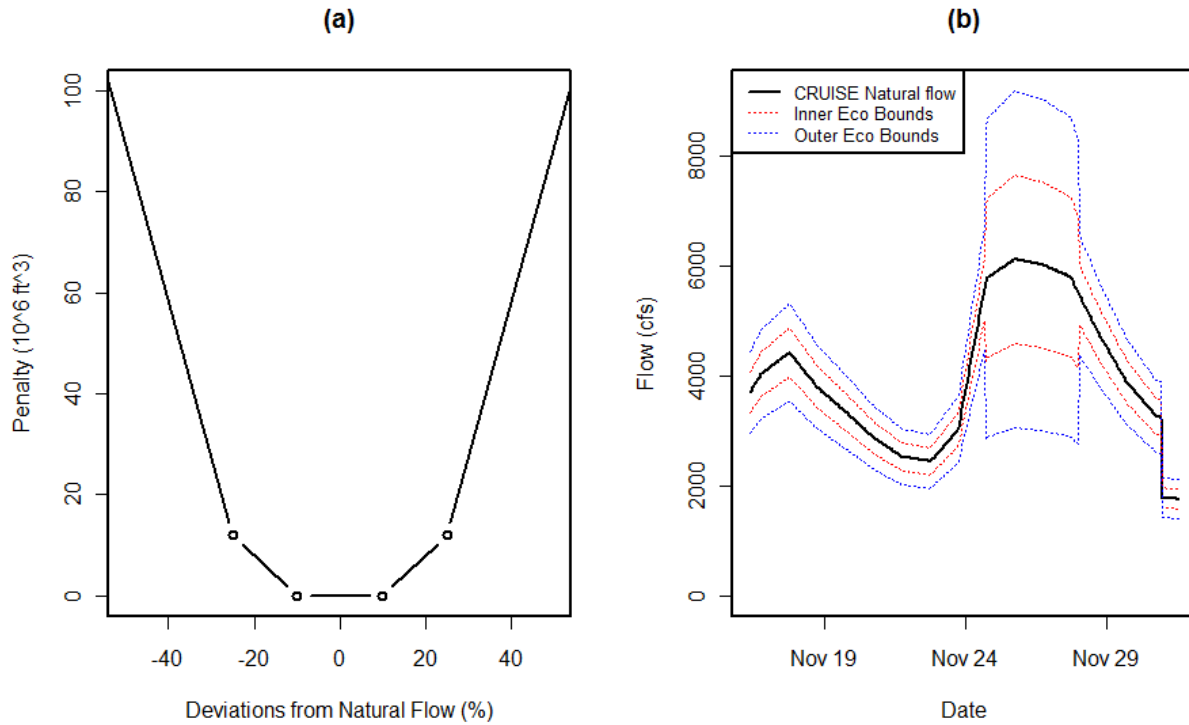
Table 2 - Eco-node targeted species

<i>Eco-Node</i>	<i>Location</i>	<i>Floodplain Health</i>	<i>Tiger Beetles</i>	<i>Mussels</i>	<i>Diadromous Fish</i>	<i>Resident Fish</i>
Eco-Node 1	below Wilder	X	X	X	X	X
Eco-Node 2	below Bellows Falls	X	X	X	X	X
Eco-Node 3	below Vernon	X			X	X
Eco-Node 4	Below Turners Falls	X	X	X	X	X

The discussions from the March 2011 workshop led to the creation of flow recommendations for each species for each calendar month. The majority of these proposed recommendations designate an allowable percent deviation from natural flow that can occur in a specific month without damaging the health of a given species and receiving a penalty in the optimization model objective function. The allowable percent deviations can change for different magnitudes of natural flow which are categorized as monthly quantile ranges of river flow. For a given species and month, a recommendation designates the percentage that flow can be altered from what it would have been naturally, as estimated using the CRUISE tool. For example, a recommendation for resident fish states that flows during all months of the year can be altered by +/-10% at low flows (flows less than  $Q_{75}$ ) or by +/-25% at high flows (flows greater than  $Q_{75}$ ). If there is a timestep where flows exceed their allowable deviation from what would have occurred naturally at a given eco-node location using CRUISE data, a penalty is incurred in the model objective function. The penalty is derived from a piecewise linear, convex loss function approximating an exponential penalty as deviations from natural flow increase.

*Figure 5a* shows a typical penalty function used for ecological targets in the model. The penalty function is comprised of 4 vertices. The inner two points represent the allowable percent deviation proposed in the flow recommendations. Reservoir management can alter flow within this range without incurring any penalty. Once flow is modeled to exceed these allowable deviation values, a penalty is incurred proportional to the magnitude of deviation relative to the slope  $S_1$  on the loss function. The outer two vertices reflect a threshold of deviation beyond which penalties become more severe. Once modeled flows deviate from the level designated by the second inflection point, the penalty grows at a higher proportional rate,  $S_2$ , greater than  $S_1$ . This function is applied for all ecological flow targets in the model. All targets are weighted

equally and the number of vertices and values for slopes S1 and S2 are kept constant for all ecological penalty functions.



**Figure 5 – a)** An example of a variable penalty function for an ecological streamflow target for a particular ecological species, calendar month, and magnitude of flow. **b)** The vertices of these penalty functions can be visualized as dynamic bounds (red and blue dotted line) surrounding estimates of natural (black) flow through time. Penalties are incurred in the objective function when modeled streamflow at this location deviates beyond the first set of bounds. Penalties increase in magnitude when the modeled flow exceeds the second set of bounds.

For a given eco-node location and species, the ecological penalty function dynamically changes each timestep depending on the month of flow, and the magnitude of the estimated natural flow. Ecosystem flow prescriptions are divided into monthly targets. These penalty functions can best be visualized as bounds around the natural estimated streamflow within which reservoirs can operate without incurring a penalty. **Figure 5b** shows a sample of CRUISE estimated natural flow for a two week period at an eco-node, as well as two sets of bounds. The inner set of



bounds reflects the first tier of penalty (the inner vertices in *Figure 5a*). Note how the range of these bounds about the natural flow changes depending on the magnitude of the natural flow. After November 24<sup>th</sup>, the CRUISE natural flow is predicted to be higher. This flow falls within a higher range flow quantile and the allowable deviation from natural flow during this time increases, as visible by the expanding bounds between November 24<sup>th</sup> and November 29<sup>th</sup>. The outer set of bounds represents the second tier of penalties (the outer vertices in *Figure 5a*). Tight penalty bounds over a given period suggest that the species at this location greatly depend on natural flow variability during that time of year and magnitude of flow. Wider bounds over a period suggest that reservoirs have more flexibility to alter flow at that location without overly disrupting the natural hydrology and ecology. The ecological objective function incentivizes the maintenance of natural flow at important ecological locations within a certain range.

Further work can be done to assess the sensitivity of the penalty function allowable deviations developed by The Nature Conservancy in conjunction with scientists and biologists. Since the research in this field is emerging, it can be beneficial to assess the true benefits associated with a wide variety of penalty function deviations as implemented into this model. Additional work can be done to assess the priorities for each eco-node location and targeted eco-species. CREAM weights all eco-node locations the same in the objective function, as is the same for all different eco-species. Future research can investigate the spatial and species priority of eco-nodes within the scope of this project, and for the entire Connecticut River Basin as part of the larger Connecticut River Project.

#### **4.4. OBJECTIVE FUNCTION WEIGHTING SCHEME**

The operational and ecological penalties previously described must be appropriately established for meaningful tradeoff between the objectives. To address this need, CREAM uses a loss

function that expresses penalties in volumetric units of water (cubic feet). Penalties for deviating from ecological targets are expressed in units of volume of water per hour. To reduce the magnitude differences associated with different variables throughout the system, each primary objective term is divided by characteristic volumes that represent the size of the system being penalized. Specifically, deviations from eco-node discharge rates are divided by the average annual flow at that location. This results in a comparison of percent deviations from targets for the eco-nodes, and not a comparison in the absolute value of the deviations

Revenue generated from the sale of hydropower, another important tradeoff component, is measured in different units. This requires additional adjustment in the objective function to calculate a weighting between hydroelectric objectives and the other normalized objective terms. These weights are needed to reflect the relative importance of different penalties in the objective function and ensure reasonable status quo operations. To perform adjustments, weights for all value of hydropower were adjusted in an iterative fashion to ensure that model results adequately reproduce historic operations.

The model has hydrologic input for the period of record January 1, 1961 through December 31, 2003. The model output of time series of flows at specified locations, reservoir storages, and annual power generation values were used to validate the results from CREAM. USGS gage data used to compare model output was compiled from fifteen-minute instantaneous Water Data for the Nation. The USGS gage Connecticut River at North Walpole is located downstream of the Bellows Falls facility and is used to directly compare modeled flow at this location to historic. Historic reservoir storage levels and reservoir releases were provided by the facility owners. These historic data allows calibration of storage and releases between 1990 and 2003.

Historic hourly storage and release data was provided from the hydropower operators through the FERC relicensing process. Historic hourly flows at other river locations are collected from data provided from the USGS. These data sets are used to conduct the validation of CREAM. The process produces a set of baseline calibration weights that are used to define the status quo operations of the basin.

#### **4.5. SYSTEM CONSTRAINTS**

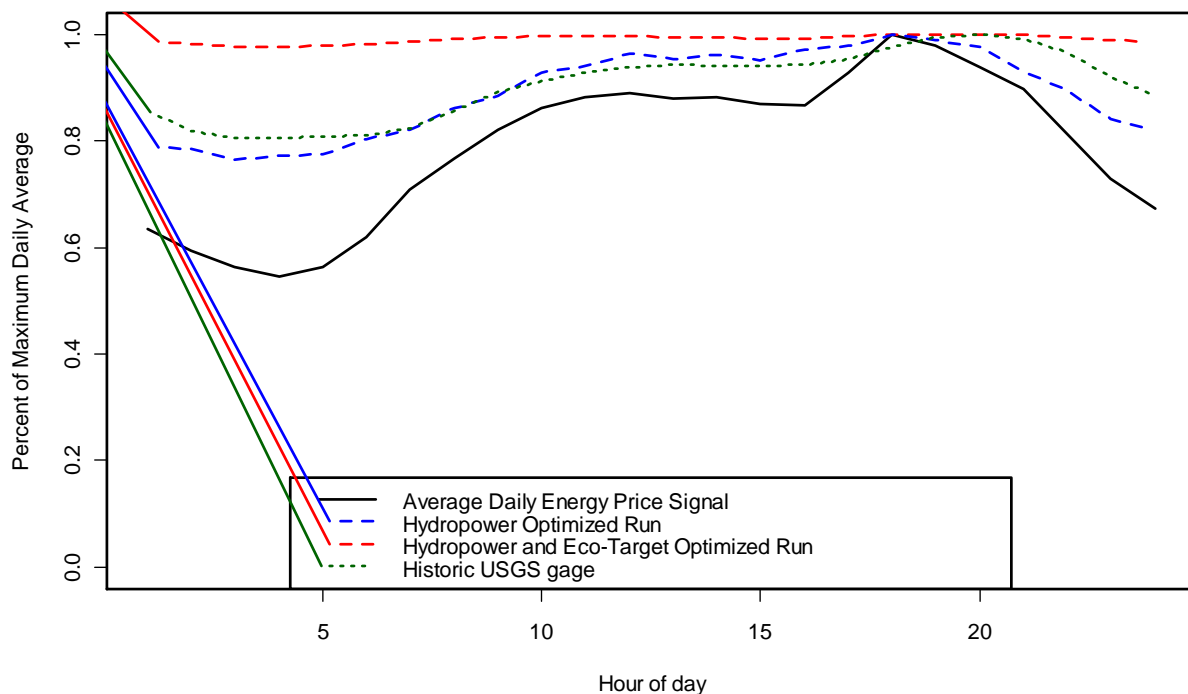
The constraints contained in CREAM reflect limitations of the system that cannot be violated due to physical capacities and considerations. These include constraints on reservoir capacity, turbine and gate discharge capacities, and ramping constraints. Ramping levels are dictated by operational reservoir discharge rules and are used to constrain fluctuations in discharge to levels representative of historic records. Continuity equations are included in CREAM as constraints set to ensure a water mass balance is preserved through the system. Evapotranspiration is ignored in mass balance equations. Minimum flow requirements at all reservoirs are included as constraints.

### **5. MODEL RESULTS**

CREAM's primary goal within the Connecticut River Project is to identify broad potential alternative reservoir operational schemes that address ecological targets in addition to current operating objectives. Optimization model outputs cannot be used directly to make specific operational changes; rather, the outputs are used to identify long-term operational trends and how the trends affect all components of the model objective function.

## 5.1. MODEL VALIDATION

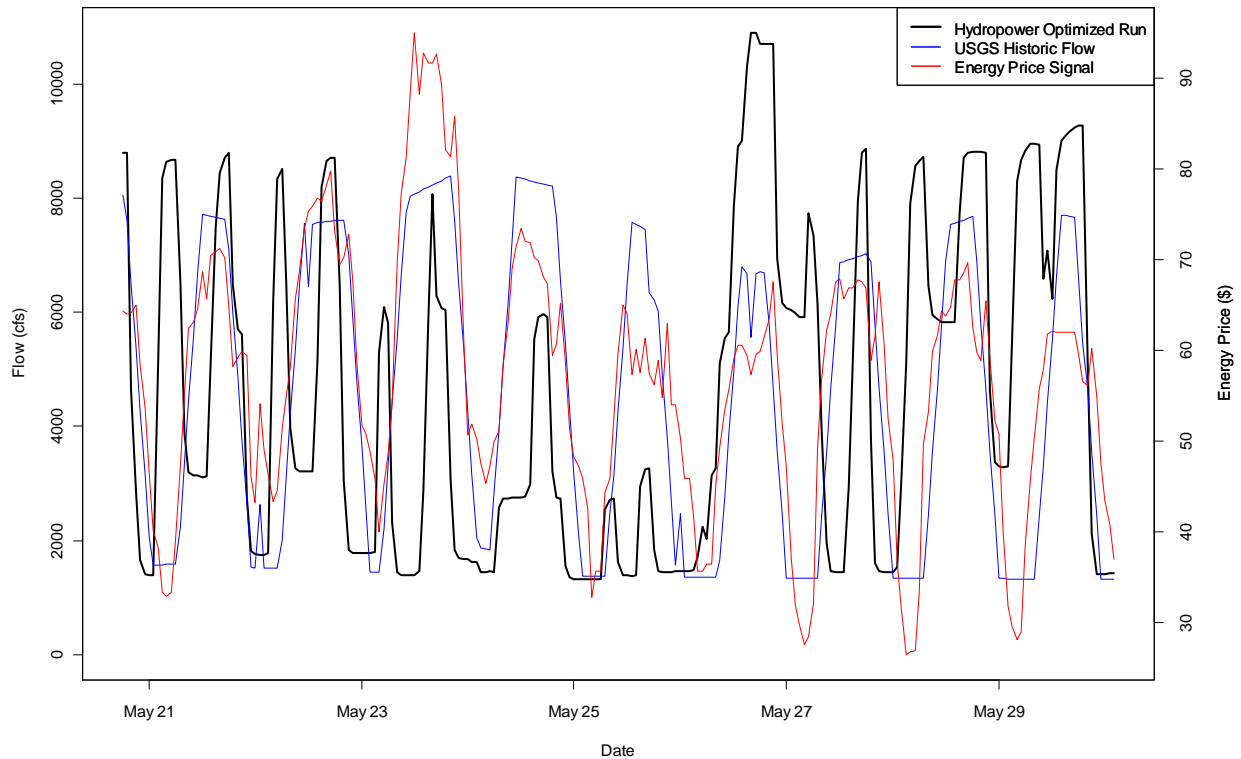
Model output was compared to appropriate historic data to ensure that the model could replicate status quo operations throughout the system. Releases from Bellows Falls can be directly compared to historic observed flows at USGS Gage Connecticut River at North Walpole. The gage is located approximately  $\frac{1}{4}$  mile downstream of the Bellows Falls impoundment and no significant side flows enter the river between the two locations. **Figure 6** compares the historic gage flow and modeled flow runs at this location as well as the average daily energy price signal.



**Figure 6** - 24 hour Normalized Average Flow at Bellows Falls. The blue line represents the historic USGS gage at North Walpole gage data, the green line represents the modeled releases from Bellows Falls, and the grey line represents typical energy price signal.

The modeled flows closely track the sub-daily variation pattern seen at the USGS gage. These flows vary in response to energy price throughout the day. Hydropower operators take advantage of a persistent daily energy price signal. When the demand is low (generally during

early morning hours) the value of the energy produced is low. Demand increases throughout the day and the value of energy production increases. Demand, energy price, and energy production peak in the evening and night. This price signal drives the operations and flow fluctuations at each facility. For Northfield Mountain Pump Storage Project, the facility operates under a store or produce plan, and the facility takes advantage of this daily consistent energy price signal to make profit. Northfield uses energy during off-peak periods to pump water to the upper reservoir when energy prices are low. When the demand increases and energy price increases in the afternoon and early evening hours, Northfield releases water and generate electricity. Although there is a net energy loss in this process, Northfield generates a new profit because of this daily price fluctuation. *Figure 7* shows 10 day time period comparing hydropower optimized flows and USGS historic flow. The modeled hydropower optimized run shows the same subdaily patterns of rising and falling each day. CREAM utilizes perfect foresight of the nuances in the subdaily energy price signal to frequently make more reversals per day that the historic period of record. This perfect foresight allows CREAM to optimize and generate the maximum amount of hydropower taking advantage of these small changes in energy price. Since the energy price signal was for 2006, and the model was run from 1961-2003, it is important to remember that the energy price signal that CREAM is optimizing for is not the same energy price signal that was used by the operators when generating the USGS historic flows.



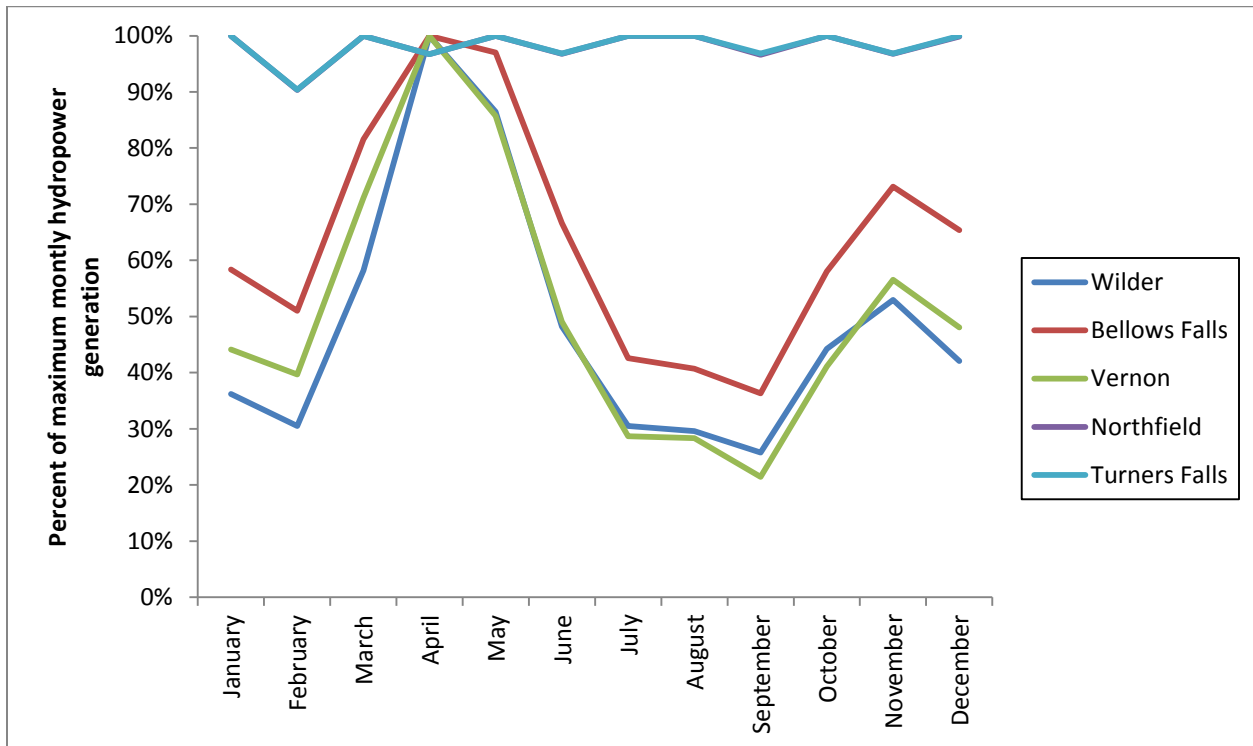
**Figure 7** - Ten day period showing USGS historic flow and Hydropower Optimized flows at Bellows Falls.

Under status quo operational conditions, CREAM performs well in modeling power generation values for the five traditional hydropower facilities when compared with historic average values provided by facility operators. **Table 4** presents the monthly average power generation values produced by CREAM and a comparison of average annual power generation values.

**Table 3** – Average Modeled Monthly Energy Price Generation for each Hydropower Facility

	<i>Wilder</i> (MWh)	<i>Bellows Falls</i> (MWh)	<i>Vernon</i> (MWh)	<i>Northfield Mountain and Turners Falls</i> (MWh)
<b>CREAM average annual generation – Hydropower run</b>	143,532	233,506	143,125	2,148,031
<b>Historic average annual generation</b>	153,738	250,249	136,583	1,463,178
<b>Percent difference</b>	6.64%	6.69%	-4.79%	-46.81%

CREAM does not predict the operations of Northfield Mountain and Turners Falls systems as well as the traditionally operated hydropower facilities further upstream in the system. *Figure 8*, shows the seasonal variation of Wilder, Bellows Falls, and Vernon. Maximum power generation occurs in the spring months, when flows are traditionally high due to snowmelt in the upper regions of the watershed. Northfield and Turners Falls are presented together since the operations from the systems are coordinated.



*Figure 8* – CREAM model results show the annual trends of hydropower generation at each facility. The traditional hydropower facilities operate with annual variation, while Northfield and Turners Falls operate with less seasonal variation.

Generation is lower over the summer when flows are low, but increase in the autumn and winter when energy prices make power generation appealing. Since Northfield Mountain and Turners Falls are operated together (i.e. the lower reservoir of Northfield Mountain is the tailwater reservoir of Turners Falls), their operations have been more difficult to model. Since the

facilities rely on each other to ensure that enough water is available to meet minimum flow requirements, in reality, their operations are coordinated.

Northfield takes advantage of daily energy price variability to ensure that a loss of energy can translate into a profit. This energy production constraint is included in the model, however, since this is not included as a component of the optimization function, and only as a constraint, (income is included as a component of the objective function) CREAM does not replicate historic generation as well as at the other traditional facilities. The estimations for energy production efficiency values were provided by operators, however, the numbers are estimates. Using an energy equation that accounts for hydropower head and turbine efficiency was not utilized, since the variability of tailwater in the reservoirs cannot be implemented in a linear optimization function. Because of hydropower production efficiency, the incentive in the optimization model to utilize Northfield to produce energy in the Northfield/Turners Falls system outweighs using Turners Falls. As a result, CREAM over predicts Northfield's hydropower income.

Since CREAM's hydropower generation value objective function is limited by a single year's energy price signal, the reality of these operations shows that Northfield is not utilized to produce as much energy as is modeled. Since the optimization solver takes advantage of perfect foresight in its solutions, the exact energy price difference during a time period (usually daily fluctuations for Northfield) is known, and the model can utilize the best volume of water to maximize the energy value produced. In reality, the accuracy of the future energy prices is limited, and operators are forced to use judgment to generate power at Northfield. The energy losses associated with Northfield, and the single year energy price signal causes the model to overestimate its generation.



## 5.2. CREAM MODEL RUNS

Model runs are produced to demonstrate the insights generated by CREAM as it incrementally evaluates the tradeoffs offered by potential operational changes. CREAM generates a plethora of output, so a structured, disciplined approach is needed in analyzing output and deriving insights. This research uses CREAM to analyze how the implementation of ecological targets can impact optimal operations within the system.

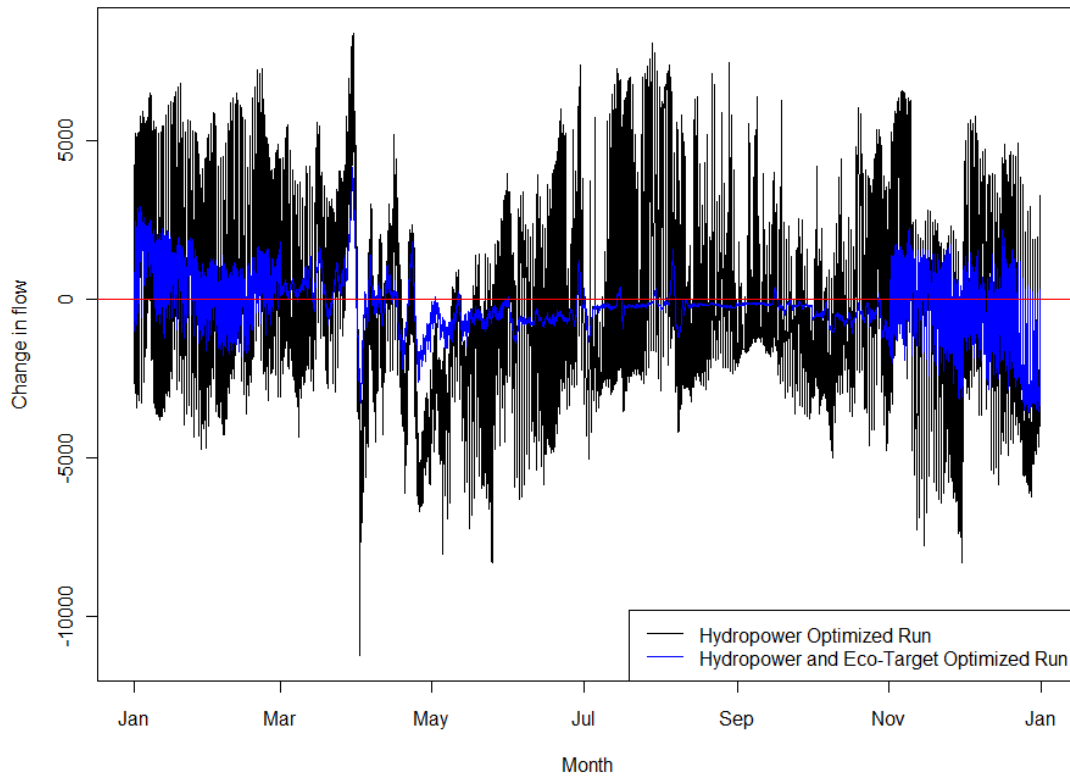
A multi-objective programming approach using the weighting method is used to generate tradeoffs between the value of energy produced and attaining desired environmental flows. Each model run was analyzed for a variety of post-processed metrics to assess how well each scenario met each objective.

Optimizing the system solely for the value of hydropower produced illustrates how optimal hydropower operations disrupt the natural flow regime while producing hydropower for the operators. The operations generated in these optimized runs closely resemble the historic patterns exhibited in the USGS historic flow data, as well as the operators' historic storage and release data (*Figure 6 & 7*). This suggests that historic operations in the system (the status quo condition) are similar to the optimized operational conditions revealed in this model. The operators are generally aware of energy price trends and currently operate the system very efficiently to generate hydropower.

A multiple hydropower and ecological objective function weighting scheme was run to investigate the flow regime when ecological targets are emphasized as part of an operations plan. For this scenario, the system is optimized for both hydropower production and meeting ecological targets. This scenario weights an objective that attempts to naturalize the flow regime

in the system. The introduction of the ecological terms as part of the optimization framework forces the model to produce flows that are more closely related to the natural flow regime. By limiting the fluctuations from natural flows, the reservoir release is more similar to the inflow into the reservoir.

These two optimization function weighting schemes have different impacts on the flow regime (*Figure 9*) and the effect that these objective function have on the deviation from CRUISE natural flow can be evaluated.



*Figure 9* -Average hourly flow deviation at all eco-nodes for two optimization model run objective function weighting schemes. Hydropower optimized run only includes the hydropower objective in CREAM, while Hydropower and Eco-Target optimized run includes both the hydropower objective and the ecological penalty objective.

To better demonstrate the alterations in streamflow that occur under different objective function weighting schemes, the average hourly deviation from the CRUISE natural flow at all four eco-node locations is calculated (*Figure 9*). This figure presents the average deviation overage over

43 years of operation for an hourly time step. The black line shows significant fluctuations, with disruptions of the natural flow regime approaching 5000 cfs often. Once the ecological objectives are weighted more heavily in the objective function, the flows at the eco-nodes more closely resemble the natural CRUISE flow. Patterns emerge, and sub-daily fluctuations show that the flow is increased in the first few months of the year, and through the summer. In the spring, flows are less than their natural values. The average deviation for the hydropower optimized run is  $\pm 2540$  cfs. For the hydropower and ecological target optimized run, the average deviation is greatly reduced, to  $\pm 700$  cfs.

When optimized only for hydropower, the system responds by timing reservoir releases to follow the energy price signal. Over the course of an average day, the flows fluctuate dramatically under this condition, as seen in *Figure 10-a*. On an average day, the sub-daily variation extends beyond 20% of the maximum daily average flow. These fluctuations are not seen, however, when the system is operated to account for the ecological targets. *Figure 10-b* shows that once ecological targets are introduced into the optimization, sub-daily fluctuation is greatly reduced.

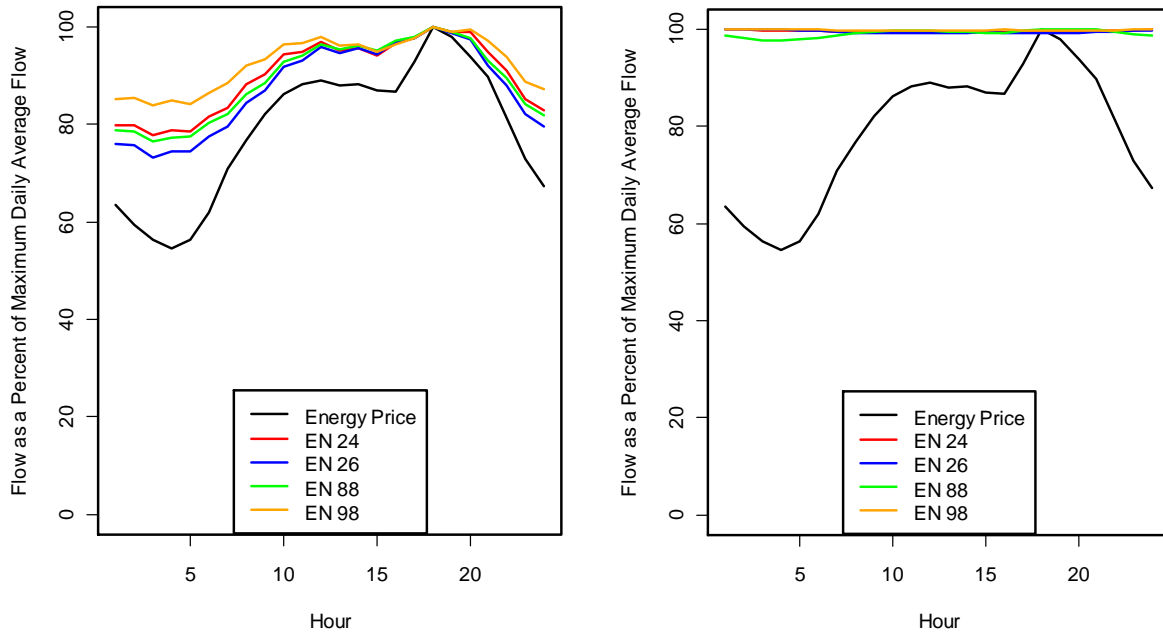


Figure 10 – a) Sub-daily Eco-Node flow fluctuations under the hydropower only optimization b) Sub-daily Eco-Node flow fluctuations under hydropower + eco optimization

### 5.3. ASSESSMENT METRICS

For each eco-node flow location, as well as releases at reservoirs, a variety of metrics is used to assess the flow regime. These metrics are used during the calibration process to calibrate the model output to historic USGS gage and historic operations data. These metrics assess and quantify sub-daily flow regime alterations that can be utilized to meet ecological targets. *Table 5* presents metrics used to assess sub-daily flow fluctuations.

Table 4 - Metrics used to assess flow fluctuations based on hourly flow data

Metric	Description	Reference
Richards-Baker flashiness	$RBF = \frac{\sum_{i=1}^n 0.5( q_{i+1} - q_i  +  q_i - q_{i-1} )}{\sum_{i=1}^n q_i}$ <p>Where q is hourly flow, n is the number of records over the analysis</p>	(Baker, Richards, Loftus, & Kramer, 2004)

index (RBF)	period (24 hrs).	
Reversals	Count of the number of changes between rising and falling periods of the hydrograph over a 24 hr period.	(Zimmerman, Letcher, Nislow, Lutz, & Magilligan, Determining the Effects of Dams on Subdaily Variation in River Flows at a Whole Basin Scale, 2009)
Percent of total flow (PTF)	$PTF = \frac{maxhourlyflow - minhourlyflow}{totalhourlydischarge}$ <p>Ratio of the range of the diurnal cycle to total daily discharge. This is a measure of the percentage of total discharge being added or removed each day.</p>	
Coefficient of daily variation	Standard deviation of hourly flows divided by mean flow for a 24 hr period.	
Eco-Node Target Index (ENTI)	$ENTI = \frac{\sum_{i=1}^n 2 * ( Dev2_{below}  + Dev2_{above}) + ( Dev1_{below}  + Dev1_{above})}{\sum_{i=1}^n q_i}$ <p>Where Dev1<sub>below</sub> and Dev1<sub>above</sub> are deviations beyond allowable flow prescription bound1, Dev2<sub>below</sub> and Dev2<sub>above</sub> are deviations beyond the second set of allowable flow prescription bounds, q is hourly flow, and n is the number of timesteps. This is a direct quantification of meeting ecological targets.</p>	

Three of the five metrics (the Richards-Baker flashiness index (RFB), ratio of the range of diurnal cycle to total discharge (PTF), and the coefficient of daily variation) quantify various properties of the volume of water that was added or removed over a 24 hour period by a reservoir, relative to the mean daily flow, or total daily discharge. These metrics are useful in determining flow fluctuations at a specific location, but do not quantify the overall pattern of variability. The Richards-Baker Flashiness Index measures oscillations in flow relative to total flow, and as such, appears to provide a useful characterization of the way water is processed through the system on an hourly scale. The Number of Reversals metric estimates overall flow

variability at a site by counting the number of changes between a rising and falling hydrograph over a 24 hour cycle. This information does not provide information about the volume of water added or removed with each reversal. The final metric is a quantification of meeting the eco-node flow prescription targets. This metric is useful to determine the severity of deviation beyond the flow prescription targets recommended at the eco-nodes.

#### **5.4. FLASHINESS THRESHOLDS**

Flashiness thresholds for each metric identify the flow characteristics above which, sub-daily flow would be considered flashy. Flashiness thresholds have been established for a variety of metrics, specifically for the Connecticut River. The flashiness thresholds were established based on previous research done by Zimmerman et. al (2009) in the Connecticut River on sub-daily flow variability. The thresholds were estimated based on the approximate inflection point on a curve of distribution of observations.

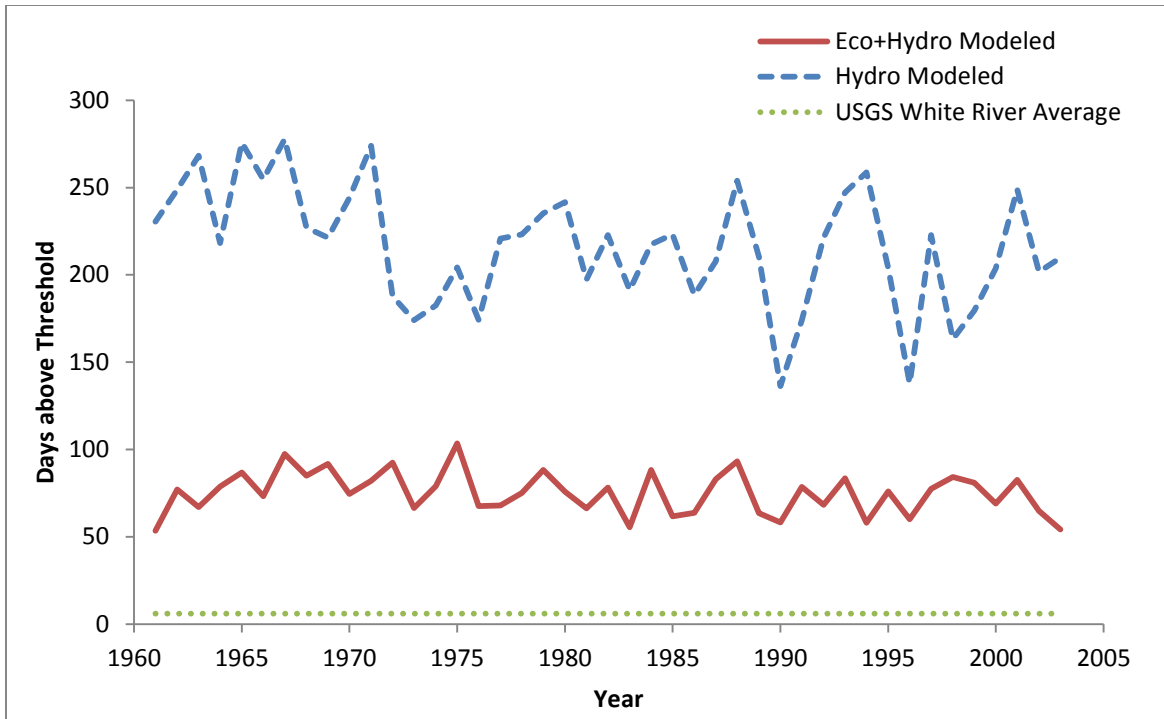
#### **5.5. FREQUENCY OF FLASHINESS FOR ASSESSMENT METRICS**

Zimmerman et. al (2009) showed that sites downstream of peaking hydropower dams had significantly more days per year with high sub-daily flow variation than unregulated sites. CREAM model results validate this hypothesis, when the model is operated to optimize for hydropower production. Their analysis showed that all sites downstream of peaking hydropower dams had more days with flashy flows than would be expected for unregulated sites for all measured metrics. The results from CREAM show that with the implementation of a dynamic eco-target into the operations of the facilities that the number of days with flashy flows would decrease per year. The White River (USGS gage 01144000 at West Hartford, Vermont) is an unregulated stream upstream of Wilder in the Connecticut River Basin which was used to provide a comparison for a natural uncontrolled system. Since a limited amount of sub-daily

data was available for this location, an average was used to assess these metrics. The period of record at this gage used for analysis is 1990-2012. There is some overlap with CREAM model results, however, an average over the entire historic period of record was used to assess metrics in this analysis.

#### **5.5.1. RICHARDS BAKER FLASHINESS INDEX**

The Richards Baker Flashiness Index (RBF) quantifies the volume of water that was added or removed over a 24-hour period relative to the total flow, and is used to provide a useful characterization of the way watersheds process hydrologic inputs into their streamflow outputs. Individual index values for each day were calculated, for each condition, and a threshold of 0.05 was used to designate flashy flow conditions. *Figure 11* presents the number of days above the threshold. This unregulated stream shows that there are, on average, few days that are considered peaky. Some years had 1 day above the threshold, with the most days above the threshold for any year at 3 days. Since the RBF is a measure of the sum of changes in hourly flow, it is expected that the natural condition would have extremely low days above this flashiness threshold.



*Figure 11* – Richards Baker Flashiness Index days above threshold. The Hydropower only modeled run shows a high number of days above the 0.05 threshold used to assess flashiness. The average unregulated White River value shows that the typical unregulated condition has significantly less days above the flashiness threshold, with the Eco + Hydro optimized run falling in between the two.

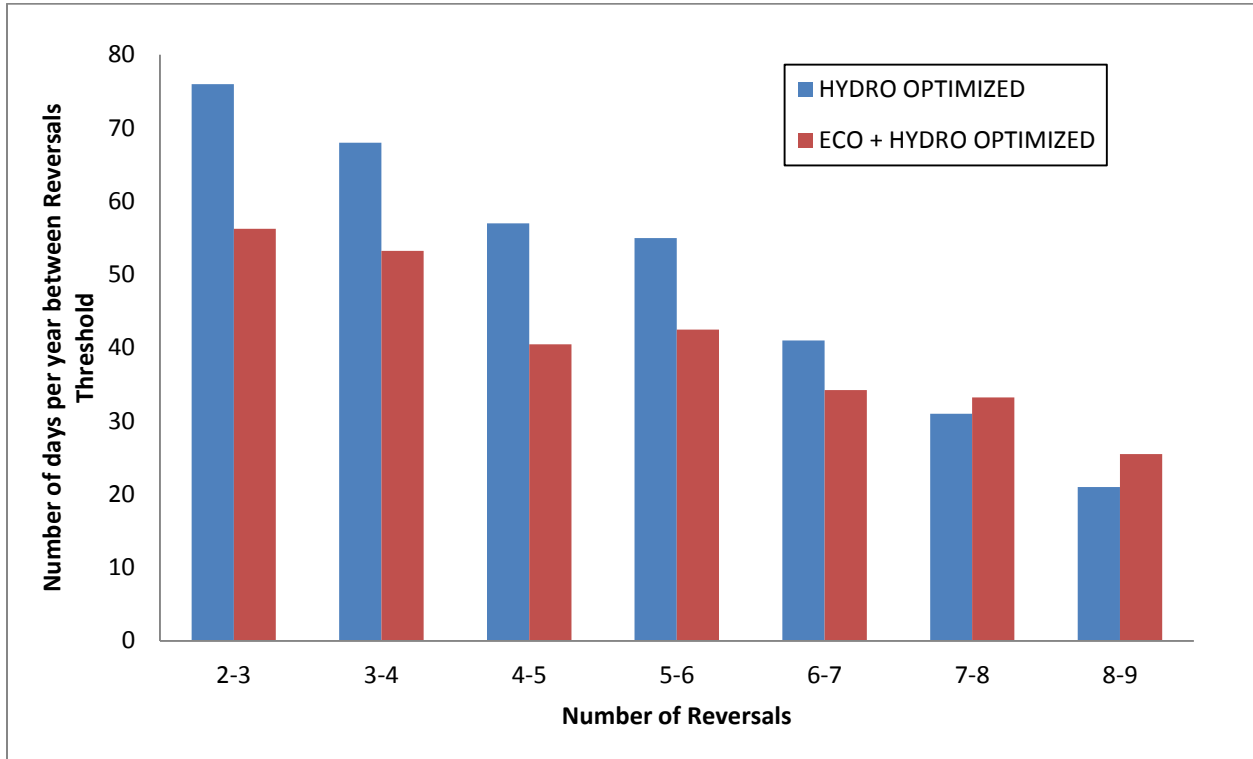
The hydropower only modeled scenario shows that there are over 150 days per year with RBF indices that exceed the flashiness threshold. This number is increased in dry years, and decreased slightly during wet years. The implementation of eco-node targets decreases the days per year that this threshold is exceeded, however, there are still between 50-100 days per year for every year where the conditions are considered flashy. Although this is still flashier than the natural condition, the addition of eco-flows improves the flow regime compared with the hydropower modeled scenario.

### 5.5.2. REVERSALS

Post-processing CREAM outputs provide insights to how the sub-daily assessments metrics for reversals are impacted under different optimization scenarios. The reversals metric is a measure of the change in rising or falling flow at each eco-node location, that is, the number of times the



hydrograph changes from rising to falling (or vice versa) over a 24-hour period provides the number of reversals per day. *Figure 12* shows the average number of days per year within a certain threshold bound, indicated on the horizontal axis.



*Figure 12* - Average days per year with reversals between thresholds, indicated on the horizontal axis.

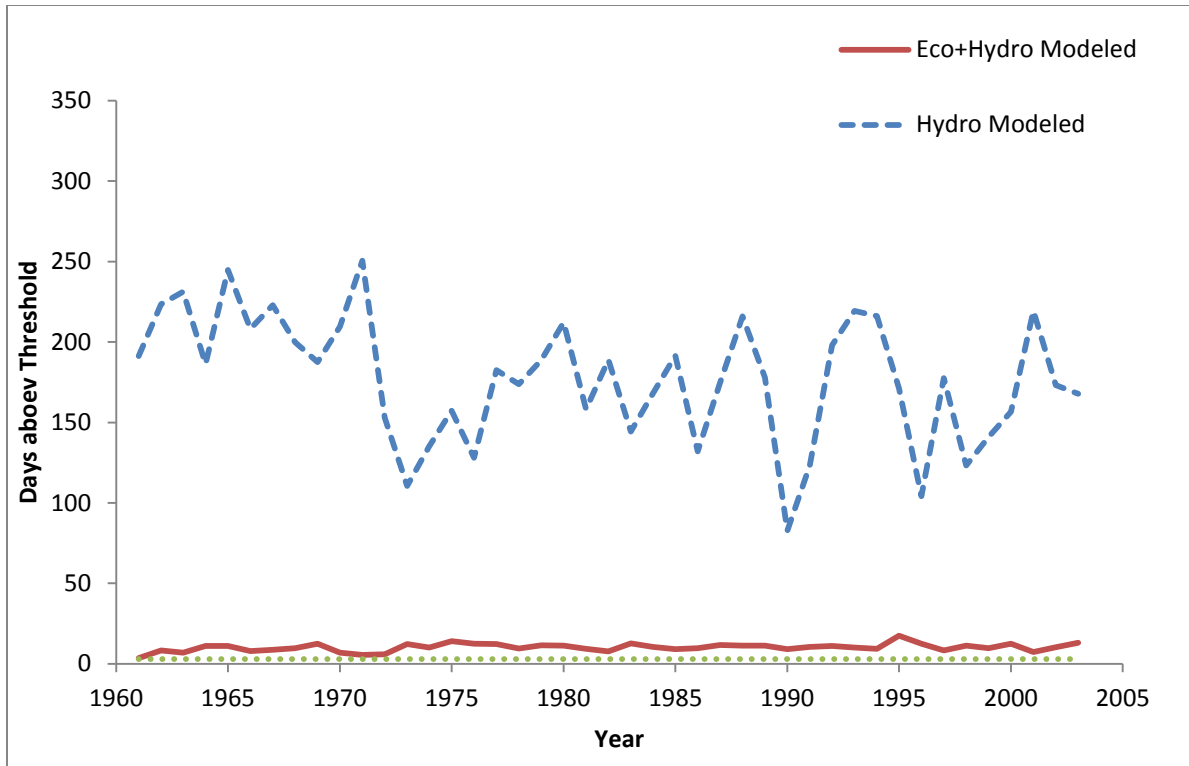
The USGS gage at North Walpole shows the average historic reversal to be 6.14 reversals per day in the observed record so an initial threshold of 6 reversals per day was used. At all eco-nodes, the average number of reversals for they hydropower optimized run is 4.84 reversals/day, and 4.75 reversals per day for the eco and hydropower optimized run. The optimized solutions produce less reversals/day compared with the historic gage, because the optimized solution accounts for perfect foresight into the future with respect to both energy prices and inflows. The energy price signal used in the model has four inflection points, so the output can be expected to

have at least four reversals. Since the optimization model can predict exactly the future hydrologic conditions, it can alter flows at optimal times to maximize hydropower production and maximizing eco-targets, eliminating the need for excess reversals.

At a threshold of 6 reversals per day, the hydropower optimized scenario actually has fewer days above the threshold. Since the hydropower optimized run operates by following an energy price signal, the repetitive nature of the daily price signal will create similar flow change patterns each day, actually minimizing the number of reversals. When the system is operated for hydropower and ecological targets, there are more reversals, since operators will not have repetitive energy price patterns to follow each day. The natural hydrology of the system cannot be predicted as well as the energy price signal may be, and more reversals come as a result of the lack of repetition in the optimization function. For the highest reversal numbers, 7-8 reversals/day, it is interesting to note that the eco and hydropower optimized run produces drastically less days with reversals over the threshold. The model is limiting days per year with high numbers of reversals.

### **5.5.3. PERCENT OF TOTAL FLOW**

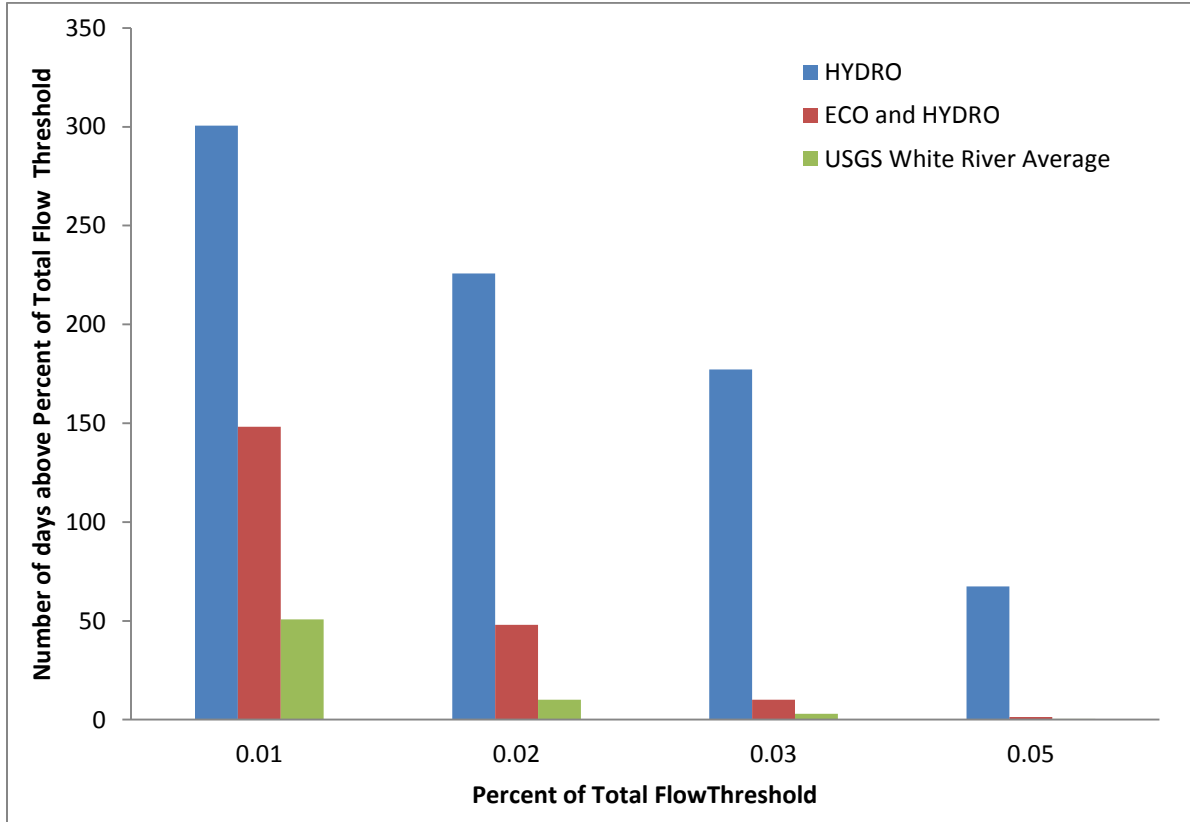
Percent of total flow is the ratio of the range of the daily flow cycle to total daily discharge. This is a measure of the percentage of total discharge being added or removed each day. In this system, most of the reservoir capacities are relatively small compared with the flows they receive, and the hydraulic retention time is lower than other facilities in the basin. As a result, these facilities do not have the volume to alter the flows significantly, and a low threshold for flashiness was used for this metric. *Figure 13* shows the average days above this threshold per year, for different operational scenarios, and the CRUISE estimated natural flow.



*Figure 13* - Percent of total flow - days above percent of total flow threshold.

A threshold of 0.03 was used, meaning that a day was considered “flashy” when more than 3% of the total cumulative flow for that day was altered. This threshold showed that the hydropower operations are significantly altering the flow, as there are more than 100 days per year, for every year, where the threshold is exceeded and more than 3% of cumulative flow is altered. The implementation of ecological targets greatly decreases the number of days per year over the threshold. With a threshold of 3% change in percent of total flow, the implementation of eco-targets decreases the number of days by, on average, over 90%. The sensitivity of this threshold, however, changes the apparent benefits of implementing eco-targets for this metric. *Figure 14* shows how different thresholds affect the number of days above the target. For a low threshold (when 1% of the change in flow is considered “flashy”), the number of days above the threshold

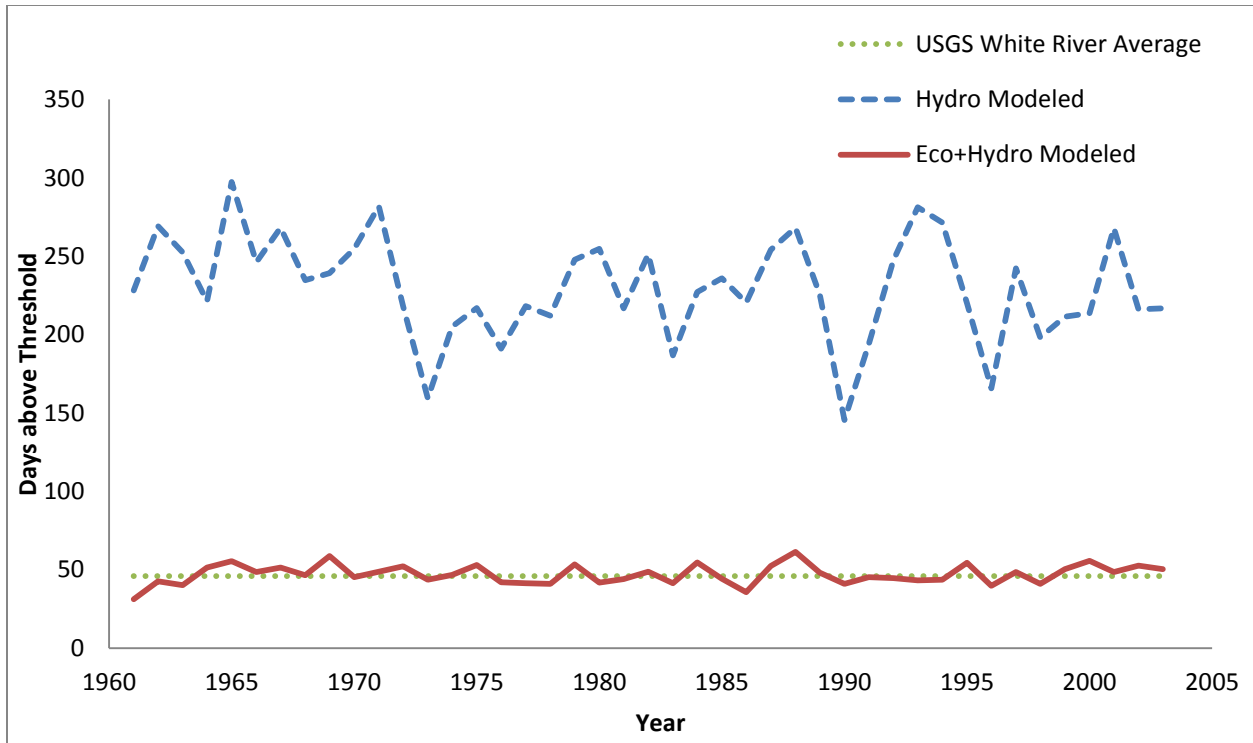
for a hydropower only run is approximately 300 days, while the implementation of eco-targets decreases by 50% to 150 days.



*Figure 14* - Sensitivity of Percent of Total Flow threshold for each optimization run. A low threshold of 0.01 shows that the implementation of eco-targets improves the number of days above the threshold by half, while a higher threshold yields less benefits returned.

#### 5.5.4. COEFFICIENT OF DAILY VARIATION

The coefficient of daily variation (CDV) is a measure of the standard deviation of hourly flows divided by mean flow for a 24 hour period. This measure quantifies the variation from the average, normalized for the mean flow over a day. A threshold of 0.15 was used and days with values above this threshold were considered to be ‘flashy’. *Figure 15* shows the days above the threshold for each modeled year.



**Figure 15** - Days above the Coefficient of Daily Variation (CDV) threshold per year. A threshold of 0.15 was used, and this figure illustrates the total number of days per year where the CDV is greater than or equal to the threshold.

**Figure 15** shows that with the implementation of an eco-node target in the objective function, the number days when CDV exceeds the threshold are less, despite still not being as low as the natural condition. There is some variability in this metric shown in the unregulated White River. The average number of days above the threshold was 46 for the White River. The eco+hydro modeled run results show that that CDV values are close to this number, and the implementation of ecological targets brings this metric closer to the unregulated condition.

Wet and dry years have different effects on this metric. Wet years (1974 and 1990 are the two wettest years) show that the hydropower only optimization run produces fewer days exceeding the threshold than an average year for this run. The increased water in the system raises the mean flow and decreases the CDV. The peaking actions that hydropower facilities operate under are less significant in the hydrograph. For dry years (the 1960s were dry, with 1965 being the

driest year), the model produces more flashy days above the threshold, as there is less water in the system to dull the effects of the peaking operations.

### 5.5.5. ECO-NODE TARGET INDEX

The eco-node target index (ENTI) is a direct measure of the ecological target function in the objective function of CREAM. It is expressed as the total volume of penalties received in the objective function as a percentage of the cumulative volume of water passing the eco-node location. It is a measure of the volume of water as an objective function penalty that flows beyond the allowable flow deviation bounds. It is difficult to quantify success at meeting these ecological targets precisely and consistently (as the potential loss associated with larger deviations is not a simple linear functions), but this index calculates one measure of the losses associated with deviations from ecological targets that can be incorporated into the objective function. **Table 6** shows the values for each eco-node location and eco optimization model run scenario. The Hydropower run scenario produces high ENTI values, as there are a higher number of penalties. The average ENTI value for the hydropower run scenario is 40.6%. Once eco-nodes are implemented, the average ENTI at the eco-nodes is 13.2%.

*Table 5* - Eco-Node Target Index values at each eco-node location for two optimization model run scenarios.

	<i>EcoNode 1</i>	<i>EcoNode 2</i>	<i>EcoNode 3</i>	<i>EcoNode 4</i>
<b>ENT I – Hydropower Run</b>	24.0%	50.3%	42.3%	45.9%
<b>ENT I – Hydro + Eco Run</b>	10.8%	11.6%	10.8%	19.7%

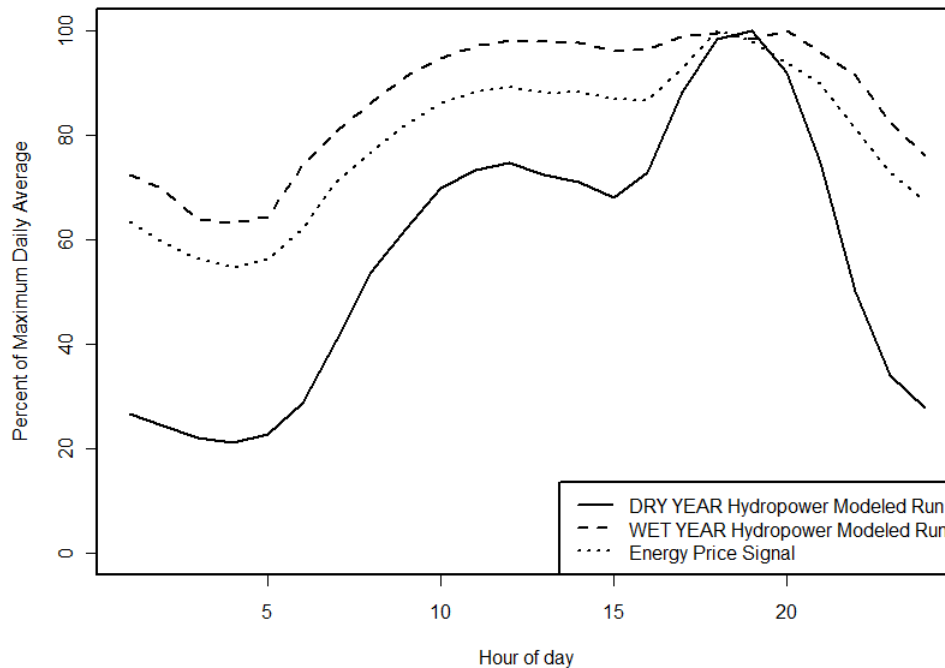
During the hydropower run scenario, there is no incentive for the model to meet the eco-targets and we would expect deviations from natural flows and a large value of ENTI to be low, emulating natural conditions. It is more useful to use the ENTI to quantify meeting natural flows

under the eco and hydropower weighted run scheme. Future research can explore the sensitivity of the ecological target flow prescriptions, to assess the optimal values for allowable flow deviations, with respect to the ENTI. *Figure 16* illustrates the pareto-optimal trade-off between the value of hydropower production and ENTI. The ENTI index decreases significantly, meaning flows are more natural, while decreasing the ability for hydropower facilities to produce income.

## **5.6. WET AND DRY YEAR VARIATION**

For different natural hydrologic conditions, different years will experience different fluctuations and variability in sub-daily flow. The total volume of water passing each eco node location was aggregated and summed for each year to calculate the driest and wettest year of record. The calendar year 1965 is estimated to be the lowest flow year on record. The highest flow year was 1974. During a dry year, the objective to produce hydropower is the same as during a wet year. Each facility has fixed turbine constraints, and during a dry year, the volumes of flow set in those constraints are a greater percentage of the total flow passing the facility. For example, at Bellows Falls, the maximum turbine capacity is 11,010 cfs. The average flow past the eco-node directly below the Bellows Falls release during the dry year of 1965 is 9,775 cfs. During the wettest year, 1974, the average flow past this location is nearly 16,000 cfs. The dry year has the potential for more sub-daily fluctuations, since the entire river can be handled through the generating turbine. Operators have the ability to alter 100% of the flow in the river in this dry year. During a wet year, the flows exceed the maximum turbine capacity, and the operators cannot alter all water passing. During a wet year, 70% of the flow can be altered. During both of these conditions, however, the flow is not altered to the maximum allowable deviation, since there are additional constraints put on the system, such as minimum flow requirements. *Figure 16* shows that there is a difference in the flow disruption between these two scenarios. This

figure shows single year average daily flow values for the hydropower optimized model run. During the dry year scenario, flow is altered to around 20% of maximum daily average flow, a change of 80%. During the wet year scenario, flow is altered to 60% of the maximum daily average flow, a change of 40%. This indicates that during years with lower overall natural inflow, the hydropower peaking fluctuations that have driven historic operations have a much greater influence on drier years than wetter years.

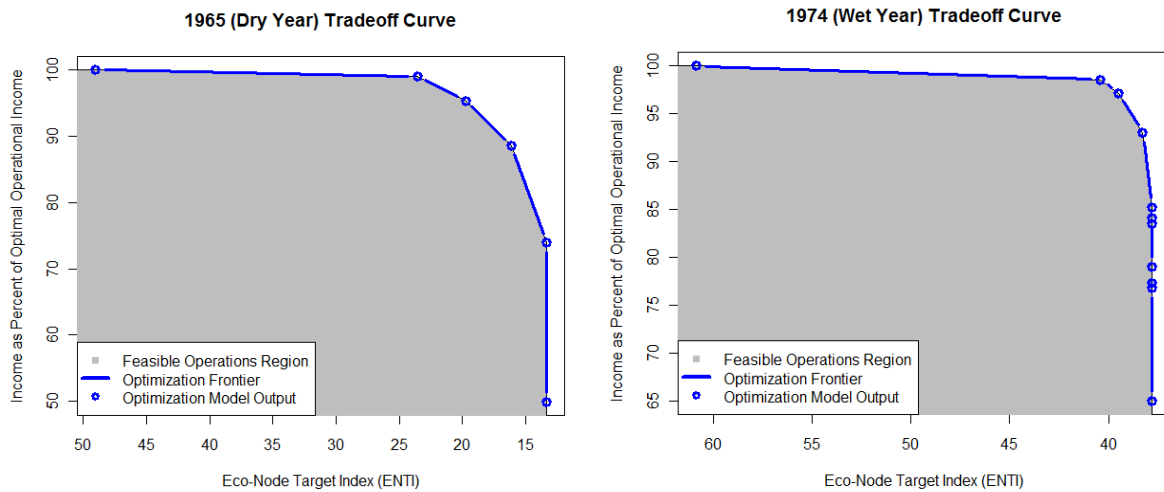


**Figure 16** - Average Flow as a percent of maximum daily average for the wettest and driest year of records. The dry year (1965) and wet year (1974) show that there is a greater flow fluctuations as a percentage of the maximum flow during the dry year, when flows are lower throughout the system.

There are significant differences in the tradeoffs associated with operating during a dry versus operating during a wet year. **Figure 17** compares the tradeoffs generated during the wet and dry years. During the dry year, 1965, the tradeoff curve shape is much more curvaceous than the wet year, 1974. The ENTI for the dry year also shows significant improvement, down from 50 to

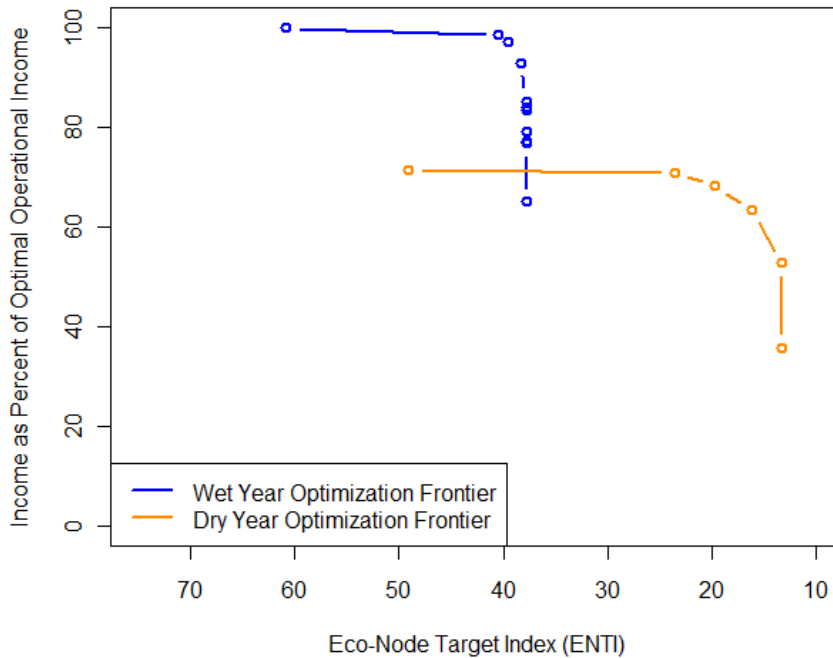


less than 15 under the most natural scenario. In the wet year, the ENTI improvement was not as dramatic, improving from 60 to 35. A more dramatic curve shown in the wet year, indicates that a specific output set of flows can generate similar income while greatly improving the ENTI. During a wet year, this change is more gradual, as there is less water – relative to the entire system – that the facility can use to generate income.



**Figure 17** - Average Flow as a percent of maximum daily average for the wettest and driest year of records. The dry year (1965) and wet year (1974) show that there is a greater flow deviation as a percentage of the maximum flow during the dry year, when flows are lower throughout the system.

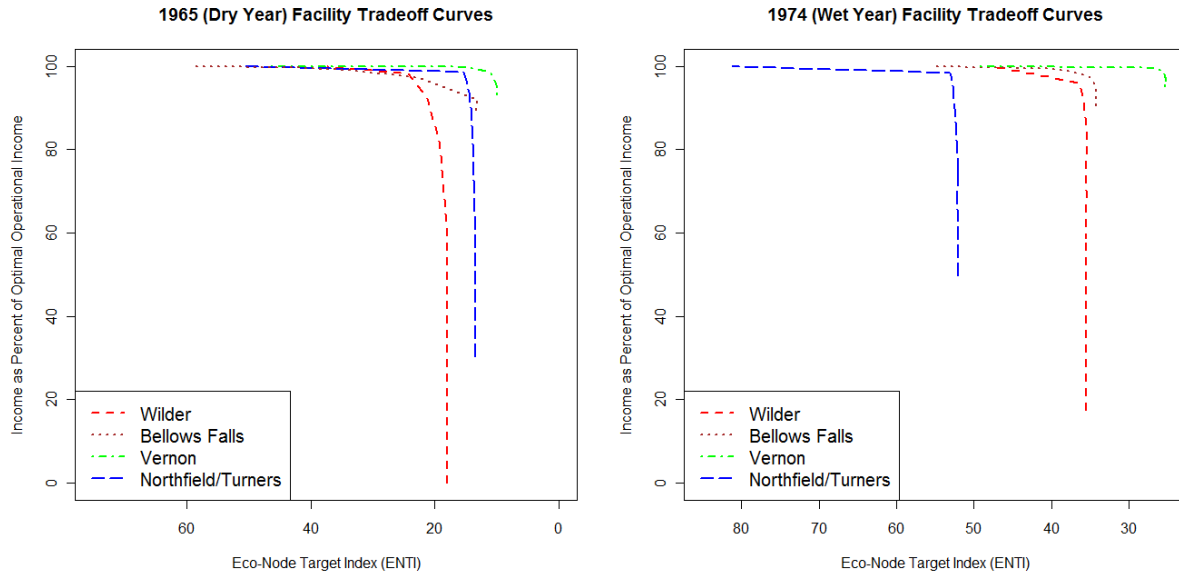
When these two tradeoff scenarios are plotted together, we see that the natural hydrology of the system has a large impact on both the amount of income generated, but also the ability meet natural flow conditions using ENTI. **Figure 18** shows that in 1965 – the dry year – the optimization frontier produces more natural flows while producing less electricity than during 1974.



*Figure 18* – Dry and Wet year Tradeoff curves.

*Figure 18* shows the range of possible tradeoff curves, assuming that 1965, and 1974 are accurate representations of the extreme dry and wet flow regimes. The period of record used in this analysis was 43 years (1961-2003). This is not a long period of record to say with certainty that these are the extreme flow regimes in the system.

*Figure 19* shows how the facilities individually respond to dry and wet years. During 1965, each facility shows a distinct tradeoff shape. Northfield’s tradeoff curve is very sharp, where Wilder, Bellows Falls, and Vernon are much more gradual curves.



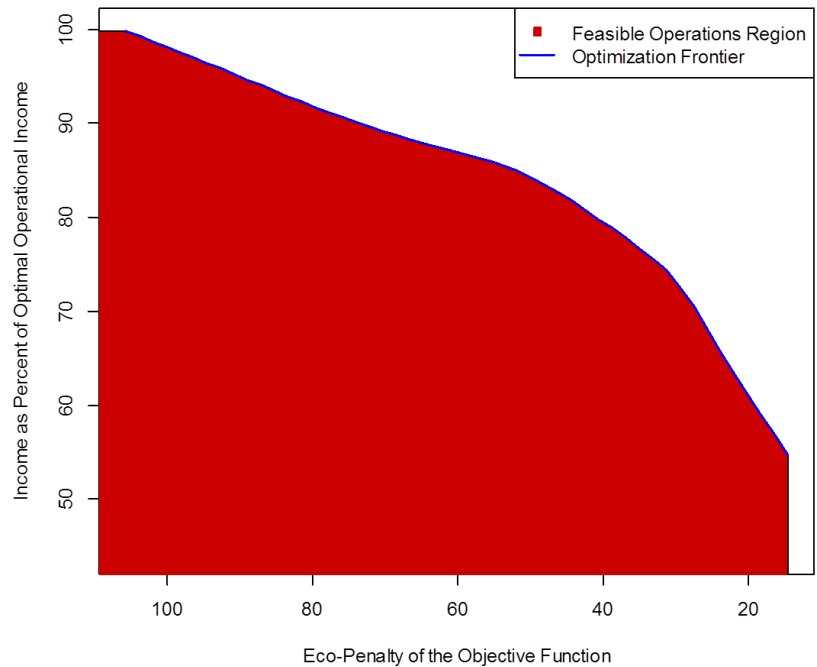
*Figure 19*– Individual system tradeoffs during wet and dry years.

During 1974, all ENTI values generally increase, but Northfield’s ENTI increases much more compared with the other facilities. The environmental impact of Northfield during a wet year is greater than the other facilities, however, during a dry year, Northfield’s impact is generally the same.

## 5.7. OPERATIONAL CHANGES

The hydropower facilities currently operate to account for sub-daily energy price fluctuations and generate power accordingly, to maximize profit. The model shows that current operations are similar to the hydropower optimized run, and that current operations are close to optimal for hydropower production. By increasing the emphasis on natural flows in the operations of each facility, some loss of hydropower production value (profit from producing hydropower, in dollars). *Figure 20* shows the tradeoff expected when hydropower operators begin to operate in a more natural way. The tradeoff curve shows that large benefits can be redeemed for the ecological targets with moderate losses to hydropower income, shown on the shallow slope on

the top of the optimization frontier. The eco-penalty of the objective function can be improved by half (i.e. flows are halfway closer to natural than during hydropower only operation) while trading off approximately 15% of income. This curve was created by constraining the hydropower income to be above a certain threshold. The model was then run to see what optimal ENTI values could be achieved. During the FERC relicensing process, the use of this tradeoff can provide insight into how much environmental progress can be made given certain income constraints.



**Figure 20**– Tradeoff showing the optimization frontier of the two components of the objective function. On the vertical axis: the hydropower facility income generated, and on the horizontal axis; a measure of the eco-penalty in the objective function. A lower eco-penalty means a more natural flow.

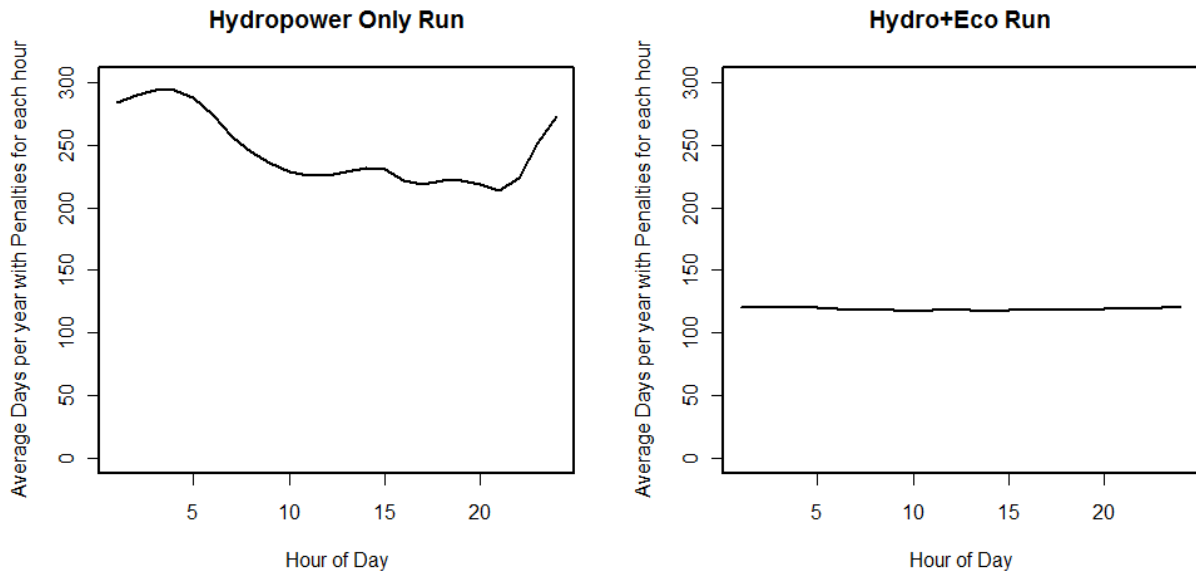
Facility operators can achieve more natural conditions by attempting to limit the sub-daily fluctuations. All of the assessment metrics presented in Section 5.5 show that there is significant sub-daily variation under the hydropower optimized solution, which is a realistic representation

of current operating conditions. Specifically, limiting the use of storage in the facility and maintaining more nature flows will decrease the sub-daily variation that has been prevalent. Facilities would need to use a simulation model to analyze how specific operational changes will affect hydropower production and profit at each facility.

## **5.8. PENALTY FUNCTION ANALYSIS**

The timing of flows that cause environmental penalties in the optimization model provides operators insights into when significant deviations from natural flow are causing detrimental flows in the system. The hydropower facilities in this system have relatively small storage capacities compared with the flow passing through them. As a result, these facilities use most of their storage capacity to alter daily flow patterns. The limited storage capacity makes it unattractive to store water for release longer time periods later (seasonally, or annually) to generate hydropower. *Figure 21* shows the average number of days per year with penalties during each hour of the day. The left plot shows results under a hydropower only scenario. This operational scheme uses the energy price signal to drive flows in the system, and when energy prices are low – in the early morning between 12:00 am and 5:00 am – the hydropower facilities use their storage capacity to hold back water. Storing water during this time produces more hours with flow penalties, as the system will release flows that are detrimentally low for the eco-targets. When water is released to generate electricity later in the day, the number of days with penalties during this time is decreased. Operators sustain the most environmental penalties when they use the facility to store in the early morning hours to generate electricity later in the day. This cycle usually involves the hydropower facility slightly altering the flow below the lower allowable flow bound for several hours in the morning as water is stored in the system. A more

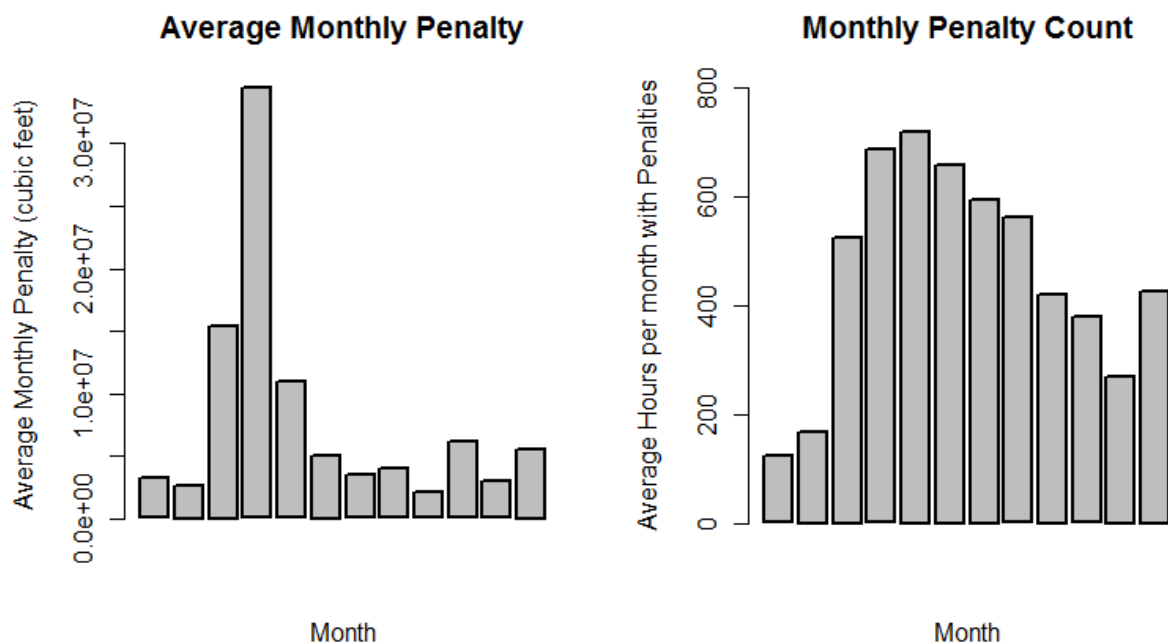
efficient way of filling the reservoir in the early morning can limit the ecological disruptions during this time.



**Figure 21** - Average number of days per year with penalties for each hour of the day. **a)** In the early morning, between 0:00 and 5:00 am, there are more penalties than during the later morning, afternoon, and evening. **b)** By implementing eco-targets, the model will attempt to meet more natural flows, although there are still days with penalties at each hour per year. These are distributed evenly throughout the day.

The Hydropower + Eco Run scenario uses the implementation of the ecological targets to minimize penalties. Once penalties are minimized, the number of days with penalties at each hour per year is decreased to just over 100 days per year. The linear shape of this curve shows that CREAM evenly distributes the penalties throughout the day, and there is no preference for the model to incur a penalty at any specific time of day.

Monthly variability in the penalty function can provide insight into seasonal penalty function trends. **Figure 22** shows the monthly variation in penalty functions.



**Figure 22** – a) Average monthly penalty (cubic feet of water) b) average hours per month with penalty. Seasonal variation in penalty as measured in total volume of penalty. The plots show that on average, the month of April causes the most days with penalties. The magnitude of the penalties in April are much greater than in other months, because of high spring flows.

**Figure 22a** shows the total cumulative volume of water that causes a penalty. This is a direct measure of the total volume of water flow that occurs outside of the allowable flow bounds for the given month. The month of April produces the greatest volume of penalty flows. April has the highest average flows of any month during the year, as snow melts to boost runoff and any penalty will be greater than during a drier month. **Figure 22b** shows the number of hours per month with penalties. Even though the month of April produces a greater total penalty volume, the total hours where penalties occur is not significantly greater than surrounding months. When there is a penalty occurring, the penalty during the month of April is much greater than in other months, although the total number of penalties is not significantly different than May and June.

## 6. CONCLUSION

The Connecticut River Environmental Assessment Model (CREAM) optimizes the operations of five hydropower projects along the Connecticut River. The model results were validated with USGS gage data, as well as historic energy price and historic facility information provided by the facility operators. To achieve this calibration, the model was operated with hydropower as the only component of the model's objective function, indicating that current reservoir operations are similar to the hydropower only optimized operations. Current operations greatly disrupt the natural hydrology of the system and sub-daily flow variations throughout the system are significant. All of the metrics used to analyze sub-daily flow variability demonstrate that current operations are similar to the "hydropower only" optimized solution and current operations respond to price signals to generate high valued hydropower energy. With a framework that brings flows closer to their natural condition, dynamic flow deviation penalty functions were implemented in the optimization objective function. These operational changes result in flows that better match a variety of ecological targeted species and produce flows that more closely resemble those found in the natural flow regime. Forecasted natural streamflow or estimates of natural flow based on the previous day's natural streamflow will be needed to guide operators to specific flow requirements that they should follow to emulate the natural condition. By reducing the depth of fluctuations while following the natural streamflow pattern will limit the environmental penalties in the flow regime.

CREAM generates tradeoffs between hydropower production and ecological flow targets.

Adjusting operations to limit the degree of sub-daily variation in historic operations provides ecological benefits to flow species within the Middle Connecticut River, but these adjustments come with losses in hydropower production income. CREAM verifies that current hydropower



facilities are causing significant deviations from natural flow in various aspects of the flow regime. Sub-daily analysis shows that significant penalties to the designated eco-species occurs when the hydropower facilities store water and decrease their releases; operating with a daily hydropower peaking cycle. For the facilities in the model, this is most extreme in the morning, when energy demand is low. Limiting the volume of storage used during this time period will provide great benefits to the eco-species by limiting the variability in the daily flow regime.

These analyses illustrate that hydropower production conflicts with the objective of minimizing deviations from natural and CREAM provides an analytical tool that quantifies the tradeoffs between these two objectives. The research results include the following:

- Current operations of hydropower facilities result in minor changes in seasonal flow, with higher deviations in the spring and little deviations in winter flow.
- Current operations of the facilities result in significant hourly variation from natural flows in the daily streamflow patterns with higher deviations occurring when demand is low and flows are reduced.
- Current operations operate with higher than natural number of reversals of flow per day, and the implementation of eco-nodes can decrease the frequency of such reversals.
- The CREAM model incorporates eco-nodes that reflect aquatic scientists and biologists consensus on preferred flows that address aquatic needs for a variety of ecological species at ecological node locations.
- The CREAM model is capable of generating operating releases that meet both environmental flow targets and hydropower production depending on the weighting of these two objectives.

- Tradeoffs between the environmental flow targets and hydropower production shows that flow penalties can be reduced by 50% with a 15% loss in hydropower.
- The results from the optimization model show that limiting the storage used and by attempting to mimic some forecasted or estimated natural flow regime will increase benefits to species.

The natural dynamic character of a riverine ecosystem affects the ecological integrity. The flow regime of a river is the most significant variable that affects the entire river ecosystem. The natural system is strongly dependent on the natural hydrologic conditions. Hydropower provides a reliable energy source that can be quickly utilized; however, these river impoundments can impose many environmental constraints on a natural system. A range of feasible tradeoffs between these two operating objectives shows that significant improvements to the natural flow regime can be achieved with modifications to the historic operating schemes of the hydropower facilities in the Connecticut River.

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