Planning for Hydrologic Resilience:

An environmental policy framework evaluating existing dams in Vermont

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Executive Summary

Many Vermonters advocate for in-state hydropower development because they believe that it is a renewable and sustainable source of electricity and that it can help reduce the state's greenhouse gas emissions. There are 1,200 dams in Vermont, and approximately 1,100 of these do not have hydropower generating capacity. The Vermont Agency of Natural Resources estimates that development could produce a potential capacity of 25 MW of electricity through retrofitting some of these existing dams. While it should be a priority for the state to reduce its impact on climate change, we cannot disregard the detrimental ecological effects of dams. Dams fundamentally alter the structure and function of river ecosystems by modifying the chemical and temperature profile of rivers, blocking the movement of aquatic organisms, and disrupting nutrient transfer. This report seeks to investigate whether the environmental benefits of avoided greenhouse gas emissions are worth the detrimental ecological effects of dams in Vermont.

In both the public and policy spheres, a perception exists that there is a dichotomy between planning for climate change mitigation and riverine ecosystem integrity. Many people believe that we cannot simultaneously plan for climate change mitigation and prioritize the health of Vermont's rivers. Much of the disconnect between these two planning processes stems from the weaknesses of the current regulatory framework for evaluating the ecological effects of dams. The Vermont Agency of Natural Resources (ANR) and the Federal Energy Regulatory Commission (FERC) implement the current regulatory framework to ensure that dams do not violate the Clean Water Act. While this framework is well suited to evaluate the local ecological effects of dams, we have identified three major flaws in the current process for evaluating proposed hydropower projects in the state:

- **Reactive**: It begins when someone proposes adding hydropower to an existing dam.
- C**ase specific**: It only considers one dam at a time.
- **Limited scope** of analysis: It does not evaluate the relative environmental costs and benefits of development or alternatives like dam removal.

Through an analysis of Vermont's greenhouse gas emissions inventory, we have concluded that the ecologic benefits of avoided greenhouse gas emissions from extensive hydropower development are not worth the costs to freshwater ecosystems. The volume of emissions that would be avoided by developing all 25 MW of potential hydropower in the state is almost negligible compared to Vermont's total greenhouse gas emissions. In order to increase the resiliency of our state's ecosystems and work toward a secure, sustainable, and renewable energy future, we propose a new planning process based on a new policy framework. We reject the notion of a dichotomy between planning for river health and mitigating climate change—these processes are fundamentally linked. By establishing a planning process that facilitates increasing the ability of our waterways to adapt to the predicted increase in the frequency and severity of precipitation events associated with climate change, both of these goals are achieved. Our proposed framework will allow lawmakers and conservation agencies to evaluate both river health and climate change mitigation simultaneously and holistically. Climate change, renewable energy, and environmental quality are all central to Vermont's legislative goals. Thus, we believe that our report can provide relevant and timely analyses and recommendations to policy makers.

This new policy framework is:

- **Proactive**: It begins before someone proposes an upgrade or retrofit to a dam.
- **Comprehensive**: It may be used to evaluate all dams in the state.
- **Has an expanded scope of analysis**: It addresses the ecological benefits and concerns of alternatives and multiple outcomes such as dam removal.

The purpose of our framework is to facilitate a comprehensive environmental evaluation of all dams in Vermont that do not have hydropower. We urge the Vermont legislature as well as conservation agencies to use our framework to evaluate all 1,100 dams that are currently not used for power production and identify which are candidates for removal and river restoration, thus increasing the resiliency of Vermont's rivers, and which might be candidates for the installation of hydroelectric capacity if social or historical factors make the dam impossible to remove.

We propose that a more ecologically meaningful way to prepare Vermont's linked social-ecological systems for climate change's effects of increased precipitation and variable, erratic weather is to systemically increase the resilience of these systems. This can be accomplished through a comprehensive ecological analysis of the dams of the state, evaluating both hydropower development and dam removal. By recognizing the interconnectedness of these issues, the state has an opportunity to increase the resiliency of its waterways, and identify economically feasible hydropower sites across the state. Our proposed framework will help the state to balance its responsibilities to mitigate both climate change and its consequences by improving the resiliency of our waterways.

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Shana Stewart, Upper Missisquoi and Trout Rivers Wild and Scenic Study

Introduction

Vermont's Uncertain Energy Future

Vermont faces an uncertain and insecure energy future. If the nuclear power plant Vermont Yankee is decommissioned, 35% of the state's electricity generating capacity could be lost (VDPS 2011). However, this impending threat gives Vermont an opportunity to reassess its existing energy portfolio, diversify its sources of electricity and plan for a sustainable and renewable energy future. As the looming threat of a large energy gap approaches, viable, alternative energy options must be explored. Diversifying the state's energy portfolio to include smaller, local sources of electricity, such as small hydropower facilities, would provide greater energy security and stability.

The Vermont Comprehensive Energy Plan sets an ambitious goal to achieve "90% of our energy needs from renewable sources by 2050" (VDPS 2011, 3). About 50% of Vermont's electricity is currently considered as being produced from renewable sources (VDPS 2011). However, the high target for 2050 includes electricity generated by the large hydropower utility Hydro-Quebec, as well as credits bought toward purchasing renewable energy from out of state sources. In state generation of renewable electricity currently accounts for roughly 13% of the state's electricity portfolio (VDPS 2011). In order to reach the goal of 90% renewable energy, the plan suggests exploring the development of the remaining potential hydropower sites in the state.

The notion that hydropower generation could help Vermont achieve its renewable energy goals likely stems from the state's long-standing history with hydropower. Prior to the 1920s, Vermont relied almost exclusively on its rivers for generating mechanical energy (VDPS 2011). Today, eighty-four hydropower facilities in Vermont (Figure 1) generate about 11% of the state's total kWh load (VDPS 2011).

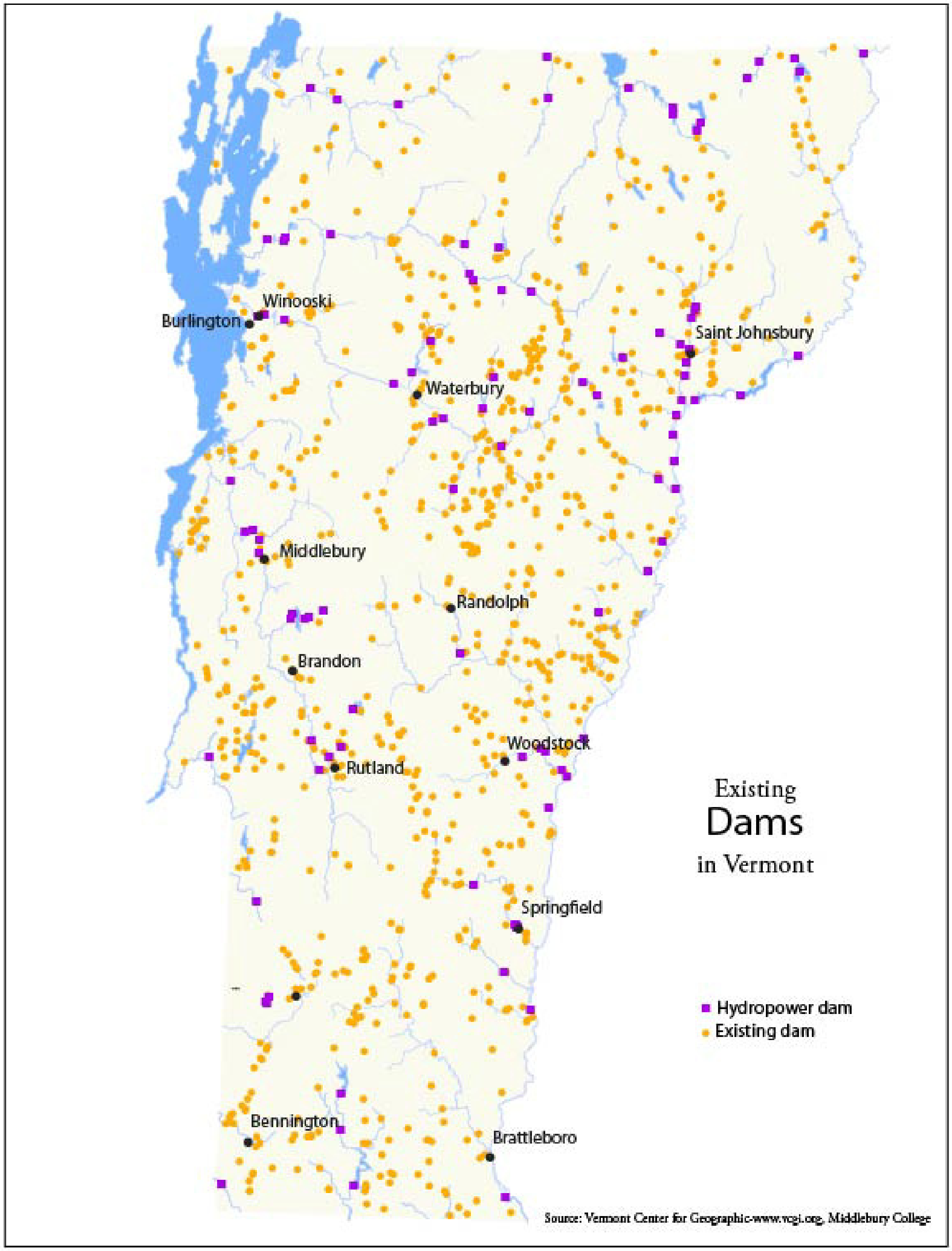


Figure 1: Vermont Dam Inventory Map. Existing dams in Vermont as well as those that are current hydropower generating facilities.

Currently, there are approximately 1,100 dams in the state of Vermont that are not used for hydropower (Figure 1). While a few of these dams are used for flood control or other purposes, most are derelict remnants of old gristmills and currently fulfill few, if any, functions (ANR 2008). Hydropower developers and community advocates have proposed that many of these dams be retrofitted for electricity generation, as it could increase the state's energy independence without increasing the state's carbon emissions.

The best sites for large hydropower projects in Vermont have already been developed or cannot be developed due to environmental restrictions. Only small-scale hydropower projects have the potential to be developed throughout the state; small-scale hydropower is commonly defined as those projects up to 5 MW (Fitzgerald 2011). These smaller projects offer unique benefits that large projects do not, including local production of energy (leading to less energy lost in transmission) and a lower magnitude of ecosystem disruption.

However, there is much uncertainty associated with the potential for small-scale hydropower development in Vermont (ANR 2008). Government-sponsored estimates for the amount of developable hydropower in Vermont vary widely, ranging from 25 MW to 420 MW (VDPS 2011). Experts in the hydropower industry believe that even the low estimate is too high, and that there are closer to 20 MW of hydroelectricity that may feasibly be developed (Warshow 2011).

The development of Vermont's potential hydropower will alone be insufficient to attain the 90% renewable energy goal set by the Comprehensive Energy Plan. Yet due to growing interest in small-scale hydropower development, it has become clear that the Vermont legislature must evaluate the inventory of all dams in the state and make a decisive conclusion about the state's approach to hydropower development.

Goals of the Project

As part of an Environmental Studies Senior Seminar capstone project, this report contains the work of a group of five students who focused on developing a new planning process to weigh the relative environmental benefits of hydropower development with the detrimental ecological effects of dams. Given the immense media coverage of hydropower and the popular pressure to develop renewable, local energy sources, this project fills a community need to deliberately assess the ecological costs and benefits of dams. Our report contains an objective analysis. It seeks to improve the current discourse on hydropower, which is dominated largely by the opposing forces of economics-minded developers who support hydropower development and anglers in favor of river restoration for the recreational benefits it would provide.

The group worked closely with community partners Brian Fitzgerald of the Vermont Agency of Natural Resources (ANR) and Luke Snelling of Energize Vermont. Through collaboration with these partners and interviews with various other stakeholders, including Trout Unlimited and hydropower developers and consultants, the group was able to gain valuable insight regarding the complexity of the issue at hand. This report addresses the ecological implications of retrofitting or removing existing dams, adding new perspective to the issue and addressing an expressed community need.

Currently, there is no structure in place to assess the differences in environmental impacts of either retrofitting or removing the 1,100 existing non-hydropower dams in Vermont. Although the addition of generating capacity to an existing dam does not substantially further harm freshwater ecosystems or increase the state's greenhouse gas emissions, an evaluation of the existing dams poses an opportunity to improve the quality of the environment if these dams are removed. The current framework used to evaluate a dam in Vermont promotes a site-specific process and lacks a comprehensive analysis of the environmental implications associated with different futures for the dam, including possible removal. While the site-specific process allows stakeholders to thoroughly investigate the implications of each individual project, the length of the process presents a significant hurdle. Assessment focuses almost exclusively on retrofitting, while alternatives like dam removal are proposed only in situations where the dam poses a safety risk. This project aims to develop a framework that will consider the ecological implications of either option for an existing dam.

We view the existing policy framework as reactive. In this project, we propose an alternative, streamlined framework that can be applied to any existing dam to determine whether removal or retrofitting provides the best ecological option in terms of river health and renewable energy production while also considering the views of community members and dam owners. This proactive framework encourages the state to immediately evaluate all existing dams, regardless of whether a dam is currently being considered for development. The framework helps choose the course of action that is most ecologically sound while also keeping in mind the goals of the local community. Ultimately, this project and the related framework seek to answer the question: **are the relative environmental impacts of avoided greenhouse gas emissions worth the detrimental effects of dams?**

Methodology

Literature Review

In order to develop a new planning process and policy framework for evaluating the ecological effects of retrofitting dams in Vermont, we started by conducting a literature review. This literature review included an analysis of empirical studies on the ecological effects of dams, of adding hydropower to existing dams and of dam removal. Additionally, we conducted a thorough review of the current regulatory framework for assessing and permitting potential hydropower projects, and an evaluation of the initiatives or mitigation strategies used to reduce the detrimental ecological impacts of these projects. The findings of these reviews were paired with the evaluation of several case studies, interviews with experts in the field, and site visits.

Case Studies

We extensively evaluated four individual case studies to help us construct and revise our framework. Winooski One Dam, Batchelder Mill Dam, Dufresne Pond Dam, and Otter Creek Falls were the four sites chosen as examples of multiple possible outcomes of our framework (Figure 2).

The Winooski One case study describes an example of an existing dam retrofitted to produce electricity. The Batchelder Mill Dam case study shows an example of where a retrofit was not economically feasible, yet cultural significance prevented the dam from being removed. The Dufresne Pond case study is a dam currently in the process of being removed. The Otter Creek Falls is a natural feature that a developer is currently attempting to add generation capacity to, so far without success.

These four case studies represent four different outcomes of decision-making and licensing processes that often took many years, so they are informative to someone who plans to use our framework; these cases bring up issues and motives that one might encounter when trying to decide a course of action. We chose these case studies because they are some of the most current examples of retrofits, removals, and failed attempts, and because we were able to talk to the people involved in these projects.

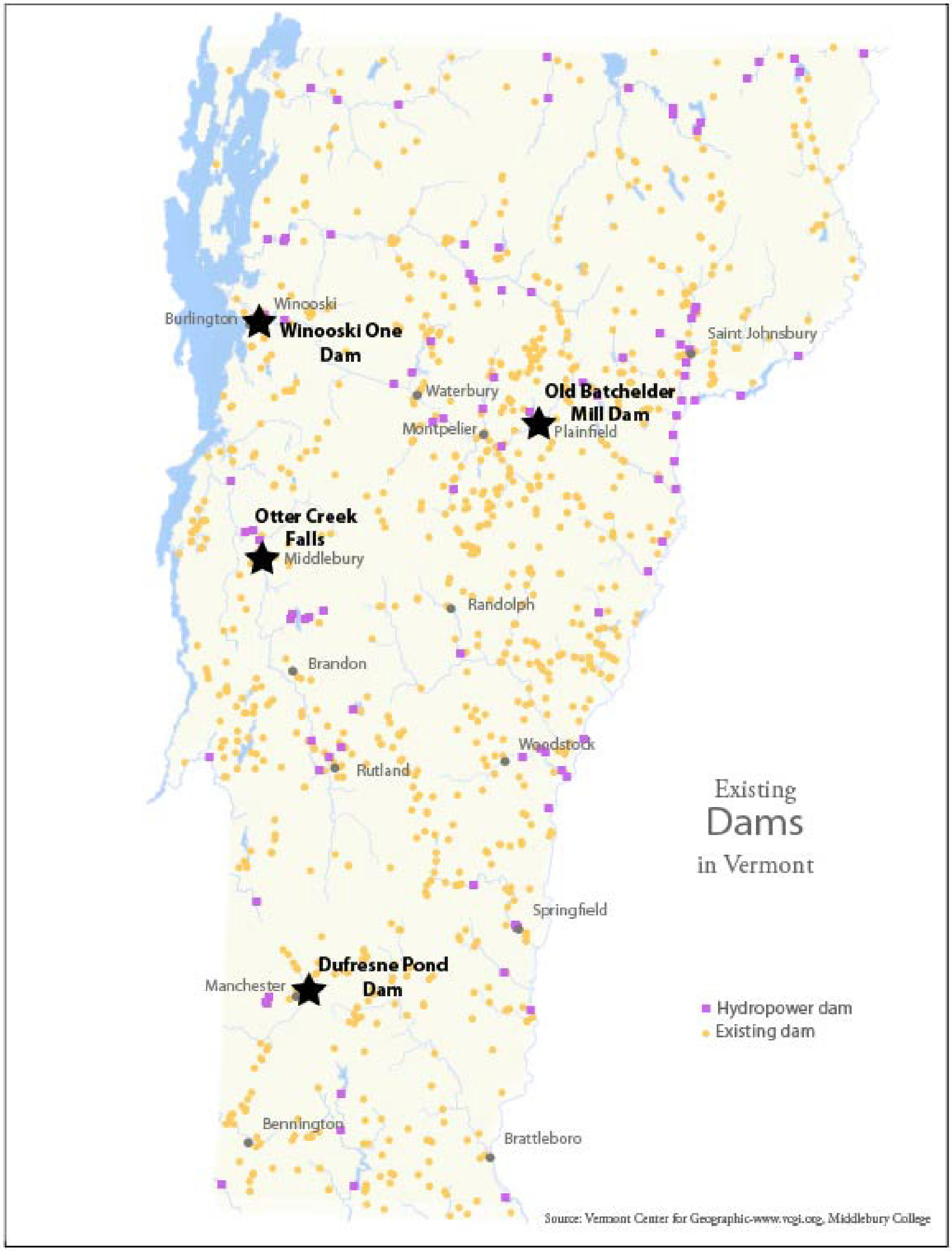


Figure 2: Case Study Locations. Map identifying location of case study dams addressed as framework examples in report.

Interviews

We interviewed hydropower developers, engineers, state and town government officials, and members of environmental groups to understand the past and current process, considerations, and challenges that are involved with dam removal or retrofitting existing dams for hydropower (Table 1).

Name	Title	Company
Andy Qua	Senior Licensing Coordinator	Kleinschmidt Associates
Bill Rodgers	Director of Marketing	Great Bay Hydro Corporation
Brian Fitzgerald	Streamflow Protection Coordinator	Vermont Agency of Natural Resources
Chris Moore	Vermont Council Chair	Trout Unlimited
Clark Amadon	President of the MadDog Chapter	Trout Unlimited
Claudia Clark	Selectboard	Town of Plainfield
Frank Magilligan	Geography/Geology Professor	Dartmouth College
Jeff Reardon	New England Conservation Director	Trout Unlimited
Lori Barg	Founder and Chief Executive	Community Hydro
Lukas B. Snelling	Director of Communications	Energize Vermont
Mark Wamser	Senior Water Resources Engineer	Gomez & Sullivan
John Warshow	Managing General Partner	Winooski One Partnership
Roy Schiff	Water Resource Scientist and Engineer	Milone & MacBroom, Inc.
Shana Stewart	Study Coordinator	Upper Missisquoi and Trout Rivers Wild and Scenic Study

Table 1: Interview Subjects. These 14 individuals shared their professional expertise with us, through conference calls, emails, and personal communications.

These interviews provided us with information for our case studies, first-hand perspectives of the licensing process and the social and political variables affecting hydropower development, and local examples of the ecological impacts faced by developers and dam removal consultants. Many interviewees possessed detailed knowledge of local ecosystems and environmental considerations that were absent in the literature. Also, direct interactions with stakeholders and professionals helped us to redefine the scope and objectives of this report to best serve the Vermont legislature and potential hydropower developers.

Site Visits

We conducted three site visits to help us design policy recommendations for improving the planning process of assessing existing dams in Vermont. We visited the Winooski One Dam in Winooski, the CVPS hydropower station in Weybridge, and the falls on Otter Creek in downtown Middlebury. These visits allowed us to see firsthand the interaction of a dam, powerhouse, and tailrace with the river and local landscape, and provided us with an opportunity to talk with people involved with dam retrofits or removal and learn the challenges and considerations they faced.

Limitations

Issues of time, bias, and information gaps in the literature challenged the completeness and neutrality of this study. Time limited our ability to visit sites and to have as much contact with relevant stakeholders as would have been ideal. Additionally, many of our interviewees had biased opinions regarding the importance of assessing the environmental impacts of proposed hydroelectric projects. Organizations value renewable energy and ecosystem connectivity differently, and interviewees sometimes provided us with little insight into the wide range of alternative views of a given hydropower project that stem from different prioritization of these values. The creation of a neutral framework that recognized both ecological and renewable energy development priorities was thus difficult.

Few studies in the literature have specifically assessed the ecological impacts of adding hydropower to existing dams. Therefore our analysis of the ecological impacts of dam upgrades relies on a small number of sources and may be incomplete or not entirely applicable to the rivers of Vermont. We have been forced to extrapolate certain impacts of dam upgrades from literature about the impacts of new dam construction and dam removal, therefore the scope of impacts is less certain. For example, while the addition of turbines to a dam will kill some fish, we found no quantitative studies demonstrating the impact of an upgrade on fish populations. The impacts of hydropower generation on fish become even more vague when accounting for new fish ladders along with the turbines. We found no information on how fish are affected by changes in dissolved oxygen and temperature that result from the addition of turbines to existing dams.

Ecological Impacts of Dams, Retrofits, and Removal

When considered in plain terms, a dam is little more than a "wall in a river," a description that reveals a substantial amount about the ecological implications of either removing or retrofitting an existing dam (Schiff 2011). Rivers and streams play a valuable role in nutrient cycling and provide habitat to a large number of diverse animal and plant species. A particularly important concept in understanding the ecological value of a river is the idea of hydrologic connectivity. Hydrologic connectivity refers to the movement of materials, including nutrients, energy, and animals, within an aquatic system and is essential to maintaining ecological health within a given system (Pringle 2003). Dams serve as an obvious example of a disruption to this connectivity. Their physical structure significantly alters the surrounding landscape and prevents the movement of materials that would otherwise occur within the ecosystem. A particularly important consideration with regard to dams and connectivity is the idea of cumulative effects, i.e., that multiple small changes will cause at least as much if not more of a disruption than one large change (Pringle 2003). While one large dam would prevent fish passage in a small area, many small dams can prevent fish passage on a watershed scale resulting in a cascade of ecosystems effects such as genetic bottlenecks and disruptions in nutrient transfer.

Impacts of Small Hydropower Development

Large hydropower dams have been shown to have devastating environmental effects both in their construction, which is often accompanied by large-scale flooding and reservoir creation, and in their continued operation, which can alter downstream river flow and disrupt natural flood cycles (WCD 2008). Small hydropower, or projects capable of producing less than 5 MW at maximum operating capacity, is often considered to have smaller ecological impacts than large hydropower because its historical use is associated with only localized environmental impacts (ANR 2008; Abbasi 2011). The Vermont ANR estimates that developing all potential small hydropower sites in the state by adding turbines to existing dams could add an additional 25 MW to the state's renewable energy portfolio (ANR 2008 and Vermont Comprehensive State Energy Plan 2011).

Knowledge of this development potential, combined with the idea that small hydropower presents a "green", renewable source of energy, has led to a surge of interest in developing this resource, both in Vermont and in other states and countries with similar water resources (Abbasi 2011; Vermont Comprehensive State Energy Plan 2011). The Vermont ANR encourages any new hydroelectric projects to conform to "low-impact" environmental standards set by the Low Impact Hydropower Institute (LIHI). These standards focus on using existing dams for hydropower sites rather than building new ones, which is the only realistic course of action for developing additional hydropower in Vermont (Vermont Comprehensive Energy Plan 2011). However, there are many other criteria set by the Low Impact Hydropower Institute. The two most commonly held beliefs about small hydropower's environmental status, namely that it either has no negative environmental impacts or that these impacts are so negligible as to be insignificant, neglect to consider several of the environmental changes resulting from dam construction and operation. It is these changes that the LIHI attempts to minimize (Abbasi 2011).

Impacts of Dam Removal

While dam removal is popularly understood as ecologically beneficial, the relative ecological impacts vary depending on the temporal and spatial scale of analysis. Using a long-term, broad-scale framework, dam removal can restore natural flow regimes and watershed connectivity, thereby helping to restore natural temperatures, structures, and fish passage routes as well as improving water quality associated with sediment transport (Bednarek 2001). While theoretical models exist to aid in the prediction of both long- and short-term ecological impacts of dam removal, the field has had relatively little opportunity for empirical study. Of the 450 dams that were removed in the United States in the 20th century, fewer than 5% were accompanied by ecological studies (Hart 2002). In general, dam removal has immediate negative environmental impacts, like the rapid release of sediments, change in water level and flow, and disruption of the chemical and physical properties of the river. However, these detrimental effects are remediated and, over time, outweighed by the environmental benefits of increased connectivity.

Any construction on existing dams, whether removal or upgrading, will have impacts on the physical, chemical, and biological conditions of the immediate site on the river as well as areas both up and downstream (Abbasi 2011). While these changes can affect thousands of characteristics and individual species, a few key river functions highlight the effects of dam removal and dam upgrading.

Connectivity

Dams provide a perfect example of a disruption in hydrologic connectivity. Hydrologic connectivity is critical to maintaining the health of a riverine ecosystem, as it promotes nutrient transport, allows for fish passage, and maintains the river's full function in the environment (Pringle 2003). Even the best designed dam will not be able to completely preserve natural conditions, and the effects of a dam last beyond the disruptions that occur with initial construction (Abbasi 2011). Removing a dam does not guarantee a quick return to natural conditions but does improve the hydrologic connectivity of a given riverine system (Pringle 2003). Fish passage, as discussed below, provides an example of the benefits of restored hydrologic connectivity.

Fish Passage

Concerns about migratory fish movement in Vermont's streams and rivers have historically prompted resignation about dam construction (Rodgers 2011). While efforts can be made to improve fish passage by installing fish ladders or elevators, both of which help migratory fish move upstream to their spawning grounds, these methods are imperfect. Fish passage is highly contingent upon hydrologic connectivity and provides an example of the cumulative negative effects that multiple dams may have (Reardon 2011). For example, if a stream that provides habitat for a migratory fish species contains three dams that are each 95% effective in passing fish, only 85% of the original migrating fish cohort will make it to the spawning ground upstream.

Improved fish passage is the most widely mentioned ecological benefit associated with improved connectivity following dam removal. Within a year of the removal of the Edwards Dam on the Kennebec River in Maine, more than 1,000 larval and juvenile American shad were collected in the stream above the dam—an area that they had been absent from for over 150 years (O'Donnell et al. 2001). At the same dam site, density of zoobenthos increased 190% in the area below the dam following removal (Stanley 2002; Casper et al. 2006). Zoobenthos comprise the base of aquatic food webs; while they are not highly visible, their abundance and health is critical from a multi-trophic ecological perspective.

Sediment Transport

A thorough analysis of the quantity and characteristics of sediment should be a chief priority when considering dam removal or upgrading. Dams obstruct the natural flow of sediment downstream. As the water enters the impoundment and slows down, sediments can no longer remain in suspension and begin to accumulate in the reservoir or stream behind the dam (Bednarek 2001). However, there are some examples, including the Winooski One Hydroelectric Dam, where the velocity of the stream is fast enough to retain most suspended sediment and carry it over the spillway or through the penstock (Warshow 2011). Sediment transport largely governs nutrient composition in a given ecosystem (Vörösmarty 2003). In turn, nutrient availability affects the number of macroinvertebrates and other organisms the river can support (Rice 2001).

Increased deposition of fine sediments in areas above dams that have reduced water velocity promotes phosphorus retention and denitrification (Stanley 2002). Dams create an imbalance in nutrient concentration—nutrient concentration can be reduced as much as 70% below a dam (Stanley 2002). Dam removal restores natural sediment transport, deposition, and nutrient cycling processes. Finally, sediment type is linked to habitat suitability for fish and the macroinvertebrates they feed on (Rice 2001). Dams create an artificial distribution of sediment types, thereby limiting the available habitat for these aquatic insects. Restored sediment transport improves habitat quality on multiple trophic levels.

While dam removal begins the process of restoring sediment transport to the previous ecological conditions of the river, upgrading a dam maintains the existing conditions for sediment buildup (Schiff 2011). However, while dam removal can have great ecological benefit, a careful analysis of the type of sediment near the dam must precede any removal activities.

Sediment contamination is one of the most serious concerns in any dam construction project and has the potential to alter the trajectory and cost of dam removal if contaminants are found. Fine grained silt or sand prompts the greatest concern, as these materials tend to absorb more contamination than coarser sediment due to their large surface area to volume ratio. While coarser sediment sinks or settles out of the water farther upstream from the dam, fine grain sediments build up directly behind the impoundment, concentrating any contamination in this area of the river (Bednarek 2001).

A well-known example of sediment contamination in a dam removal project is the release of PCB-contaminated sediments from the Fort Edwards Dam on New York's Hudson River (Stanley 2003). Removal of the dam led to the release of PCB-contaminated sediments downstream into the Hudson River, which contaminated fish and led to restrictions on fish consumption from the area as well as the eventual designation of the area as a Superfund site (Stanley 2003). Despite Vermont's reputation as an environmentally pristine state, examples like the Fort Edwards Dam stress the need for environmental assessments prior to dam removal, as contaminated sediments are a serious concern in many of Vermont's rivers. A 2008 Fish and Wildlife study of the sediment impounded behind four Vermont dams considered for removal found that three of the sites exceeded sediment quality guidelines for toxic substances like heavy metals, organochlorines, and polynuclear aromatic hydrocarbons (Major 2008).

When evaluating a dam for removal, a comprehensive chemical sediment analysis should be one of the first elements of a feasibility assessment because of the threat that contaminated sediments pose to downstream water quality. The sediment analysis, however, is not technically or socially simple. Unfortunately, many contaminants may be extremely localized or difficult to detect (Stanley, 2003). Furthermore, many dam owners are reluctant to complete these studies for fear of finding contaminants and becoming liable for removing them in a costly cleanup process (Wamser 2011).

Dissolved Oxygen

Dissolved oxygen refers to the level of oxygen present in the water of a stream or river. Dams reduce the level of dissolved oxygen in waterways, and this reduction can have substantial negative effects on aquatic species. During warm summer seasons, water impounded behind a dam often stratifies into two layers. Warm water sits on top of a lower layer of water that remains cool and poorly mixed, therefore failing to incorporate any additional oxygen into the water. When this low oxygen water passes through a hydropower plant's turbines before continuing downstream, it does not become oxygenated and inundates downstream species with a hypoxic habitat. Adequate levels of dissolved oxygen are necessary to ensure the health and vitality of macroinvertebrates—a substantial portion of the food chain in aquatic ecosystems—and fish. Without enough oxygen, species experience diminished health and increased mortality (Cada 2003).

The Clean Water Act is designed to restore the ecological integrity of waterways and does so by requiring EPA or state-issued permits for any dumping of chemical pollutants. While most chemicals have maximum allowable concentrations, dissolved oxygen is a desirable feature and therefore must meet minimum standards, which range from a low of 3 mg/L for warm waters holding adult fish to 9.5 mg/L for spawning grounds of cold water fish (Cada 2003). Because dams contribute significantly to the problem of low dissolved oxygen, removing a dam can make a substantial difference in restoring natural levels of dissolved oxygen and improving the health of aquatic species.

Conclusions

Retrofitting an existing dam with small hydropower generating capability has fewer environmental impacts than construction of a new hydropower dam. However, even the most ecologically conscious dam will continue to interfere with watershed connectivity and natural processes related to sediment transport. While the sediment released by removing a dam can cause short-term increases in water turbidity and fish mortality, the long-term, watershed-scale ecological gains of restoring rivers to natural flow patterns suggest that dam removal will almost always prove more environmentally beneficial on the watershed scale than upgrading a dam to produce hydropower. Although it is important to keep the significant environmental benefits associated with watershed connectivity in mind, many of these benefits are hard to quantify and operate on a longer timeframe than is satisfactory for many decision makers. It may take several decades for riverine activities like sediment transport and fish migration to return to pre-dammed conditions. Furthermore, the comparison of the ecological benefits of dam removal to the benefits of renewable energy will lead different people to different conclusions about which option is best. Ultimately, we find that the long-term ecological benefits of dam removal are worth waiting for, as dam removal is the best ecological decision in most instances.

The Current Regulatory Structure for Hydropower Development

Currently, both state and federal regulatory frameworks consider maintenance of water quality a primary goal when considering the development of hydropower. This section describes the role that federal and state agencies play in the regulation of riverine resources, placing the Federal Energy Regulatory Commission (FERC) and the Agency of Natural Resources (ANR) in charge of the regulatory process (ANR 2008).

The Federal Energy Regulatory Commission

Rivers have long been considered important environmental and economic resources in the United States and have been under control of federal legislation since the late 19th century. The federal government began regulating river development in 1899 when the Rivers and Harbors Act was passed and has focused specifically on hydropower regulation since the Federal Water Power Act was passed in 1920 (Kosnik 2010). Both of these acts served to improve coordination and efficiency of riverine resource regulation by centralizing regulation within the federal government. In 1935, the Federal Power Act replaced the Federal Water Power Act "to create a single regulatory agency focused entirely on developing and encouraging hydropower production"; today, this federal agency is called the Federal Energy Regulatory Commission (FERC) (Kosnik 2010).

The FERC is an agency within the Department of Energy (DOE) and has jurisdiction over any hydroelectric projects that are located on navigable waters and that are not owned by the federal government, as well as any projects on non-navigable waters that were built after August 26, 1935 and that affect interstate commerce (ANR 2008).

In the 1960s and 1970s, legislation enacted to improve environmental protection mandated that FERC no longer focus solely on hydropower production and instead incorporate the protection of riverine ecosystems into its objectives (Kosnik 2010). In 1972, Congress passed the Clean Water Act, which requires states to certify that a project site meets federal regulations for water quality before a license or relicense can be issued. The 1973 Endangered Species Act also had implications for hydropower projects, as it mandated that FERC ensure that any hydroelectric project would not further threaten endangered species (Kosnik 2010).

The Clean Water Act Section 401

Under Section 401 of the Clean Water Act, anyone applying for a license or permit "to conduct any activity that may result in a discharge to waters of the United States" must first obtain a 401 Certification (Copeland 2006). The certification is made in the state where the discharge occurs, and the state can impose conditions on the licensing (Meltz & Copeland 2006). The 401 Certification process allows states to create their own water quality regulations in addition to those already mandated by the federal government. The role of states and FERC in the hydropower licensing process has been highly contentious, as states generally favor stricter water quality standards than developers would prefer (Copeland 2006). Hydropower developers want FERC and other federal agencies "to determine what conditions of a project are necessary for protection of water quality" (Copeland 2006).

Cases involving states and developers concerned about the Section 401 Certification have ruled in favor of the states and are unlikely to be overturned in favor of developers. In 1994, the Supreme Court heard *Public Utility District No. 1 of Jefferson County and City of Tacoma v. Washington Department of Ecology* and ruled that the state is allowed to impose any conditions it chooses on the 401 Certification "to ensure that the facility will not violate state water quality standards" (Copeland 2006). This same topic was revisited in 2006 with *S.D. Warren Co. v. Maine Board of Environmental Protection*, where the Supreme Court unanimously ruled that states "can impose conditions on Federal Energy Regulatory Commission licensing of hydropower facilities" (Meltz & Copeland 2006). Despite strong opposition from the development sector, the courts have ruled in favor of the states in matters pertaining to Section 401 Certification, and it is unlikely that these decisions will be overturned in the future.

Since the Court's 1994 decision, Congress has tried repeatedly to introduce legislation to modify Section 401 but has never been successful. While some proposed amendments aimed to clarify the scope of Section 401 or to overturn the Court's decision, others would have given FERC power to exempt certain hydropower projects from Section 401 regulations (Copeland 2006). None of these bills passed. In 2001, Vice

President Cheney's National Energy Policy Development Group "recommended that the hydropower licensing process administered by FERC undergo administrative and legislative reform so that hydropower can contribute to meeting the nation's energy needs" (Copeland 2006); this measure was also unsuccessful.

FERC Application Process

The traditional FERC process for licensing a hydroelectric power plant is made up of four stages and is expected to take five years from beginning to completion. However, in the past several decades this process has often taken significantly longer (Kosnik 2005).

First, a project owner must file a notice of intent to seek a FERC license for a hydropower project. This entails providing all known and available information regarding the engineering, economics, and environmental characteristics of the proposed project (Kosnik 2010). The second stage, which takes about three years to complete, involves conducting studies to evaluate the environmental impacts of the project. This is when a project owner must consult with state agencies regarding the Clean Water Act and eventually obtain a 401 Certification, a process that will be explained in greater detail in the "Vermont State Provisions" section below.

If the 401 Certification is granted, then the project moves to the third stage, in which an official licensing application is submitted to FERC for review. If FERC approves the application, it is posted on the *Federal Register* and made open to public comment (Kosnik 2010). During this stage, interest groups and citizens are able to raise concerns about the project, request information, and request additional studies of potential impacts. Environmental impact statements must also be completed during this time.

In the final stage of the process, FERC "holds a hearing regarding the license application and issues its regulatory decision" (Kosnik 2010). FERC can choose between granting a license for a 30 to 50 year period, not issuing a license, or recommending that the project become government operated. This last option involves essentially purchasing the project from the owner (Kosnik 2010).

While these four stages are mandatory in the FERC licensing process, two additional stages can also occur. Before the first stage is underway, pre-filing consultations can take place for years before a notice of intent to seek a license is filed. In addition, after FERC issues a decision in the fourth stage, an appeals process can occur and U.S. Court of Appeals makes the final decision (Kosnik 2010). Figure 3 summarizes the process of issuing a hydroelectric dam license in Vermont.

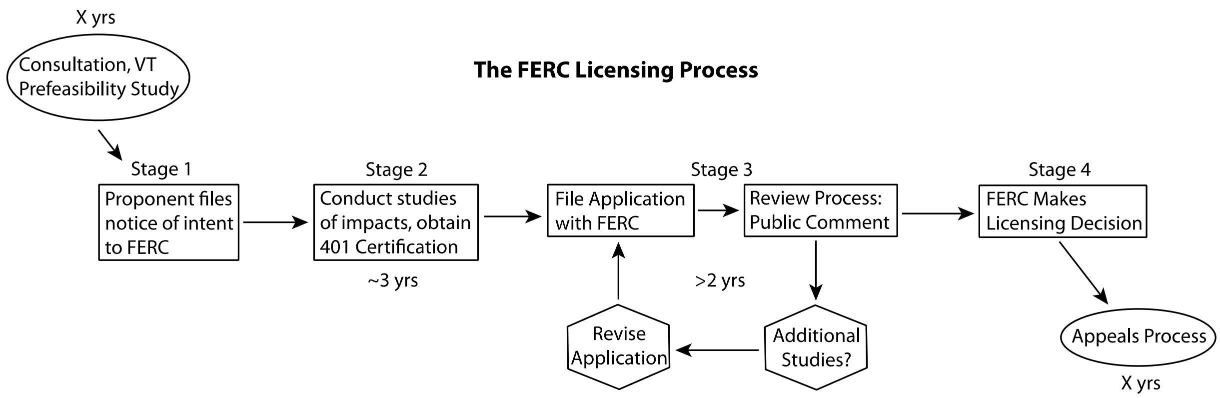


Figure 3: The FERC Hydroelectric Project Licensing Process. Adapted from Kosnik 2010.

FERC Exemptions

Small hydropower projects, those that will generate 5 MW or less, are able to receive exemptions from FERC permits. These projects must still go through a similar process, but the permits received remain active for an unspecified amount of time instead of the typical 30 to 50 years of a FERC license (ANR 2008). However, to get a FERC exemption, a project must meet all federal and state regulations pertaining to fish and wildlife, and projects are "subject to a review under the National Environmental Policy Act (NEPA)" (ANR 2008).

Vermont State Provisions

According to the federal process and FERC regulations, all proposed hydropower projects must meet Vermont's 401 Certification standards. State concerns include environmental impacts, recreational impacts, and effects on the electric grid (ANR 2008).

The Vermont Natural Resources Board is charged with developing water quality standards and classifying the state's waters based on how they feature into the natural landscape (ANR 2008). Temperature, phosphorous and nitrate levels, pH, presence of toxic substances, and hydrology are among the parameters the Natural Resource Board monitors and regulates (Natural Resource Board 2008). All of the state's waters are classified based on characteristics of size, use, and species present, and each class of water is subject to specific provisions. Proposed hydropower projects are studied for their effects on these and other water quality factors.

Several Vermont statutes pertain to dams and hydroelectric projects and any proposed project must also meet these criteria. Specific statutes regulate dam construction, repair, and rehabilitation; regulate stream flow requirements, impacts on fish and wildlife and flooding hazards; prohibit activities that inhibit fish movement; and contain provisions for connecting an electric generating facility to the electric grid (ANR 2008). These statutes give a variety of agencies including the Public Service Board, the Department of Environmental Conservation, and the Agency of Natural Resources the power to enforce these provisions (ANR 2008).

In order to obtain a 401 Certification in the state of Vermont, and be able to apply for a FERC license, all state policies and laws must be upheld. Thus, the process for getting a project certified in Vermont is quite extensive and involves working with numerous agencies to ensure that all provisions are met before a project is given approval from the state. **FERC will not approve any project without prior state approval**, which highlights the regulatory authority of the state in the development process.

Analysis

Small Hydropower Development as a Green House Gas Mitigation Strategy

Many environmental activists emphatically promote small-scale hydropower development in Vermont as a way to reduce the state's greenhouse gas emissions. While the current regulatory framework for evaluating hydropower development projects allows for a thorough analysis of local-scale detrimental environmental effects, this framework is limited in scope. This framework does not provide a mechanism to weigh the relative environmental benefits of avoided greenhouse gas emissions with the detrimental ecological effects of dams. This mechanism is absent largely because Vermont's current planning processes for climate change mitigation and maintaining the quality of the state's hydrologic ecosystems are erroneously disconnected.

Given this significant shortcoming, we deemed it necessary to quantitatively assess the potential for small hydropower development to reduce the state's greenhouse gas emissions and to determine whether this environmental benefit is worth the detrimental ecological effects of dams. In Vermont, however, it is not meaningful to assess the greenhouse gas benefits of hydropower on a dam-by-dam basis because most dams proposed today are less than 5 MW. The Vermont ANR's estimates that there are only 25 MW of potential hydropower available by retrofitting non-generating dams to produce electricity in the state. While estimates of the amount of potential hydropower range from 12-420 MW, we determined that 25 MW is the most reasonable of current estimates, if not too generous (ANR 2008). The estimates of potential hydropower that are large, such as the Department of Energy's estimate of 420 MW, are outdated and most of the potential sites have not been ground-truthed. Therefore, our analysis is largely based on the ANR's estimate of 25 MW of potential hydropower in the state, which has been assessed for accuracy in more depth.

Using the Vermont ANR's greenhouse gas inventory and estimates for potential hydropower development, we evaluated electricity's contribution to the state's total greenhouse gas emissions currently and in a variety of future scenarios Our analysis determined that electricity consumption in the state contributes 4% to Vermont's total annual greenhouse gas emissions, which totals to about 8,340,000 $MTCO_{2e}$ (ANR 2010, Figures 4 & 7).

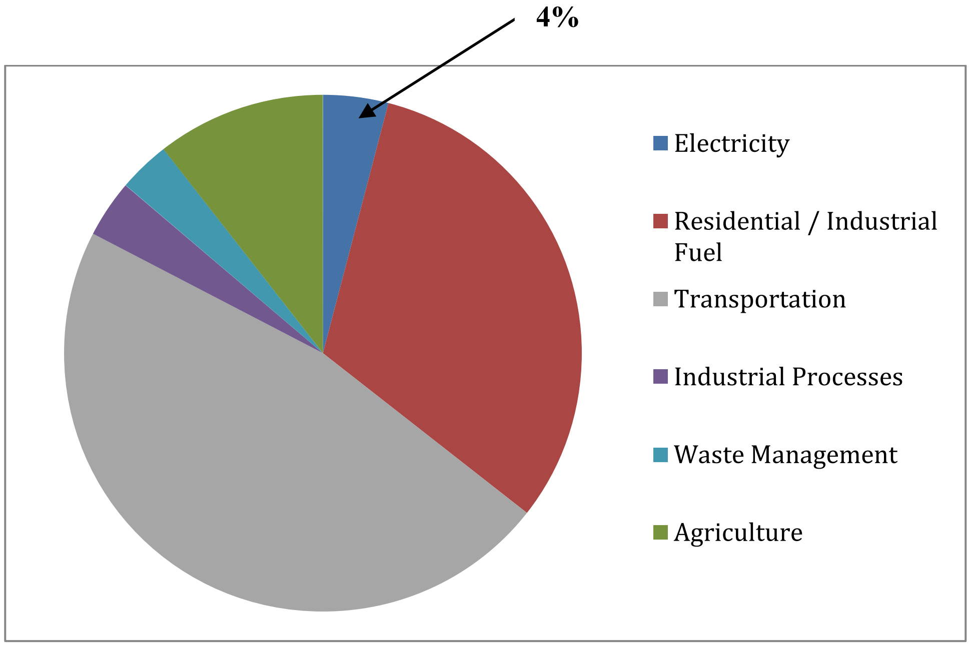


Figure 4: Current Emissions Inventory. This pie chart illustrates Vermont's current inventory of greenhouse gas emissions by sector, highlighting that only 4% of its greenhouse gas emissions come from generating electricity.

Vermont has not yet made a firm commitment regarding where the state will purchase electricity from in the event that Vermont Yankee is decommissioned; however, Vermont will likely be forced to purchase electricity from the New England grid, which is dominated by natural gas generation (VPR 2007). This increase in reliance on fossil fuel generating sources will increase the state's greenhouse gas emissions by 450,000 $MTCO_{2e}$ overall and will increase electricity's contribution to the state's carbon footprint to 9% (Figure 5 & 7).

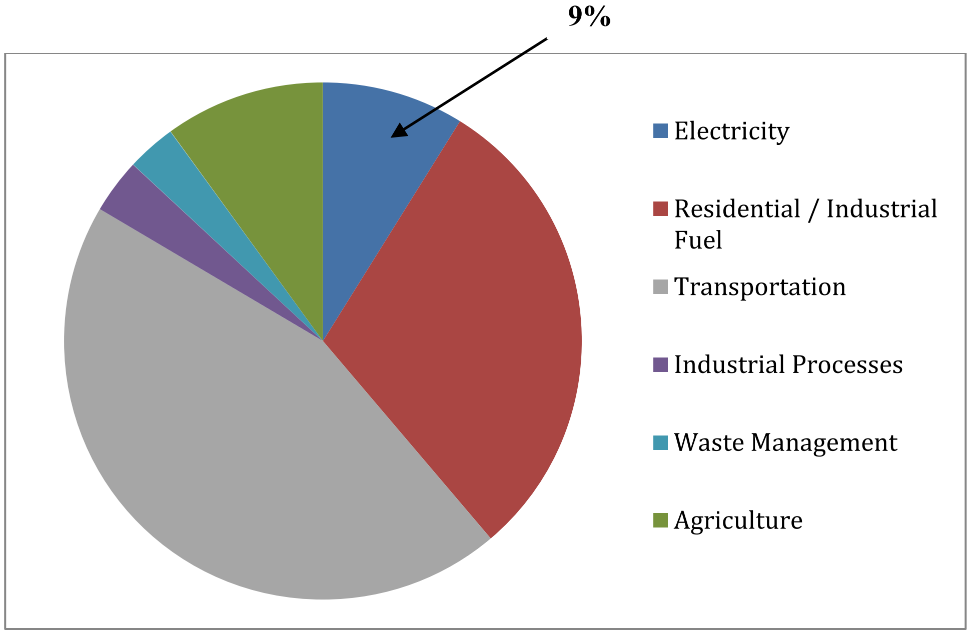


Figure 5: Future Scenario 1. This pie chart illustrates Vermont's inventory of greenhouse gas emissions by sector if VT Yankee was replaced by natural gas, highlighting that Vermont's greenhouse gas emissions from generating electricity would increase to 9%.

If all 25 MW of potential hydro were developed, a combined total of 54,750 avoided $MTCO_{2e}$ would result. However, even if all 25 MW of hydropower were developed, electricity would still contribute 8% of the state's total annual greenhouse gas emissions, avoiding only 1% of emissions (Figure 6). To avoid all of the GHG emissions that would result from purchasing electricity from the New England grid, Vermont would need to develop approximately 205 MW of hydropower.[1] While this fits within the range of some estimates of hydropower potential in Vermont, we do not think this is a feasible estimate. Given that most hydropower development projects today are less than 5 MW, developing 205 MW of electricity would require development of at least 41 dams. Some professionals in the field, such as Lori Barg, founder of Community Hydro, estimate over 400 MW of potential hydropower; as previously mentionted, we think these estimates are unrealstically high.

[1] Purchasing electricity from the New England grid will increase the state's emissions by 450,000 $MTCO_{2e.}$ Every MW of hydropower development avoids 2,190 $MTCO_{2e.}$ 450,000 $MTCO_{2e}$/2,190 $MTCO_{2e\ per\ MW}$ = 205 MW.

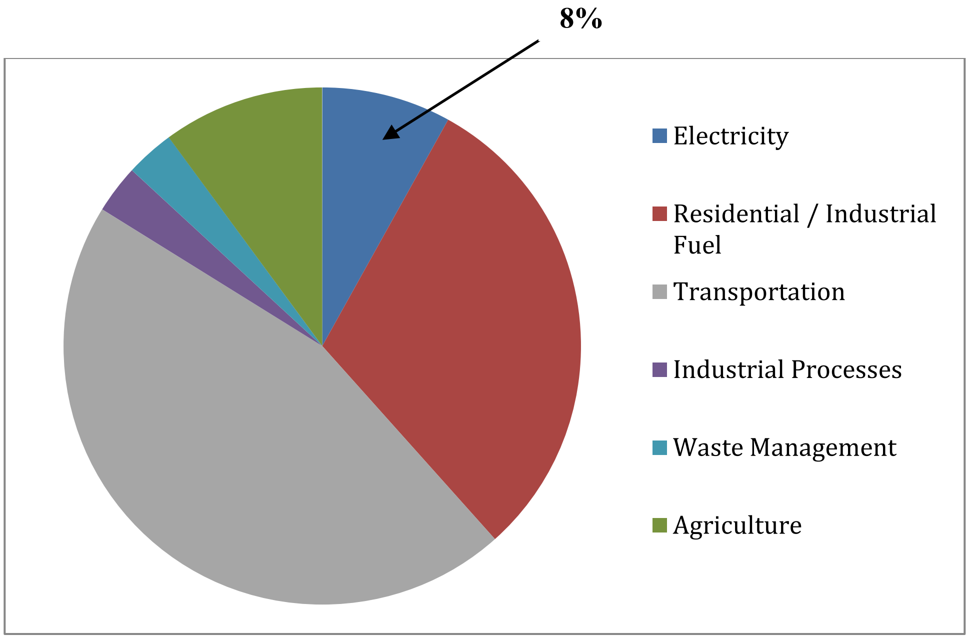


Figure 6: Future Scenario 2. This pie chart illustrates Vermont's inventory of greenhouse gas emissions by sector if VT Yankee was replaced by 25 MW of hydropower development and natural gas, highlighting that Vermont's greenhouse gas emissions from generating electricity would decrease to 8%. In sum, developing the state's hydropower potential might only create a 1% decrease in emissions.

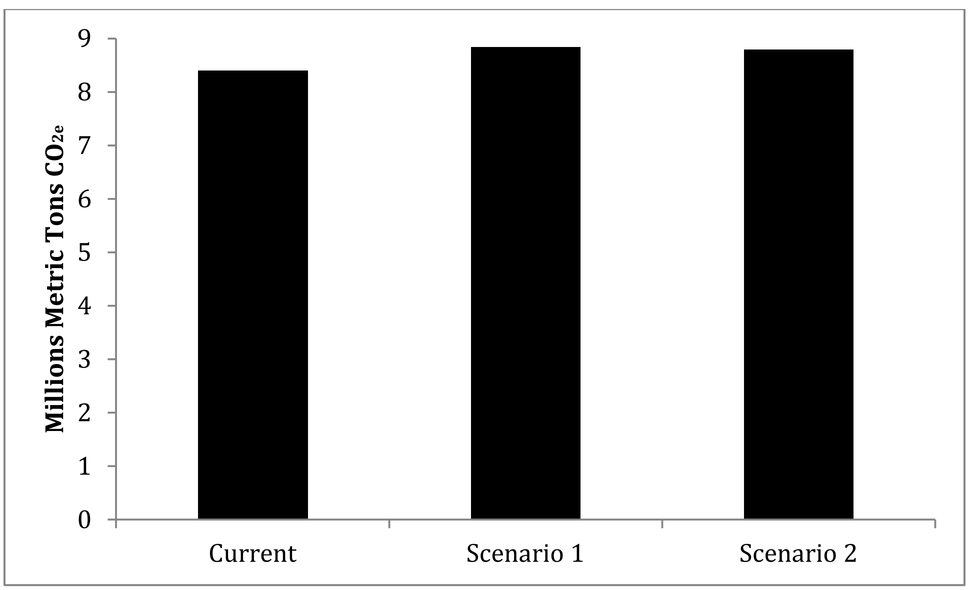


Figure 7: Greenhouse Gas Emissions. Vermont's total annual greenhouse gas emissions based on current conditions; Scenario 1, in which Vermont Yankee is decomissioned and Vermont is forced to purchase natural gas generated electricty from the New England grid; and Scenario 2, in which Vermont Yankee is decomissioned and Vermont develops all 25 MW of hydropower and purchases some natural gas-generated electricty from the New England grid.

These scenarios of how Vermont Yankee's impending energy gap might be filled show us that the development of in-state, small-scale hydropower will not affect the state's overall greenhouse gas emissions in a significant way (Figure 7).

Discussion

While there is indisputable evidence that the roughly 1,200 dams in Vermont are ecologically detrimental, there is not significant evidence that retrofitting these dams to hydroelectric facilities will have a considerable effect on lessening Vermont's contributions to climate change. Therefore, we have concluded that the ecologic benefits of avoided greenhouse gas emissions from thorough and extensive hydropower development are not worth the costs to freshwater ecosystems.

There is a profound sense of urgency among many environmental activists to rapidly develop Vermont's renewable energy infrastructure, especially given the impending consequences of climate change; however, the assertion that the ecological benefits of reduced emissions in Vermont outweigh the cost to freshwater ecosystems is uninformed and incorrect. Despite the perception that "we are Nero fiddling while Rome burns"—that the state is wasting time and resources arguing about the regulatory process when it should be reducing carbon dioxide emissions as quickly as possible—hydropower development will not significantly reduce the state's emissions (Barg 2007).

Furthermore, we disagree with the perspective that the only way to prepare for climate change is by reducing greenhouse gas emissions regardless of any associated detrimental ecological impacts. Instead, we stress that planning and managing for climate change involves increasing the ability of Vermont's linked social-ecological systems to adapt to change. Dams, and in particular, series of multiple dams on one river, reduce a river's ability to contain fluctuations in water level. While undeveloped rivers have natural riparian floodplains, dams often inundate these riparian zones and reduce the effectiveness of these floodplains. Our conclusions and our proposed regulatory framework draw heavily from the concept of resilience. While the concept has been part of the lexicon of the field of human ecology for decades, Walker and Salt reintroduced the concept of "social-ecological systems" or "linked systems of humans and nature" in their 2006 book *Resilience Thinking* (11). Modern, industrialized ideology is based on "optimizing the delivery of […] goods and services" while trying to maintain a stable state. However, a static condition "is not how the world works" (Walker & Salt 2006, 6). Instead, social-ecological systems exist in a "stable state" until changes in the system push it across a threshold to a new regime. Therefore, Walker and Salt advocate that social-ecological systems should be managed for “resilience,” which they define as “a system’s capacity to absorb disturbances without a regime shift” (38).

According to the Intergovernmental Panel on Climate Change’s (IPCC) 2011 Special Report on Renewable Energy Sources and Climate Change Mitigation, climate change could dramatically alter patterns of precipitation, specifically in high-latitude states like Vermont. Local and regional climate changes may also lead to increased runoff, increased temperatures, and alterations in seasonal flows. In terms of resilience thinking, these changes represent a “disturbance” to river systems and threaten to push these systems into a “new regime.” If Tropical Storm Irene is any indication of the potential for an extreme precipitation event to spur a regime shift, it is clear that Vermont’s waterways are not resilient to change. These floods dramatically changed the course of many stream sections, washing out roads and threatening communities (Figures 8 and 9).

Figure 8: Flooding in Bolton, VT as a result of Tropical Storm Irene. Photo: Phebe Meyers

Figure 9: Flooding in Woodstock, VT as a result of Tropical Storm Irene. Photo: Phebe Meyers

Dams represent an attempt to optimize a natural system for human gain. However, as Walker and Salt hypothesize, and as Tropical Storm Irene demonstrated, dams are ineffective at optimizing rivers and maintaining a stable state. Dams threaten the ability of rivers to contain fluctuations in water volume, therefore reducing the resiliency of the system.

Finally, hydropower itself is not resilient to the regime shifts associated with climate change. Local and regional climate changes may lead to increased runoff, increased temperatures and variations in seasonal flows, all of which would create risks for hydropower generation. While increased precipitation might initially seem like it would increase the potential for hydropower generation, the issue is more complex. Climate change's altered precipitation patterns will result in greater flow variability, which will result in lower than normal river discharge (and therefore lower power generation) in some seasons, and higher than normal river discharge in others. In 2011, for example, Vermont experienced a record volume of snowmelt that resulted in major flooding and altered sediment load and hydrology. The increase in sediment load is known to cause turbine abrasions and decrease efficiency, and also fills in reservoirs more quickly than normal sedimentation (IPCC 2011).

Given the consensus that dams negatively affect freshwater ecosystems; the evidence that the amount of greenhouse gases that would be prevented through hydropower development are almost negligible; the threats to hydropower's efficiency that are almost certain; and the impending effects that climate change poses, we ultimately do not recommend that the state pursue extensive small-scale hydropower development in Vermont. Instead, we recommend a new planning process and policy framework that prioritizes increasing the capacity of Vermont's rivers to adapt to change through wide-scale dam removal. Dam removal allows for redevelopment of natural floodplains and increases the overall connectivity of river systems.

Recommendation to the Legislature

We recommend that the legislature proactively evaluate all existing dams in Vermont through an environmental perspective using the framework we have developed (Figure 10). A dam task force could use our framework to identify those dams that ought to be removed, thereby permanently removing them from consideration for hydropower development, and to identify dams that are less viable candidates for removal, and which of these could be upgraded to produce electricity.

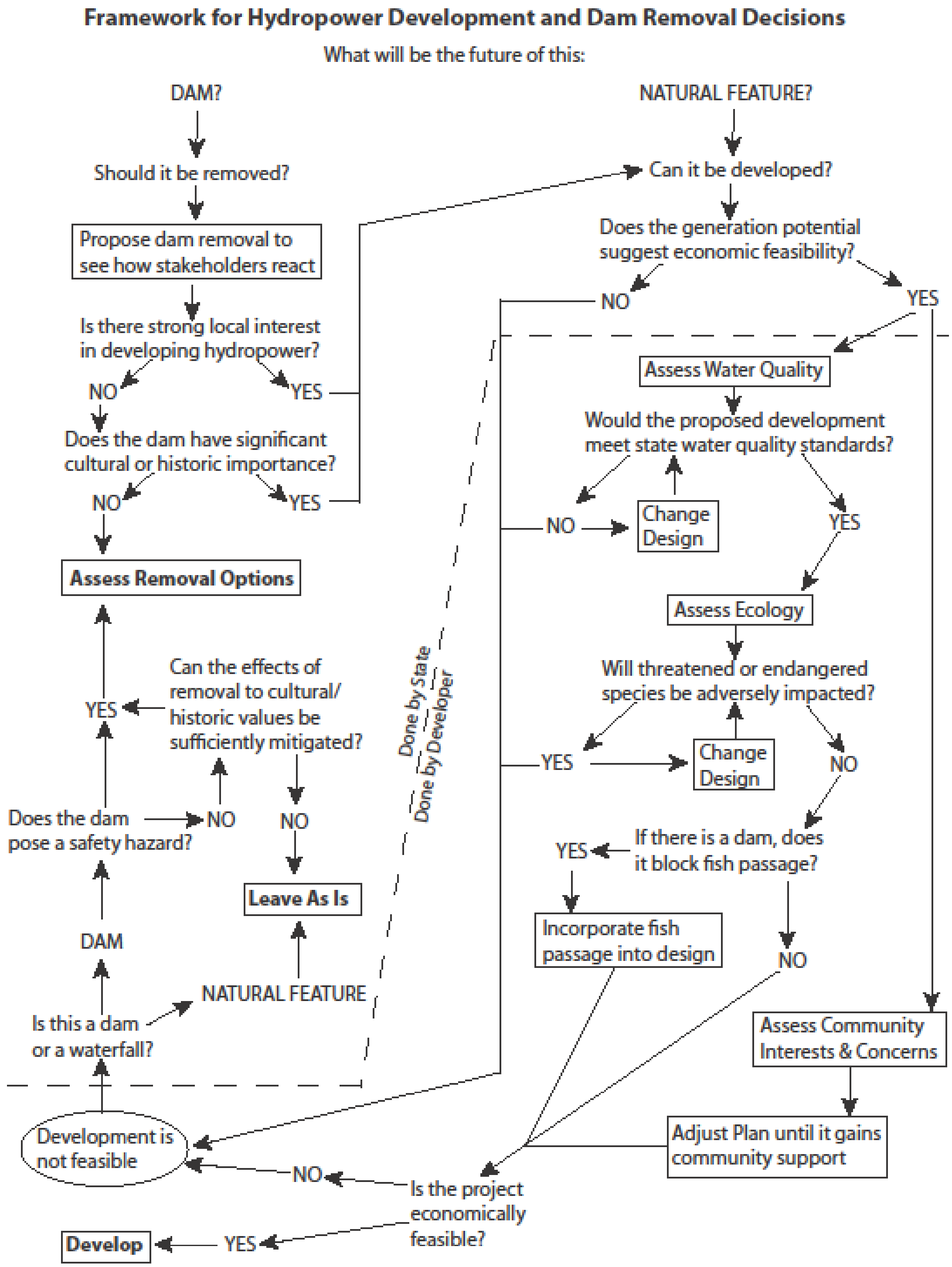
We contend that the state should seriously consider dam removal as a viable option to restore the quality of Vermont's rivers, thereby increasing the resiliency of the state's water systems to adapt to climate change. Our framework acknowledges that there are dams in Vermont that will not be removed due to their social or historical significance. In these cases, we recommend that these dams either be improved or retrofitted for hydropower development in ways that will also reduce the dam's detrimental environmental impacts. Retrofitting a dam mandates that it go through the FERC permitting process, requiring it to comply with water quality standards and requiring it to allow for migratory fish passage.

Future Research

Our recommendations listed above stem from the recognition that developing small hydropower projects in Vermont at existing dams would be neither an adequate way to close the energy gap that would result should Vermont Yankee be decommissioned, nor an ecologically sound process. The low-emission energy produced from small hydropower projects are, in most cases, not worth the ecological harms associated with a continued dam presence. However, it is important to keep in mind that the state has set a goal to have an energy portfolio consisting of 90% renewables by 2050. Thus, if the state wants to increase its renewable energy portfolio, it should also pursue other renewable energy sources. While this report looks exclusively at the ecological implications of installing small hydroelectric projects at existing dams in Vermont, future research should investigate the ecological implications of other hydroelectric energy sources. Specifically, there ought to be an investigation of the ecological implications of upgrading existing hydropower (making existing hydroelectric facilities more efficient and able to generate more power) and of pursuing non-dam hydropower such as hydrokinetic generation through water distribution pipes. For more information on non-dam hydropower, we refer the reader to Appendix A of the Fall 2011 ENVS 0401 report "Understanding the Upfront Costs: An Economic Feasibility Study of Increased Hydroelectric Generation at Existing Dam Sites in Vermont."[2]

[2] Available from the Middlebury College ENVS 0401 project archive: http://www.middlebury.edu/academics/es/work/communityconnectedlearning/envs0401/archive.

Figure 10: Our Proposed Framework



Benefits of our Framework

While the current regulatory structure is reactive, case specific, and limited in its scope of analysis, our new framework is proactive, comprehensive, and has an expanded scope of analysis.

This framework is proactive because a state or a conservation agency can use it to analyze potential hydropower sites before these sites have attracted interest from developers. Users of our framework will begin to evaluate a dam without a bias toward one desired outcome, thereby preventing many ill-fated plans for development or removal that are instigated without understanding the plan's feasibility. Since the state has limited resources, it will be tasked with only the "easy" decision of whether it makes sense to remove or retrofit a dam, while the actual planning for a hydropower facility will be turned over to a developer.

Although the best option for a dam's future will be determined based on site-specific factors, this framework is comprehensive because it can be used to analyze all dams with the goal of restoring river connectivity. In most cases, utilization of our framework will lead to the removal of a dam or improvements in fish passage along with the installation of generating capacity. Our framework will have greatest success if the state uses it to analyze all dams in a single watershed at a time, rather than analyzing dams at random, because an understanding of watershed-scale connectivity issues will better inform decisions of which dams should be prioritized for removal and which dams require adjustments to allow fish passage.

Finally, this new framework has an expanded scope of analysis because it considers dam removal and retrofits simultaneously. Currently, dams are only considered for removal if they are deemed to pose a significant safety hazard, and dams are only considered for hydropower if someone with significant time and money becomes interested in the site. If the state wants to decrease its greenhouse gas emissions and also prepare itself to deal with the effects of climate change, it should use our framework in order to identify all sites where one or both of these objectives can be met.

Using the Framework

Our framework is organized into a series of guiding questions that frame the series of actions, decision-making questions that determine what actions should be taken, and actions (framed by boxes). All decision-making questions are binary, leading to one of two possible actions. The dotted line demarcates the section of the framework that should be undertaken by the state (top-left) from the section that will be used by the developer (bottom-right). This division will be explained further below.

The first action in this framework is "propose dam removal to see how stakeholders react." Given that hydropower has received so much media attention recently, it is almost certain that someone will demand that a dam be evaluated for hydropower potential before it is considered for removal. In many instances—such as that of the Kendrick Pond dam in Pittsford—this recommendation is unrealistic due to the dam's tiny capacity and sedimentation issues (Fitzgerald 2011).

If there is no significant or realistic interest in developing the dam, the other question that must be asked before proceeding with dam removal is, "does the dam have significant cultural or historic importance?" Some dams have attained such cultural importance in the town that efforts to remove the dam will be met with immovable opposition. For example, Trout Unlimited once explored the possibility of removing a dam in Warren, but found that it had "attained somewhat mythic proportions over the decades" and realized "there would probably be citizens standing in the river" if they tried to remove the iconic dam (Amadon 2011).

If a site does not fit the criteria for dam removal, then it should be assessed for hydropower development viability. The first question regarding viability is, "does the potential generating capacity suggest economic feasibility?" This question does not provide a definitive answer of whether or not the project will be economically feasible, as that will depend on the final project design (see the Fall 2011 ENVS 0401 report "Understanding the Upfront Costs: An Economic Feasibility Study of Increased Hydroelectric Generation at Existing Dam Sites in Vermont"[3] for a detailed analysis of hydropower economics). Rather, this question is intended to weed out those projects that are definitely not feasible. The potential generating capacity of a site may easily be estimated based on head and the size of the watershed. Multiple developers have indicated that only sites with a generating capacity of around one megawatt or greater will be economically feasible (CVPS 2011; Warshow 2011).

[3] Ibid.

This first part of the framework is best suited for use by the state or a conservation agency. Although there are a large number of dams in the state, the task of determining whether a site should be considered for dam removal or a retrofit should not require any expensive scientific or engineering studies, so the state should find it possible to fund a new Dam Task Force to accomplish these goals. Developers do not approach dams from the same starting point that the state would, and they are mostly interested in dams that appear to have economic potential. Thus the adoption of our framework by a state organization that is tasked to examine all dams would make the system for dealing with the state's derelict dams proactive, comprehensive, and broader in scope.

The remainder of the framework (determination of whether a site can be developed) is best suited for use by the potential developer. This part of the framework can be used during the FERC licensing process to ensure that the developer is asking the right questions of the right people and is on task with environmental studies. Stakeholder involvement is an important component of the process; without the support of the town and other groups with strong voices, the project will fail. When developing hydropower, "there has to be a lot of interaction with the public to make it a smooth project" (Schiff 2011). Thus the public are involved at the outset of our framework (when identifying whether a dam should be removed or considered for development) and during the assessment of project viability. Community involvement must happen concurrently with environmental planning, so the process outlined in our framework is not entirely linear. Realistically, the community must be involved in every step of the process to avoid unforeseen conflicts of interest or a lack of trust, and should continue to be involved and kept informed during the development of a site or removal of a dam.

If a project is ultimately determined to be uneconomic and cannot be developed, there are two options for the dam's future. The first option is to leave the dam as is. If public opposition to dam removal was already identified, or if the site could become economically viable in the future, inaction may be the best option. However, if the dam poses a safety hazard in its current state, it cannot be allowed to remain as is and must be either removed or modified/reinforced to eliminate the danger. If development is uneconomic, it is unlikely that work will be done to strengthen the dam, so removal will probably be the best option in this scenario. As developers are unlikely to undertake a dam removal project, the final part of our framework for uneconomic retrofits falls again to the responsibility of the town or state or a conservation agency that is interested in restoring river health.

Our framework is not entirely new: the questions within it have been asked before. However, there are many developers who have recently stumbled over one or more parts in this framework, causing their projects to fail, so this framework may serve as a guide for inexperienced developers. Furthermore, the initial portion of the framework is intended for use by the state to identify which dams have development potential and which should be removed, so the state may advise a prospective developer whether or not to bother pursuing a project. Thus our framework may serve the dual purposes of helping the state to plan for the future and of saving many prospective developers from headaches.

Case Studies

We include here four case studies to illustrate several points. First, these case studies demonstrate the diversity of outcomes or best options that may be determined from the examination of dams and natural features with potential for electricity generation. Second, we describe the four cases to show how our framework would be used in different scenarios. Finally, the case studies indicate places where the current regulatory system is lacking and how our new framework would improve the evaluation of a site.

These four case studies represent four different outcomes of decision-making and licensing processes that often took many years, so they are informative to someone who plans to use our framework; these cases bring up issues and motives that one might encounter when trying to decide a course of action and enact this decision.

Case Study for a Retrofit: Winooski One Hydroelectric Dam, Winooski

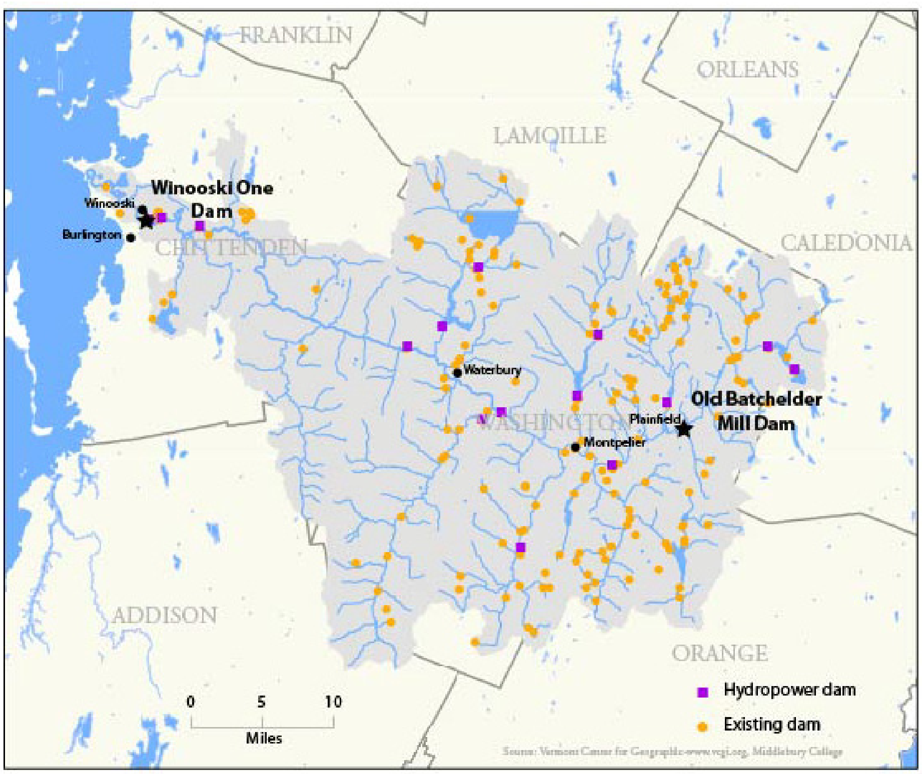


Figure 11: Map of Winooski One and Batchelder Mill Case Studies. Map of the Winooski River Watershed in which the Winooski One Dam and the Old Batchelder Mill Dam case studies are located, showing the existing and hydropower generating dams.

Figure 12: Winooski One Dam.

The 7.3 MW Winooski One (also known as Chace Mill) Hydroelectric Project, conceived in 1984 by the Winooski One Partnership and operating since 1993, was one of the last dams to be developed for electrical production in the state of Vermont (Figure 12). It was also the first Vermont facility to be certified as "low-impact" by the Low Impact Hydropower Institute (Goldfarb 2009). Although the developers did not have our framework in hand, it is useful to compare the process leading to the Winooski One retrofit with the steps we advocate here.

The Winooski One project began to move forward due to interest in hydropower development, rather than interest in dam removal. However, if dam removal had been proposed, it seems clear that many voices would have spoken out in opposition, including the cities of Burlington and Winooski, local residents, and developers, because a good hydropower site does not go unnoticed; the city of Burlington had previously considered diversion of water from the site to produce electricity. Thus, although the starting point for our framework is the guiding question "should the dam be removed?" we do not believe that any good sites for hydro development would be removed because hydroelectricity is a popular concept in Vermont. Furthermore, sites with high generating potential tend to have a strong history of mechanical energy production, and townsfolk will be interested in restoring this piece of the town's heritage. Winooski One is on the National Register of Historic Places, as it had been a site of mechanical energy production since 1790 and the existing timber-crib dam was built in 1876 (Warshow 2011).

The Water Quality Certificate from the Vermont ANR took less than one year for the Winooski One partners to obtain, although Warshow concedes that the US Fish and Wildlife Service sets more rigorous aquatic base flow requirements today (Warshow 2011). To maintain water quality, the Winooski One partners were required by the state Department of Water Resources and Environmental Engineering (DWR) to submit "a comprehensive erosion control and water management plan to cover construction activities" before construction began (DWR 1987). The state was particularly concerned with dissolved oxygen (D.O.) levels given that there were already 16 wastewater treatment plants and 14 commercial hydroelectric projects operating in the watershed upstream of Winooski One (DWR 1987). The ANR set a bypass flow requirement of 168 cubic feet per second (cfs), which would be in effect regardless of available water (except in winter, because of ice), meaning that the flow through the turbines must be reduced during low flows in the summer (DWR 1987). The state mandated monitoring of D.O. both upstream and downstream of the dam for the first five years of its operation, during which time they found no problem with the D.O. levels due to oxygen saturation in the bypass flow (Warshow 2011).

The blasting that was required for construction of the powerhouse and tailrace affected the populations of two rare plants living on the rock ledges, one proposed for the Vermont Endangered Species List and the other for the Vermont Threatened Species List. The ledges on either side of the river at the Winooski lower falls comprised the only site in Vermont where *Anemone multifida* could be found, and its local population was about 250 individual plants (DWR 1987). *Carex garberi* occurred at only three known sites in

Vermont, one of them the bedrock depression where the tailrace was to be excavated (DWR 1987). In recognition of the benefits of the hydropower facility, the State Endangered Species Committee recommended that the loss of these plants should be allowed with certain conditions for mitigation, such as protection of *Anemone multifida* plants located on ledges outside the construction limits (DWR 1987; Goldfarb 2009). The original proposed site of the powerhouse was further downstream where the rare plants are, but their discovery caused the powerhouse to be constructed closer to the dam (Warshow 2011). This demonstrates how a project can adapt to meet the requirements outlined in the framework.

The Winooski One Dam is located ten miles upstream of Lake Champlain (Figure 11). The remnant timber-crib dam presented the first obstacle on the river to anadromous (migratory) fish such as walleye, landlocked Atlantic salmon, and steelhead rainbow trout; no fish could pass this barrier (Goldfarb 2009). Walleye spawned in the "Salmon Hole" pool located downstream of the dam, and state biologists determined that the fish would be unaffected by construction and operation of the dam as long as water quality was maintained (DWR 1987). The construction of a fish lift and trap-and-truck system as part of the project has facilitated the upstream migration of steelhead rainbow trout in the spring and landlocked Atlantic salmon in the fall (Figure 13) (Goldfarb 2009). A small waterfall at the base of the dam attracts migrating fish, which jump up the waterfall into a trap tank that is raised and from which the fish are transferred into a holding tank, where the state biologist can identify and tag them (Warshow 2011). The operation of the facility allowed the passage of the first salmon since 1790 (Warshow 2011). Typically, groups such as Trout Unlimited oppose hydropower projects whether they contain fish lifts/ladders or not, because "even if each dam is 95% effective in passing fish, passage over 3 or more dams will likely result in a substantial reduction in migratory fish populations . . . the cumulative impacts of fish passage inefficiency are substantial" (Reardon 2011). In the case of Winooski One, however, Trout Unlimited is generally positive about the project because the existing dam blocked all fish and was unlikely to be removed.

As this case study shows, the current regulatory framework provides fairly strong standards for environmental protection on the local scale. The ANR looks in-depth at issues of water quality, local ecology, and the passage of anadromous fish. However, the ANR does not always require fish passage. Passage was required at Winooski One because of the dam's location within the watershed, while our proposed framework seeks to improve connectivity throughout the watershed by requiring all dams that block fish passage to be removed or to add fish passage mechanisms.

According to the Low Impact Hydropower Institute (LIHI), "nearly every one of the federal, state, and local agency staff . . . commented that the applicant had demonstrated extraordinarily good corporate citizenship in carrying out and often exceeding the requirements associated with the project's construction and operation" (Goldfarb 2009: 1-2). The partnership's cooperation and civility helped them gain the support and trust of the cities of Winooski and Burlington, and their willingness to protect the aquatic and riparian ecosystems prevented future litigation over environmental matters. In total, the Winooski One partners obtained 18 permits with 200 conditions from the city, state, and federal government levels before they could begin construction (Warshow 2011). Yet Warshow is not critical of the process; he and his partners recognized that they must let all stakeholders be involved in the determination of the many conditions so that the project would be accepted. Overall, the Winooski One Partnership followed a course similar to that outlined by our questions and actions.

Figure 13: Winooski One Fish Lift. Diagram of Winooski One Dam outlining fish lift, an ecological mitigation strategy

Case Study for Inaction: Batchelder Mill Dam, Plainfield

Figure 14: Batchelder Mill Dam. Photo from the Town of Plainfield website, http://www.plainfieldvt.us .

The Batchelder Mill Dam (Figure 14), located on the Winooski River in Plainfield, provides an example of how historical significance and economics play into our framework (Figure 10). This dam has not been considered for removal, as our framework recommends, because the future of a dam is currently only evaluated if someone is interested in installing hydroelectric capacity or if the dam has been identified as a safety hazard. However, we can use our framework to see what would happen with a dam such as this if a more holistic approach were taken to determining its future.

A Plainfield resident and hydroelectric equipment supplier approached the town's selectboard to propose that the dam be retrofitted as a run-of-river hydroelectric project (Clark 2011). Dam removal was never considered as an option. We do not know whether or not town officials or citizens would have objected to removal of the dam on the basis of interest in hydropower if this resident had not brought up the possibility. However, the dam would definitely have been diverted to the "Can it be developed?" side of our framework at the question, "Does the dam have significant cultural or historic importance?" because the dam has been located at the center of the town since its establishment and its image is on the town seal (Clark 2011, Figure 15). The adjacent property, formerly the site of a sawmill, is now a town park. The physical and mental centrality of the dam to the town and its residents creates a strong barrier to the dam's removal. Thus, according to our framework, a retrofit should be considered.

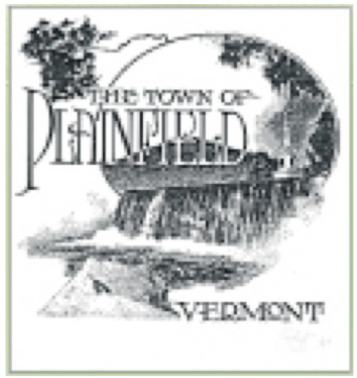


Figure 15:Plainfield Town Crest. The crest of the town of Plainfield, depicting the Batchelder Mill Dam. From the Town of Plainfield website, http://www.plainfieldvt.us

The Batchelder Mill Dam, at the height it currently stands, is only capable of generating 90 kW, so the generation potential does not suggest economic feasibility (ANR 2008). However, sometimes a town is willing to pursue a retrofit even if the economics do not make sense, because the idea of renewable energy is appealing even if it will cost more than non-renewable energy, and hydroelectric generation is compatible with the historic image of the town. The town of Plainfield applied for and received a $250K grant from Vermont's Clean Energy Fund (Clark 2011).

The primary ecological concern with the Batchelder Mill Dam retrofit was fish passage. The town took the position that a requirement for fish passage should not be inflicted on the hydroelectric project, because the dam has been there since the 1700s and the addition of fish passage would make the project uneconomical (Clark 2011). As it turned out, the project was later deemed uneconomical for other reasons (including unforeseen regulatory issues). However, it is interesting to note that economic considerations sometimes trump environmental considerations in the real world, even though our framework places greater emphasis on the environmental considerations. We reason that if the addition of fish passage is the factor that makes a project uneconomic, then the project is probably of little value in terms of offsetting greenhouse gas emissions. A resilient river may better prepare us for climate change than a hydroelectric facility that offsets only 90 kW of fossil fuel energy. Furthermore, if some of the other dams within the watershed are removed (by a Dam Task Force with our framework in hand), then there will be a greater desire to provide fish passage at the Batchelder Mill Dam, so the project should not be approved when it might face severe economic harm in the future due to the increasing importance of fish passage.

The proposed microhydropower facility was eventually determined to be economically infeasible, so the dam remains as it was. "The dam is inspected by the state on a regular basis" and has been found to pose no significant safety hazard, so our framework does not mandate an assessment of dam removal options (Clark 2011). However, since the dam cannot be economically retrofitted, our framework recommends seeking a strategy for dam removal that will provide ecological benefits such as fish passage and stream connectivity. The dam's strong historic and cultural importance will block removal in this case, though one solution to improve fish passage would be to add a fish ladder to the existing dam.

Case Study for Removal: Dufresne Pond Dam, Manchester

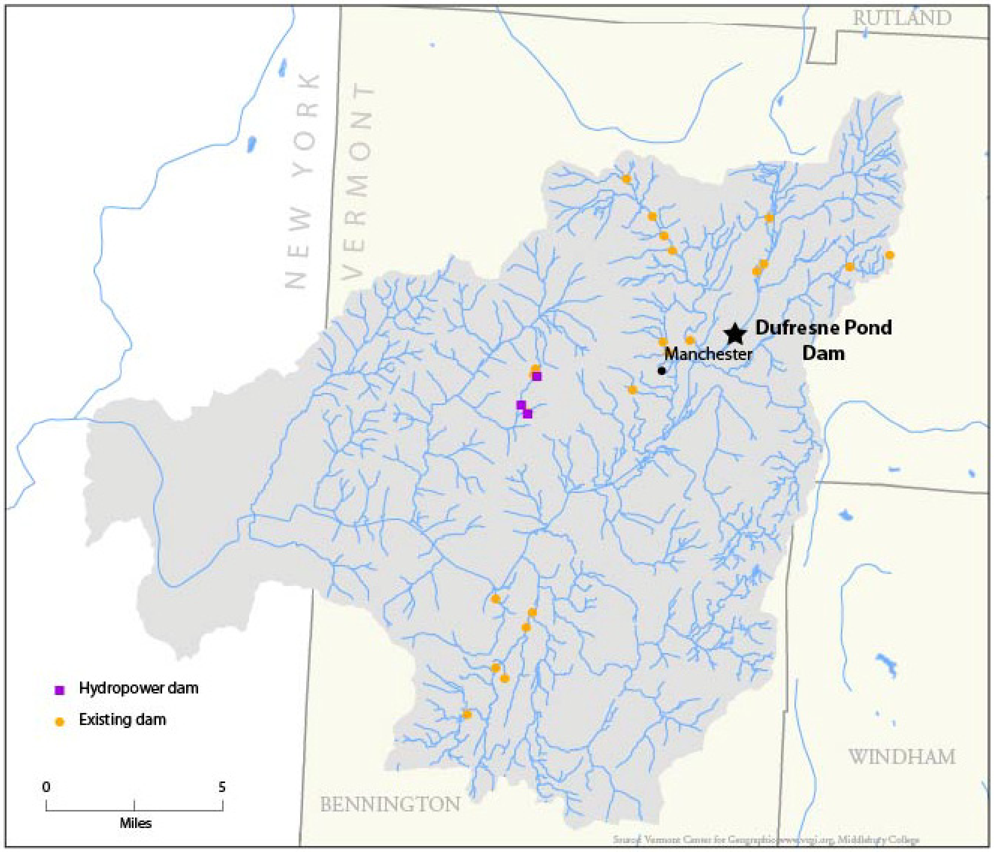


Figure 16: Map of Dufresne Pond Dam Case Study. Map of the Batten Kill River Watershed in which the Dufresne Pond Dam case study is located, showing existing hydropower and non-generating dams.

Figure 17: Dufresne Pond Dam**,** Photo courtesy of Roy Schiff, 2011

Project goals and objectives (Milone & MacBroom, 2011):

1. *Remove the Dufresene Pound Dam during the 2011 construction season*
2. *Create a dam removal/channel restoration design and construction sequence that manages the deposited fine sediment in the existing impoundment to minimize the chance of a large single-sediment erosion event*
3. *Restore fish passage and channel habitat in the vicinity of the dam*
4. *Maintain or improve the existing public fishing access*
5. *Create a cost-effective design*
6. *Continue ongoing outreach efforts to improve local support for the dam removal project and restoration of the Batten Kill*

The Dufresne Pond Dam is located on the Batten Kill River in Manchester, VT, and is currently undergoing the dam removal process (Figure 17). We identified this as a prime example of a dam that our framework would determine as a candidate for removal. There is little historical significance, the river is prized for recreation and fishing, the dam is not structurally sound, and there was minimal interest from the community in power generation.

Originally built in 1908 by the Dufresne family to power their sawmill, this dam was considered a major hazard by the ANR in 2004 (DEC 2009). It is the only dam on the main stem of the Batten Kill River, and has been owned by the Vermont Department of Fish and Wildlife since 1957. About seven years ago, the Department of Fish and Wildlife proposed installing a fish ladder at the dam to allow trout and other species to migrate beyond the dam upstream. After conducting a comprehensive economic feasibility and alternatives assessment, the Department of Environmental Conservation (DEC), the Army Corps of Engineers, and the ANR suggested removal as the best option. It was the cheapest alternative in relation to spending money on maintenance, and removal would save both taxpayer and sportsmen dollars (VNRC 2005). The state dam safety engineers said that inaction was not an option since the dam was emitting uncontrolled seepage and had inadequate spillway capacity, resulting in frequent over-topping (Schiff 2011; ANR and DEC 2009). This was linked to numerous failed attempts to control the long history of seepage (Milone & MacBroom 2011). The dam also served no current useful function. The dam itself was eleven feet high and approximately 270 feet long, with a forty foot spill way (DEC 2009). Behind the dam, an 11-acre impoundment stretched, providing recreational fishing and water activities (Figure 18).

Figure 18: Dufresne Pound Dam Impoundment. Photo of the Dufresne Pond Dam impoundment before removal project (Roy Schiff, 2011)

The Batten Kill River was home to a large Brown Trout fishery, as well as other migratory species. The dam, however, obstructed fish movement, blocked the flow of nutrients and woody debris, and increased sedimentation in the adjacent impoundment (VNRC 2005). Removal was projected to restore viable trout habitat, facilitate natural movement of fish, as well as improve aquatic habitat. The impoundment had filled with sediment, resulting in a shallow and warm aquatic ecosystem (Schiff 2011). Temperatures rose to 70 °F, a temperature dangerous to trout.

If we were to run the Dufresne Pond Dam through our new framework, we would start with the question, "should it be removed," with a follow up question of proposing dam removal to see how townspeople would react. This was done in 2005 in an open discussion headed by the Manchester Conservation Commission and Manchester Rod and Gun Club. The ANR gave a presentation on their study and the possibility of dam removal. According to the ANR, the structural integrity of the dam was failing, causing maintenance and repair costs to outweigh the benefits of renovation. The Batten Kill Alliance supported removal because of the direct benefits it would have in eliminating the fish passage barrier, reducing negative effects on trout habitat from warming water in the impoundment, and the reduced cost.

There was not a strong local interest in developing hydropower, since most interest focused on recreational fishing and the idea of river restoration (DEC 2009). Since the impoundment behind the dam would be drained, fish populations would be transported to a nearby state owned pond. The dam, even though it was about 100 years old, possessed no significant cultural or historic value. This led to the assessment of removal options, which was done through experts, locals, government agencies, and non-governmental agencies.

The state placed the DEC as project managers, and Milone & MacBroom, Inc. (MMI) were hired to design the removal of Dufresne Pond Dam and oversee its deconstruction. They were required to comply with the following nine conditions (DEC 2009):

1. *Develop 100% plans and specifications for the removal.*
2. *Develop a plan for management of impounded sediment.*
3. *Perform hydrologic and hydraulic analysis necessary to meet FEMA floodplain management requirements.*
4. *Ascertain the supporting structural integrity of the soil under each railroad bridge abutment and determine the ability of the abutments to provide continued adequate support of loads transmitted from the superstructure during and after dam removal.*
5. *Assess the potential impact of loss of the impoundment on shallow drinking water wells in the vicinity.*
6. *Develop post-removal photo simulations of the dam and impoundment* (Figure 19).
7. *Prepare information necessary to obtain state and federal (U.S. Army Corps of Engineers) permits.*
8. *Participate in up to two public meetings to inform the public of the project plan.*
9. *Provide contractor oversight during the deconstruction process.*

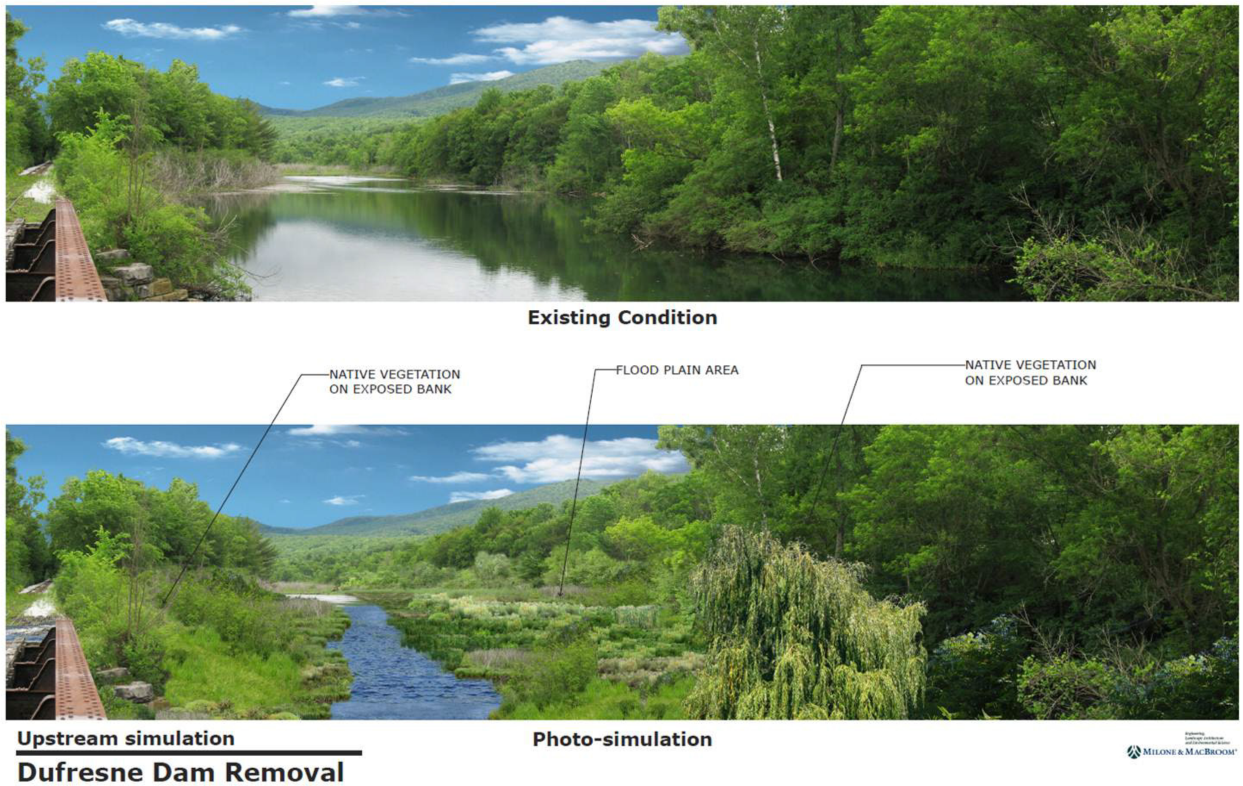


Figure 19: Dufresne Pond Dam Photo Simulation. Photo simulation of riparian habitat above the Dufresne Pound Dam, comparing habitat before and after removal

The DEC began to draw water in August 2010, reducing the impoundment level by five feet. Following this drop in water levels, a woman complained that her well had dried up. In order to mitigate the situation, the state drilled a new well for her. They refilled the impoundment to sustain her water supply during this process, only to begin to draw it down again in the summer of 2011 (Figure 20). The dam has yet to be fully removed, but drawdown is complete and drinking water concerns have been resolved. The DEC is poised for dam deconstruction in the summer of 2012.

This dam fits into the context of our framework of a successful dam removal example. Even though the process followed essentially what our new framework lays out, it is necessary to look at this example in order to facilitate such decision-making processes across the state.

Figure 20: Dufresne Pond Dam. Photo of Dufresne Pond Dam impoundment after drainage (Roy Schiff, 2011)

Case Study of a Natural Feature: Otter Creek Falls in Middlebury

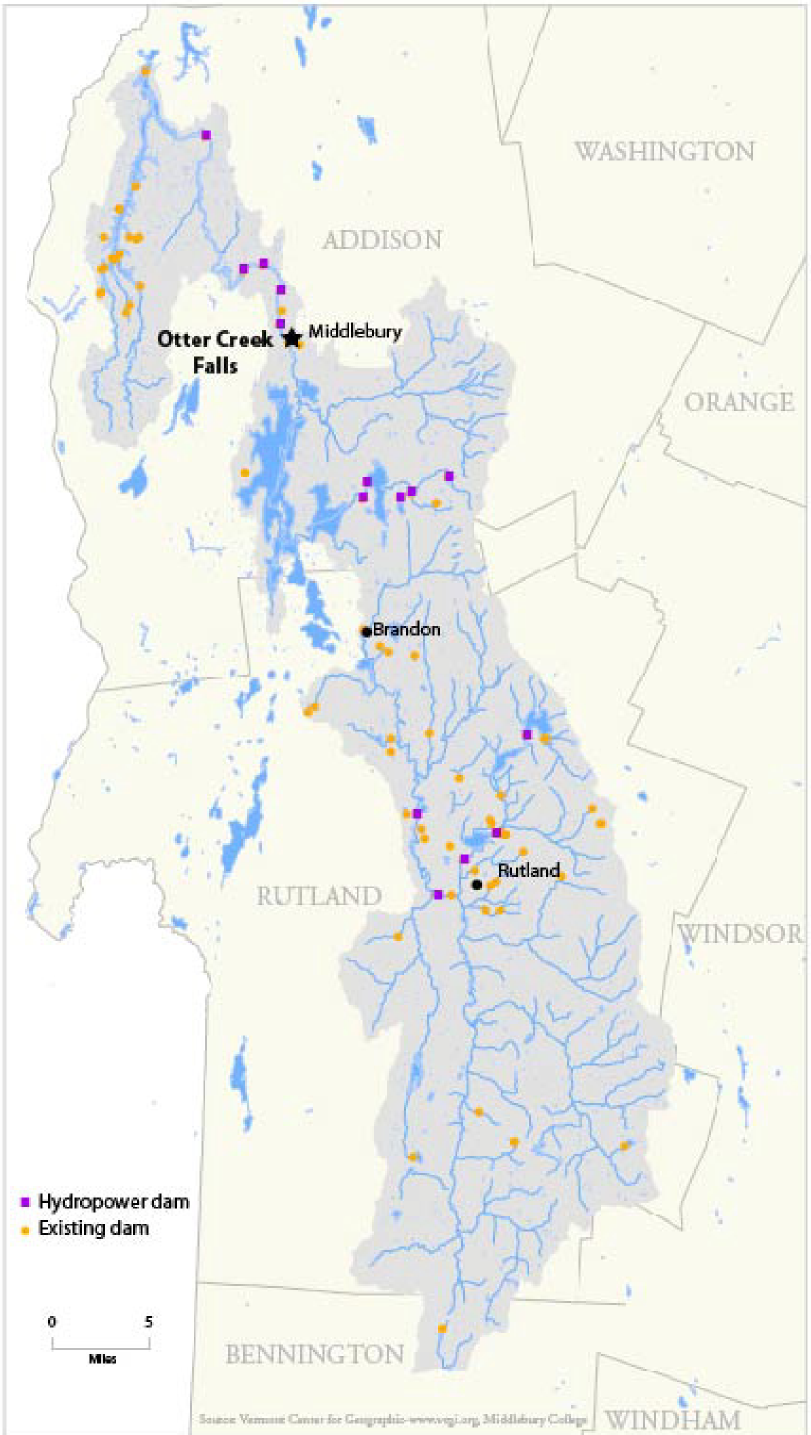


Figure 21: Map of Otter Creek Falls Case Study. Map of the Otter Creek watershed in which the Otter Creek Falls case study is located, showing the existing and hydropower generating dams.

Figure 22: Otter Creek Falls. Photo by Kathy Morse.

If the waterfall in downtown Middlebury was analyzed according to our framework, the first question would be “Can it be developed?” since there is no dam to remove (Figure 22). The existing infrastructure (sluice, former diversion) has no current effect on the river’s flow since it is not in use. The site has a potential generation capacity of 1,083 kW, and an expected yearly net production of about 5,000 MWh of electricity (Kleinschmidt 2008). At the present time this project appears to be economically feasible, although a drawn-out permitting process and dispute between the Middlebury Electric Company and the town caused costs to rise above what the proponent could afford (Flowers 2011). Efforts by CVPS to develop this site were abandoned in the mid 1980s due to cheap oil prices, indicating that sites much smaller than one megawatt are unlikely to be economically competitive as long as there is cheap oil (Eccleston 1995).

Of the ecological criteria, the most significant issue at stake in this case is the volume of bypass flow. If the company hoped for a minimum bypass flow of less than 324 cubic feet per second (cfs) (the flow rate the Fish and Wildlife Service determined as the aquatic baseflow), the ANR would require a D.O. study, fish study, and an aesthetics study to determine whether the proposed flow would inflict significant harm; the ANR would not require these studies if flows above 324 cfs are maintained (Gjessing 2009). Although a 1980 study suggested that a bypass flow of 142 cfs should be sufficient to protect D.O. levels, the current opinion of the ANR, along with community concerns, swayed the company to increase the minimum bypass flow in its plan to 324 cfs (Cueto 2009). Dissolved oxygen is perhaps the most significant factor in this case from a watershed viewpoint, because there are multiple operating hydroelectric dams downstream that block fish passage.

The townspeople of Middlebury also demand maintenance of some level of bypass flow over the falls due to aesthetic and business interests (CVPS and the Town of Middlebury 1982). The visual appeal of the falls is important for tourism. The majority of citizens support the project as long as it is done with consideration of aesthetics, because they see that the project could enhance tourism by providing better access and vantage points to the falls in the Frog Hollow District. Improvement of the Jessica Swift Memorial Park below the falls and public access to the area are a priority for the town. These interests have not changed since the 1982 agreement between CVPS and the town; rather, the specifics of the hydropower development plan have been evolving to satisfy these interests. The plan currently appears close to gaining final approval from all stakeholders and from FERC (Flowers 2011). However, town officials and abutting property owners are not yet willing to allow the development to commence due to issues of involvement and transparency. The current trouble highlights the importance of community involvement in any hydroelectric project, even one that utilizes a natural feature and has minimal negative environmental impacts.

The final step in the framework is economic feasibility. Due to the high legal and permitting costs, Middlebury Electric is looking for investors to help get the project started, as the project failed to gain acceptance in time to claim a financial incentive from Vermont's Sustainably Priced Energy Development (SPEED) Program (Flowers 2011). Once the company has the means to develop the site, the turbines will generate power worth a monetary amount greater than that of the cost to continue the plant's operation; despite high startup costs the project will be economic in the long run.

Lessons from the Case Studies

These case studies informed the creation of our framework in three important ways. First, they showed the dire need for a more comprehensive and broad-scope approach to evaluating the state's 1,100 non-generating dams. The watershed figures shown in the case studies above depict vast numbers of existing dams that currently serve no purpose, yet fragment riverine ecosystems and reduce their resilience. Many of these dams could be removed to restore ecological health and connectivity and increase resilience, while a select few could be developed for hydropower to help reduce our greenhouse gas emissions and work toward the state's goal of increasing its reliance on "renewable" energy sources. Currently, only high-danger dams such as the Dufresne Dam in Manchester are considered for removal. There is a dearth of information about the hundreds of low-danger dams in Vermont and their ecological impacts. Our new framework will help the state deal with the many dams that are not such obvious candidates for removal or development.

Second, the case studies showed the need for proactive evaluation of dams. Developers are driven by economic interests and/or ideals, and sometimes these drivers result in a large amount of wasted time and money. Microhydro projects such as the one proposed for the Batchelder Mill Dam are far from economical, so a proactive analysis undertaken by the state could save many towns a lot of trouble and money (and save the state money, too; developers will pursue Clean Energy grants to make a project "economical"). Developers also never consider alternative options such as dam removal or—where removal is not an option—the addition of a fish ladder.

Third, these case studies illustrate the importance of community involvement. The Winooski One retrofit and the Dufresne Pond Dam removal were both successful because they had significant public involvement from the outset. The Otter Creek Falls project has been struggling for nearly a decade despite consensus on how most aspects of the project should be done, primarily because community members do not feel that they have been adequately involved or have received the information that they require. This lack of involvement led to the erosion of trust in the developer, and without concrete plans for every detail of the project the town cannot be convinced that the project will be successful in the long term, which is an important consideration since hydroelectric infrastructure stays around for a very long time.

Conclusions

In response to a community need for an environmentally conscious decision-making process to determine the optimal fate of Vermont's many existing dams, we conducted a literature review, case study, and interview-based investigation of (1) the ecological effects of dams, of adding hydropower to existing dams, and of dam removal; (2) the current regulatory framework for assessing and permitting potential hydropower projects; (3) an evaluation of what initiatives or mitigation strategies are used to reduce the detrimental ecological impacts of hydropower projects; and (4) the potential for hydropower development to reduce the state's greenhouse gas emissions. Based on our findings during this investigation, we conclude that Vermont requires a new, proactive and comprehensive planning process for making decisions regarding climate change mitigation and hydropower development.

Because the current framework does not allow conservation agencies and lawmakers to weigh the relative environmental benefits of avoided greenhouse gas emissions against the detrimental ecological effects of dams, we empirically addressed this question for all 25 MW of estimated potential hydropower development in the state. If Vermont Yankee is decommissioned and Vermont is forced to purchase electricity from the New England grid and this power is generated from natural gas, the state's emissions will increase. While electricity currently contributes 4% to the state's total emissions, replacing Vermont Yankee's electricity with electricity from the grid will increase electricity's contribution to 9%. We conclude that developing small-scale hydropower in Vermont will not lead to meaningful reductions in the state's greenhouse emissions. Even if all 25 MW of hydropower in the state were developed, electricity would still contribute 8% of the state's total, annual greenhouse gas emissions, avoiding only 1% of emissions. In order to avoid all of the greenhouse gas emissions that would result from purchasing electricity from the New England grid, Vermont would need to develop approximately 205 MW of hydropower. We do not think that this is a feasible target.

Thus, the state of Vermont needs a new planning process to comprehensively evaluate all non-generating dams in the state to determine the most ecologically responsible future for the structure. We have proposed a new regulatory framework that lawmakers and conservation agencies can use to evaluate dams in Vermont and determine the candidates for removal and river restoration and the candidates for hydroelectric retrofit if social or historical factors make the dam impossible to remove (Figure 10).

Since Vermont will face more frequent and extreme precipitation events in the coming years as a result of global climate change, we must think of our waterways in terms of resilience. Through a comprehensive, proactive, and multi-outcome framework, we hope to influence policy makers and conservation agencies to think of river restoration and climate change mitigation efforts as two interrelated issues. While proponents of hydropower development claim that it will reduce greenhouse gas emissions, the development of small-scale hydropower in Vermont will not significantly mitigate climate change, and Vermont must therefore prepare for its effects. River restoration and efforts to increase connectivity through dam removal can help mitigate the impacts of climate change. By recognizing the interconnectedness of these issues, the state has an opportunity to increase the resiliency of its waterways, and identify economically feasible hydropower sites across the state. Our proposed framework will help the state to balance its responsibilities to mitigate both climate change and its consequences by improving the resilience of our waterways.

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