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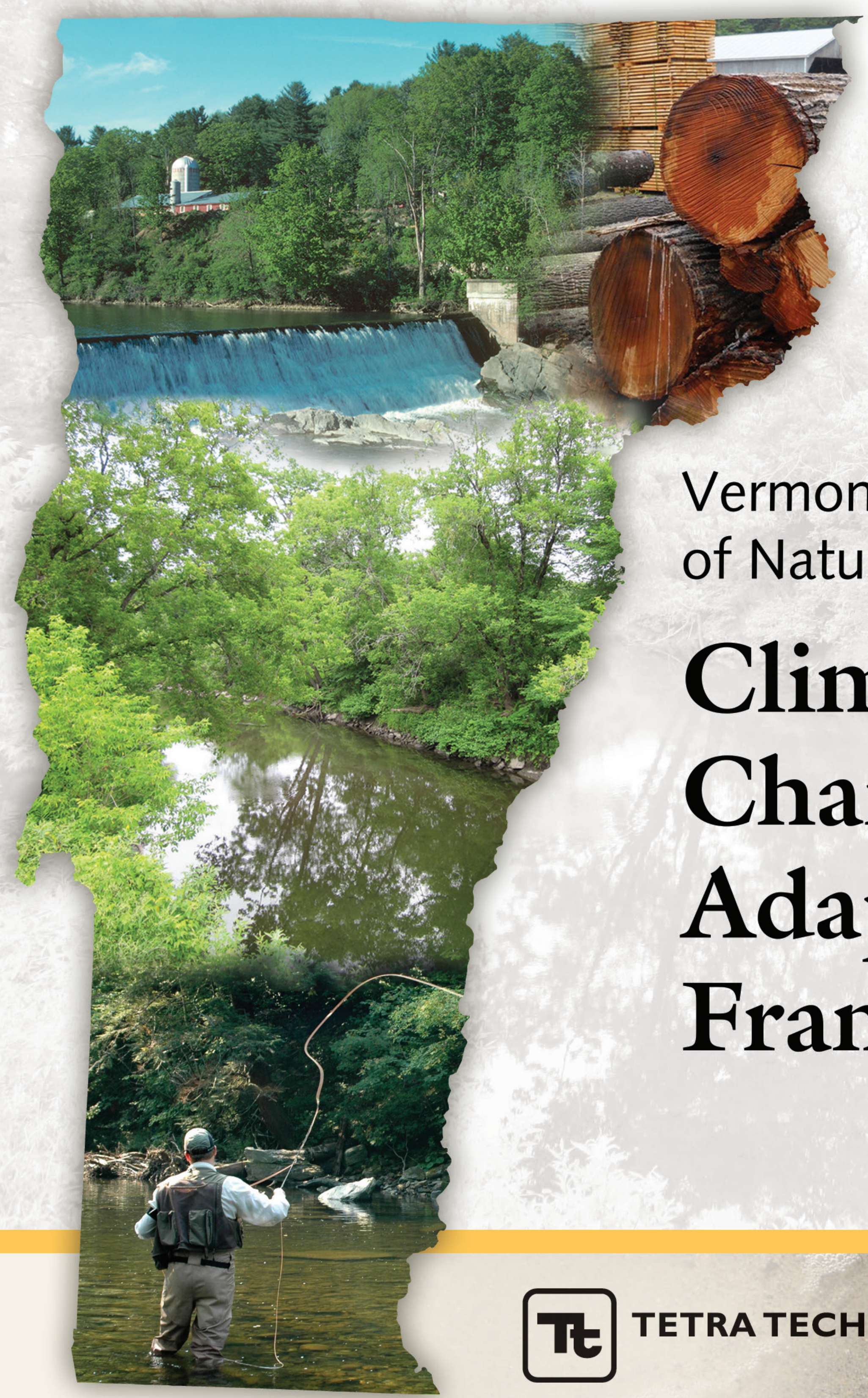

Vermont Agency of Natural Resources

Climate Change Adaptation Framework

TETRA TECH

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VT Agency of Natural Resources

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Executive Summary

INTRODUCTION

If you don't like the weather in Vermont, wait ten minutes. So the saying goes. The weather is in the conversations of Vermonters, those who visit for sports and scenery, and those who depend on Vermont products and commerce. Recent flooding events, especially Tropical Storm Irene in 2011, were catastrophic for several communities and natural areas throughout Vermont. These required heroic responses and unanticipated resources from individuals and towns, as well as State and Federal agencies. Climate affects so much of our lives that the possibility of significant disruption in patterns due to global climate change spurs us to speculation, and preparation. The regional climate models predict that the changing patterns we have observed so far – increases in temperature and more extreme fluctuations in precipitation – are likely to continue. If you don't like the climate in Vermont, wait 50 years, but we can't promise you'll like it any better.

While impacts on communities and infrastructure tend to grab the spotlight after storms and other extreme weather events, Vermont's natural resources are the backbone on which our livelihoods and quality of life depend. **Changes to climate will directly affect Vermont's natural resources, the services they provide, and the natural heritage they bestow**. Therefore, through this report and efforts that will follow, the Vermont Agency of Natural Resources (ANR) is addressing climate change impacts on four natural resource sectors: wildlife, (Division of Wildlife), fisheries (Division of Fisheries), forestry (Division of Forestry), and water resources (Watershed Management Division).

> *"The purpose of this report is to gather information about climate change in Vermont as it relates to natural resources and to propose a strategic framework for continued climate change vulnerability assessment and action planning."*

The purpose of this report is to gather information about climate change in Vermont as it relates to natural resources and to propose a strategic framework for continued climate change vulnerability assessment and action planning. Climate-driven changes in plant and animal communities, and climate change impacts on other aspects of Vermont's environment, will likely affect the way Vermonters perceive their natural surroundings, engage with natural resources for livelihoods and enjoyment, and do business in the state. Developing **vulnerability assessments**, which describe the types of changes expected, and **adaptation strategies**, which help manage or reduce negative effects, will be essential to prepare Vermonters for these impending changes. The **strategic adaptation framework** in this report is based on our scientific understanding of climate change exposures (the types of climatic changes expected that affect resources), our understanding and expectations of natural resource vulnerability to those exposures, and our perceptions of cooperative opportunities for addressing these vulnerabilities. In this report, we present the groundwork for the framework through chapters addressing climate change exposures, vulnerability-specific elements within each of the natural resource sectors, and ongoing and proposed actions that can be or have been taken to prepare for the expected changes.

There are two types of adaptation strategies that we do not address in this report: Mitigation of climate change exposures by reducing greenhouse gas emissions; and adaptation strategies involving the modification of infrastructure, such as roads and water/wastewater systems. Mitigation is an essential strategy for reducing the exposures, vulnerabilities, and the need for adaptation actions. However, Vermont is already addressing mitigation through established goals for reduction of greenhouse gas emissions. These goals require broad participation beyond that of the ANR, so while those efforts are supported strongly by ANR they are not described in this report. Likewise, infrastructure modification can have important links to natural resources, but infrastructure modification and maintenance is beyond the scope of ANR's immediate responsibilities. That being said, many infrastructure adaptation strategies, such as promoting stable stream and river channels, can also be beneficial to vulnerable habitats and species.

EXPOSURES

One component of vulnerability assessments is to evaluate **exposure**, or the amount of climate-related change a species or habitat is likely to experience. For this project, we assessed exposure by examining historical trends in climatic data and future modeled projections. Together, the historical and projected trends provide a best estimate of exposures that will be experienced in Vermont through mid-century (Betts 2011a).

During the past 50 years, there has been a consistent pattern of warming in Vermont. Mean annual air temperature at long-term weather stations in Vermont has been increasing at a rate of 0.28 °C (0.5 °F) per decade (Betts 2011a, Betts 2011b). Seasonal differences are evident, with mean winter temperatures rising fastest. There has also been an increase in the number of extremely hot days and a decrease in the number of extremely cold days (DeGaetano and Allen 2002, Hansen et al. 2012). The length of the growing season has increased (Betts 2011a). **These warming trends are projected to continue** (UCS 2006).

Historical trends in annual precipitation are highly variable **but there has been a long-term trend towards overall wetter conditions in the Northeast** (Karl et al. 2009, Hayhoe et al. 2007). In Vermont, precipitation has increased by 15-20% in the past 50 years, and total precipitation is expected to continue increasing in all seasons except summer (Betts 2011a, UCS 2006). Heavy precipitation events also have been increasing across much of the Northeast in recent decades, and **this trend is also expected to continue** (Hayhoe et al. 2007, UCS 2006, Karl et al. 2009).

These warming temperatures and changing precipitation patterns affect snowpack and the timing and volume of streamflow. Over the last several decades in the Northeast, less winter precipitation has been falling as snow and more as rain, resulting in a reduced snowpack, more streamflow in winter and spring, and less streamflow in summer and fall. There also has been a clear trend towards earlier snowmelt runoff/spring peak flow (Hayhoe et al. 2007). Ice dynamics are changing as well. The duration of ice on rivers and lakes has been decreasing, with later freezing dates and earlier ice-out dates (UCS 2006). All of these trends are projected to continue (UCS 2006, Hayhoe et al. 2007).

Extreme weather events have become more frequent and intense during the past 40 to 50 years (Karl et al. 2009). In the Northeast, more frequent short-term droughts are projected to occur as the rising temperatures increase evaporation rates and reduce soil moisture in the summer. There are also projected to be reduced streamflows during the summer due to declining springtime snowpack and rises in temperatures and evaporation (Karl et al. 2009, Hayhoe et al. 2007).

VULNERABILITY

Vulnerability assessments were conducted to identify which habitats or species are likely to be most strongly affected by projected climatic changes and to understand why these resources are likely to be vulnerable. **The habitat assessments focused on 4 major habitat groups: upland forests, wetlands, rivers, and lakes.**

A number of climate-related impacts are expected to affect all habitat groups, including: compositional shifts resulting in the eventual loss of cold-adapted species and an increase in warm-adapted species; an increase in physiological stress from heat and/or water limitation in the summer, which is likely to result in increased susceptibility to pests and disease; and an increase in the spread of invasive species due to increased disturbance from extreme climatic events. Habitats in the Champlain Valley could be particularly vulnerable to heat stress and water limitation since this area is naturally warmer and drier than other parts of Vermont.

Forest health and productivity are likely to be compromised in many regions of the state. With respect to forested habitats, montane/high elevation spruce-fir forests in southern Vermont and associated species like the Bicknell's thrush are expected to be most vulnerable, while oak-pine forests are likely to benefit from warming temperatures and expand northward. Of particular, immediate concern are impacts from increased heat stress and water limitation in the summer, increasing spreading of pests like the hemlock and balsam woolly adelgid, and weather patterns with early spring thaws and late frosts, which can impact regeneration in species like apples and sugar maples by damaging buds, blossoms and roots.

Water sources and soil composition are the key factors in the vulnerability of wetland habitats. **Acidic bogs are expected to be particularly vulnerable** because of their specialized habitat requirements (cold climate, short growing season, and slow rate of decay of organic matter). Wetlands that receive groundwater inputs are expected to be less vulnerable to changing precipitation patterns, since regional ground water flow systems provide buffering from possible disruptions in surface water inputs to wetland areas.

Coldwater habitats and species associated with river and lake habitats (e.g., brook trout and eastern pearlshell mussel) **are expected to be highly vulnerable to climate change**. Impacts from warming temperatures will be mediated and potentially reduced by localized, protective factors, such as groundwater influence, stream shading and orientation.

Due to expected changes in precipitation patterns, both increased flooding and extended dry periods are expected. The increase in heavy precipitation events could lead to more flooding and is likely to exacerbate existing problems related to nutrient (particularly phosphorous) and sediment loading, as well as shoreline erosion. Extended summer low flow periods in combination with warming temperatures are likely to cause increased physiological stress, mortality to aquatic species, along with algal blooms and decreases in water quality.

Assessments of vulnerabilities in this document should be reviewed and further developed as more information becomes available. The process that was developed for documenting exposures, sensitivities, and mediating factors at the vulnerability workshop could be used if additional habitats and species of interest are assessed in the future, or to update the initial assessments prepared for this report.

ADAPTATION

The Vermont ANR can prepare for the changes associated with vulnerabilities by planning and implementing adaptation actions. Climate change adaptation actions are *adjustments in natural or human systems in response to actual or expected climatic effects that moderate harm or exploit beneficial opportunities*. Specific actions that can be taken were cataloged during a climate change adaptation workshop. These steps represent individual strategies that will move ANR towards a comprehensive adaptation plan.

During the workshop, it was made clear that **many of the actions needed to adapt to climate change are strongly aligned with actions needed and already initiated to reduce various types of pollution in Vermont's watersheds**. This alignment relates to the ecological resiliency that is built into an environmentally intact system. For example, many of the non-climatic stressors affecting lakes and streams are likely to be exacerbated by climate change. These stressors include nonpoint source nutrient and sediment runoff, reductions in groundwater flow during summer, loss of riparian shading, degradation of shoreline habitat, loss of river functions from encroachment, spread of aquatic invasive species, etc. Many potential climate change adaptation strategies could entail management of these same stressors to protect habitats and biological communities from the effects of warming and changing hydrology.

More than in almost any other area of environmental management and policy**, climate change will require the use of innovative management approaches**. For example, adaptive management will be required as we make assumptions about future conditions and how best to cope with them, monitor the results of management actions closely, and then use the monitoring results to inform future decision making. In addition, management actions will include many sectors and many managers that might otherwise remain focused on a single sector. The climate change strategies will be most effective if they address common ground and common objectives for climate and sound natural resource management. Management actions will have four general goals, as follow:

- **Increase Resistance**: Retain existing ecological conditions, assist the habitat or species forestall impacts
- **Promote Resilience**: Buffer impacts and improve the capacity of a system to return to desired conditions after disturbance, or as a means to retain the same essential function, structure, identity, and feedbacks in an altered state
- **Enable Transformation**: Efforts that enable or facilitate the transition of ecosystems to new functional states; proactive strategies that anticipate the nature of climate-change induced transitions and, working with these anticipated trends, include actions that facilitate transitions that are congruent with future climate conditions, while minimizing ecological disruption and undesired outcomes
- **Realignment**: Focus on systems that already have been disturbed beyond historical ranges of natural variability, and recognizing the irreversible change, plan to optimize the system, which might not necessarily include restoration to the historic or pre-disturbance condition

Within the management goal types, the actions can be further categorized by action type:

- **Monitoring and assessment**
- **Technical assistance related to climate and adaptation issues**
- **Regulation**
- **Education and outreach/engagement**
- **Conservation/land stewardship and land use planning**

Finally, the applicability of actions can be qualified by evaluating the following aspects:

- **Effectiveness at mitigating** (and the scientific basis for recommending actions)
- **Operational feasibility** (amount of money and resources required to implement)
- **Degree of current implementation**
- **Level of alignment with current policies, procedures, BMPs**
- **Social/political acceptability and feasibility**
- **Potential for securing funding**

With this structure for identifying management actions in place, a list of potential actions was compiled for each natural resource sector by reviewing regional climate change strategies and through the interactive workshop of ANR and other scientists and managers. The actions and strategies were varied, though cross cutting themes were identified and selected actions were explored in further depth. Some of the critical actions are extensions of existing efforts. The specter of exacerbated effects due to climate change adds urgency to these actions. Examples of critical actions are as follow:

- **Restoring beneficial functions of natural areas**
- **Identifying and conserving natural areas that provide important ecosystem services**
- **Capturing as much clean water precipitation as possible using low impact development**
- **Building bigger crossings and culverts to accommodate sediment transport and connectivity**
- **Analyzing groundwater issues related to agricultural tile drainage and water withdrawals**
- **Promoting riparian stability and filtering functions through appropriately sized stream, river, lake, and wetland buffers.**
- **Improving connectivity and corridors for wildlife movement through intact habitats**
- **Monitoring pests and invasive species**
- **Wetland mitigation in relation to disturbance and increased water stress at both flood and drought stages**

Climate Change Planning Actions

The next steps that the ANR needs to take to move ahead with climate change planning can be implemented in three areas, including establishment of guiding principles, continuing work on vulnerability assessments and adaptation strategies, and follow-up in specific focus areas. At a broad scale, the ANR should **adopt guiding principles and tools for managing** in light of uncertainty, including a formal endorsement or acknowledgement of the spectrum of management actions (resistance, resilience, enabling transformation, and realigning management). In addition, a formal process should be established for integrating climate change and management actions into Agency planning processes. The Agency also needs to define end products and objectives of the climate change adaptation planning process. One possible end product is a comprehensive adaptation plan. These plans are typically a multi-sector effort involving water resources, agriculture, forest and terrestrial ecosystems, bay and aquatic ecosystems, growth and land use, energy development, and public health. The higher level and other efforts should be supported by the Agency through planning for programs, budgets, staffing, and regulations.

A cooperative effort must continue so that work initiated at the vulnerability assessment and adaptation strategies workshops can be completed or resolved as needed. The workshops successfully introduced planning and assessment processes that should be repeated to address remaining questions about vulnerability and exposure, and to go further in depth for certain vulnerabilities and adaptation strategies. ANR could continue the work that was initiated during the vulnerability assessment and adaptation strategies workshops by reconvening the four major habitat work groups (forests, rivers, lakes/ponds and wetlands) to continue and build on this work. In addition to the four major habitat groups, we recommend initiatives to address climate, species-specific planning, and documentation of existing on-the-ground management actions.

At a smaller scale, focus areas were identified as **important cross-sector themes** at the adaptation strategies workshop. The areas identified were as follows:

- **Promote resilience and resistance by reducing other stressors**
- **Conserving refugia**
- **Monitoring and assessment**
- **Data infrastructure**
- **Landscape-level planning**
- **Groundwater**
- **Sustainable flows**
- **Ecosystem services**

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Acknowledgements

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Several others also made major contributions to this project. We owe special thanks to Chris Hilke from the National Wildlife Foundation and Andy Whitman from the Manomet Center for Conservation Sciences. Chris and Andy continually updated us on relevant efforts underway in other states, acted as facilitators at both workshops, participated in numerous calls and meetings, and reviewed sections of the report. We also want to thank Chris Hilke and Steve Parren for facilitating a follow-up effort to complete additional vulnerability assessments, and owe thanks to Hector Galbraith and Chris Hilke for briefing us on results from the regional NEAFWA report. In addition, we would like to express our gratitude to Eric Sorenson from the Vermont Department of Fish and Wildlife (VDFW), Arthur Brooks from the Vermont Federation of Lakes and Ponds, and Alan Betts for their many contributions.

The participants of two day long workshops gave us invaluable information on the applicability of processes for developing vulnerability assessments and adaptation strategies as well as concrete ideas for further development. They are too numerous to mention here, but their dedication is recognized and their willingness to address climate change issues is appreciated. We would also like thank the following people, some of whom were workshop participants, and all of whom contributed or encouraged the efforts of ANR in this project. They include Rich Kirn and Jon Kart from VDFW, Chris Koliba, Lesley-Ann L. Dupigny-Giroux and Beverly Wemple from the University of Vermont, Kim Greenwood from the Vermont Natural Resources Council, Glenn Hodgkins and Thomas Huntington from the USGS Maine Water Science Center, Jeff Deacon, Denise Argue, Laura Medalie, Joseph Ayotte, Greg Walsh and Jamie Shanley from USGS, Emily Brunkhurst from NH Fish and Game, Elizabeth Burakowski and Cameron Wake from the University of New Hampshire, Justin Sheffield from Princeton University, Evan Girvetz and Chris Zganjar from The Nature Conservancy, Robert White and Mark Gerrish from Vermont's Intelligent Transportation Systems (ITS) program, Max Olsen from Utah State University and Anna Hamilton, Shann Stringer, Hope Herron, Charlie Macpherson and Regina Scheibner from Tetra Tech. Jen Stamp and Ben Jessup of Tetra Tech and Juli Beth Hinds (formerly of Tetra Tech and now with Birchline Planning LLC) were the primary authors on this report and managed the project, including workshop facilitation, information gathering, report writing, and coordination of contributions from the many participants of this project.

1.0 INTRODUCTION

Global climate change represents an unprecedented challenge to ecosystem management, and to the natural heritage and resources of the State of Vermont. Scientists predict that climate change will affect virtually all sectors, from food and water security, to disaster risk reduction and human health, to opportunities for business investment and private sector growth. In Vermont, average temperatures have increased by 0.28 °C per decade in the last fifty years (Betts 2011a, Betts 2011b), signaling that the effects of climate change are already being felt. In addition to shifts in habitat and natural communities, recent increases in the frequency, intensity and amount of precipitation may be driving delayed agricultural plantings, flooding damage to public infrastructure, and changes to river and watershed systems throughout Vermont.

Hermit thrush

Changing temperature and precipitation patterns will directly and indirectly affect Vermont's natural resources, the services they provide, and the natural heritage they bestow. The Vermont Agency of Natural Resources (ANR) is focused on potential impacts on four natural resource sectors: wildlife, (Division of Wildlife) fisheries (Division of Fisheries), forestry (Division of Forestry), and water resources (Watershed Management Division). Some climate-related impacts, such as compositional shifts in plant and animal communities, will affect all four sectors. Warming temperatures are expected to contribute to eventual reductions in cold-adapted species and range expansions of warm-adapted species (Manomet & NWF 2012a, Manomet & NWF 2012b).

Other impacts will be more sector-specific. Forest health and productivity may be affected by increased heat stress and water limitation in the summer and an increase in the spread of pests like the hemlock and balsam woolly adelgid. Expected water quality impacts include increased flooding and erosion, intensified storm water runoff, and more algal blooms in nutrient-rich waters due to increasing temperatures. More frequent or severe storm-flow events, such as those that Vermont experienced in 2011, could increase physical damage to public and private structures, exacerbate existing problems related to nutrient and sediment loading and require more extensive treatment to remove these excess pollutants.

These and other climate-related effects will likely affect the way Vermonters perceive their natural surroundings, engage with natural resources for livelihoods and enjoyment, and do business in the state. Developing vulnerability analyses and adaptation strategies will be essential to preparing Vermonters for these impending changes. The purpose of this report is to propose a strategic framework for climate change vulnerability assessment and action planning, especially for coordination among Vermont ANR departments and actions. Towards that end, this report attempts to standardize the terms that are used in climate change analyses, describe predicted changes in climate patterns, summarize the habitats and species within each of the four ANR sectors that are vulnerable to changes in climate exposures, and recommend strategies for adaptation that would reduce detrimental effects of climate change.

1.1 State and Climate Change Team Response

With leadership from the Governor's office and the Vermont Climate Cabinet, agencies and organizations serving Vermont are developing many different climate change assessments, action plans, and responses. The Vermont Comprehensive Energy Plan and VTrans Climate Change Action Plan, among others, address greenhouse gas (GHG) emissions and agency-specific actions such as renewable energy generation. All of these related actions offer perspectives, research, action plans and templates that may be useful in building the State's strategy. Because of its role as steward of the state's natural resources, the ANR has a particular need to integrate adaptation planning as well as mitigation into action alternatives. To do so, the ANR requires detailed assessment and planning in order to anticipate and manage climate change impacts on the State's natural resources and communities.

American black bear

1.2 Technical Methodology

In developing a State Climate Change Adaptation Strategy, the ANR Climate Change Team will need to work across many parts of the agency, often with different missions, authorities, and resources. ANR must determine how to adapt to climate-related changes that may have already begun, to strategically plan for future climate scenarios that could impact wildlife, fisheries, forestry, and water resources, and to develop a basis for setting adaptation priorities across sectors with different characteristics and values. The tasks to develop an adaptation strategy include data gathering on climate change exposures and perceived or expected impacts on resource, descriptions of regional vulnerability analyses that incorporate exposures and impacts and that could be used as examples of approaches to a Vermont-specific vulnerability analysis, interactions with stakeholders to present and refine conclusions, and development of the adaptation strategy itself.

One of the purposes of this project was to lay the groundwork for continuing efforts towards Vermont-specific vulnerability analyses. Before this project was initiated, there had been no attempt to generate a Vermont-specific analysis for all sectors being addressed in this report. To inform Vermont's approach, the ANR sought examples of vulnerability analyses and adaptation strategies from the region (Appendix 1A). By compiling regional examples, the ANR may decide to apply regional findings in Vermont either selectively or without modification, to apply approaches from the regional examples in Vermont-specific analyses, or to recognize data gaps that should be filled through continuing research.

Painted turtle

This project involved understanding and evaluating the activities of several divisions and sectors of ANR, housed in different departments of the Agency. The recommended adaptive strategies include both broad and specific approaches, so that the overall strategy will be cohesive within the Agency and will also address unique concerns within each division. Recommendations developed for this project targeted each specific division, but also took into account possible regulatory overlap and potential inter-agency conflicts.

1.3 Climate Change Vulnerability and Adaptation

One of the first hurdles to clear when communicating about climate change is explaining the terms used to describe processes, analyses, and outcomes.

Vulnerability is a function of the sensitivity of a particular ecological system or species to climate changes, its exposure to those changes, and its capacity to adapt to those changes (Figure 2) (Glick et al. 2011a) Vulnerability is expressed as a predicted impact. Unless a focused and intensive analysis is conducted, the predicted impact will be on a narrative or ordinal scale, such as “improved conditions”, “no effect”, “degraded conditions”, or “severely degraded conditions”. The statements of predicted impact should be accompanied by statements of ***uncertainty*** **–** the likelihood of predicted impacts based on assumptions, variability, and unknowns that were part of the prediction.

Exposure is a measure of the amount of a change in climate and associated problems a species or system is likely to experience (Glick et al. 2011a). Exposures can be observed in historical data and can be projected using climate models. ***Climate models*** are hypothesized and calibrated estimates of changes expected in climate variables over time into the future. The ***time frame*** for the models usually depends on the initial perception of critical changes and the urgency of management actions. Typical time frames estimate climate conditions in 50 or 100 years (mid-century or end of century), with more accuracy expected for nearer term predictions. The ***variables*** addressed in climate change models tend to focus on patterns and extremes of temperature and precipitation, though these two factors are related to additional variables such as wind, drought, peak and low flows, and other complex secondary effects. Climate models are usually spatially explicit because the effects can differ by topography, latitude, and prevailing spatial weather patterns. ***Downscaling*** is the technique by which patterns observed in large scale models are applied to a smaller scale, as when a northeastern U.S. model is used to predict climate change effects in Vermont.

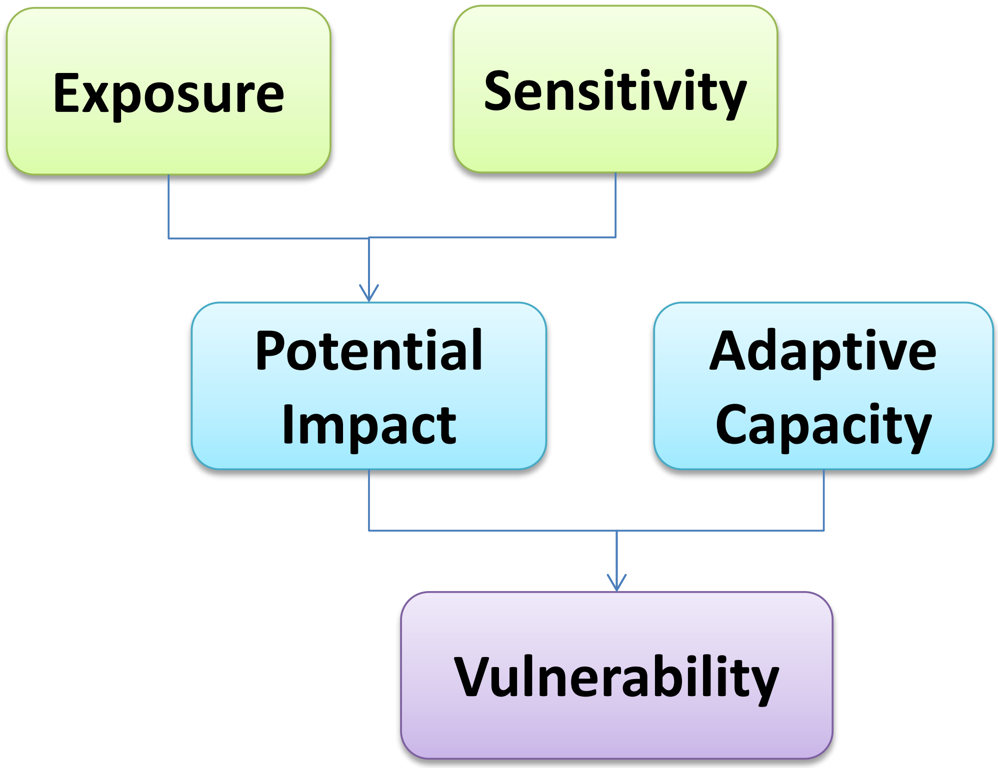

Figure 1. Key components of vulnerability, illustrating the relationship among exposure, sensitivity, and adaptive capacity (IPCC 2007a in Glick et al. 2011a).

Sensitivity measures whether and how much a species or system is likely to be affected by a given change in climate (Glick et al. 2011a). For example, temperature tolerances in fish are well established in the context of preferential ranges and limits of tolerance for growth, reproduction, or survival. Likewise, the sensitivities of plant species have been categorized according to hardiness, which corresponds to hardiness zones that are mapped across Vermont and the U.S. (USDA 2012). Sensitivity can be assessed at ***multiple scales***, from individual species (where more detailed information may be available) to mid-scale assemblages of organisms or habitats to large scale ecosystems (where some conjecture is necessary due to complex and increasingly unpredictable interactions among ecosystem components). The sensitivity of individual species is relevant for those species that are of particular importance in Vermont because of heightened sensitivity and already limited habitat (threatened and endangered species) or for species that are culturally significant, such as brook trout or maple trees. However, assessing the sensitivity of all species in Vermont is not feasible because the shear diversity of flora and fauna would overwhelm our ability to catalogue each species and their sensitivities to multiple climate change variables. Even narrowing the focus to Species of Greatest Conservation Need (SGCN) in the VT Wildlife Action Plan would result in too many species to possibly summarize. In addition, SGCN species may have been identified for reasons not related to climate change. For efficiency and because protection of habitats is the mechanism by which sensitive species will be protected, this report focuses mainly on vulnerabilities of habitats and assemblages of organisms.

Adaptive capacity refers to the opportunities that may exist to reduce the potential impact of exposures to sensitive species or systems (Glick et al. 2011a). Adaptive capacity is usually limited to the natural qualities, acclimation tolerances, and behavioral traits that are inherent to a species, assemblage, or habitat. To continue the example with fish species, though the temperature tolerance of a species may be exceeded by exposure to increased temperatures, fish have the adaptive capacity to migrate, thereby decreasing their vulnerability as long as cooler water bodies are accessible. Adaptive capacity is sometimes thought of in terms of responsiveness to societal efforts to protect against the harmful effects of climate change exposures.

An ***adaptation strategy*** is a proposed activity or management process that is intended to reduce or eliminate the potential impacts of climate change on vulnerable natural resources. The process includes identification of management options (activities) as one step in the framework (Figure 2). Adaptation strategies can include mitigation of climate effects; regulation; incentives; education and outreach; urban and watershed planning; monitoring of species, habitat and ecosystem change; physical habitat manipulation; and individual species management. Within these categories and others, specific goals, objectives, and actions can be proposed, implemented, and monitored for effectiveness in their intended outcomes. An additional type of adaptation strategy is realignment of restoration and management activities to reflect changing conditions. These types of strategies prepare for inevitable changes if impacts cannot be averted.

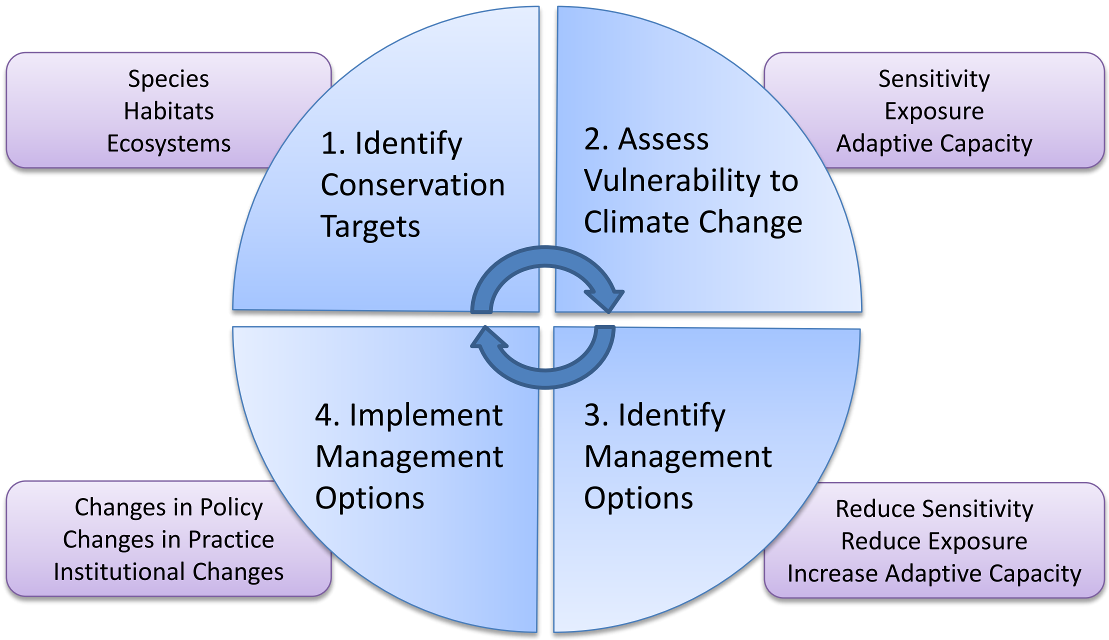

Figure 2. Framework for developing climate change adaptation strategies (Glick et al. 2011a).

There are two types of adaptation strategies that are not addressed in this report: mitigation of climate change exposures by reducing greenhouse gas emissions; and strategies related to modification of infrastructure. Vermont has established goals for reduction of greenhouse gas emissions in statute that call for a 50% reduction in state greenhouse gas emissions from 1990 levels by 2028. Vermont also participates in a regional program (the Regional Greenhouse Gas Initiative) to reduce emissions from the electricity sector. These efforts are important but in order to have an effect on the forecasted change in the regional and global climate in the second half of the century a much more robust international effort to reduce greenhouse gas emissions will be required. Mitigation and other types of adaptation strategies are linked, in that effective mitigation reduces the need for adaptation. Both are essential parts of a comprehensive response strategy. The threat of irreversible impacts makes the timing of mitigation efforts particularly critical.

Climate change effects can include changes in the landscape that impact societal investments such as roads, buildings, bridges, utilities, and other structures. In turn, protection and improvement of those investments can occur in tandem with protection of natural resources. For example, stable stream channels generally provide better aquatic habitat than unstable ones. Stable stream channels are also better than unstable ones for protection of roads, bridges, and buildings. Therefore, adaptation strategies that promote stable stream channels are beneficial to both aquatic life and infrastructure near the channels. Such strategies include appropriate bridge and culvert design and maintenance of a functional floodplain for water storage during flooding events. Adaptation strategies should not be blind to efforts to manage the built environment, especially when there are multiple purposes for adapting to climate change. The effects of tropical storm Irene were acutely obvious in the context of infrastructure and personal properties. Vermont's response to that event and to the possibility of more frequent extreme flows in the future should consider both the built and natural environments.

1.4 Regional Resources

There are several states in the northeast that have prepared or are working to prepare vulnerability analyses, climate change adaptation strategies, or resource specific action plans. These examples as well as regional efforts conducted by federal agencies and regional groups are the primary resources for information and approaches. They include:

- **Maine** is working on species- and habitat-based vulnerability assessments, using expert elicitation and online surveys
- **New York** has used both species-level (using NatureServe; see Schlesinger et al. 2011) and habitat-level approaches (Galbraith 2012), has published The ClimAID Integrated Assessment for Effective Climate Change Adaptation (Rosenzweig et al. 2011) and recently held a workshop to brainstorm climate change adaptation strategies.
- **New Hampshire** has just finished a series of adaptation strategies workshops. They are using the vulnerability assessments that they have completed as baselines for system-specific adaptation strategies. They are not taking a species-specific approach, but rather a habitat-based approach, and are identifying key species within each habitat. Draft data are available (New Hampshire Fish and Game 2012).
- **Massachusetts** was the first state to conduct a habitat-based vulnerability assessment. They used expert elicitation and Hector Galbraith was the lead on these efforts (Manomet 2010a-c (Volumes 1-3)). The 'Massachusetts Climate Change Adaptation Report' was published by the Massachusetts Climate Change Adaptation Advisory Committee in 2011. MA is one of the first states to start implementing climate change adaptation strategies.
- **Connecticut** published results from species- and habitat-based vulnerability assessments in 'The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources and Public Health' (Adaptation Subcommittee to the Governor's Steering Committee on Climate Change 2010).
- **Rhode Island** is conducting an assessment of climate change effects on water utilities, which may have some bearing on issues in VT.
- **Pennsylvania**. The Union of Concerned Scientists published the report 'Climate Change in Pennsylvania - Impacts and Solutions for the Keystone State - A Climate Impacts Assessment for Pennsylvania' in 2008. PA has conducted climate change vulnerability assessments for 85 species using NatureServe's Climate Change Vulnerability Index (CCVI v2.0).
- **Wisconsin.** Reports generated by WDNR provide high quality examples of vulnerability analyses and adaptation strategies – there are some differences in focus due

to different environmental settings and institutional structures, but the approach and content are largely applicable in Vermont.

- **Northeast Association of Fish and Wildlife Agencies** (NEAFWA) has supported research to generate the following highly relevant reports: Northeastern Terrestrial Habitat Classification System (NETHCS); The Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change; and Climate Change and Cold Water Fish Habitat in the Northeast: a Vulnerability Assessment.
- **The U.S. Global Change Research Program** (GCRP) oversees the quadrennial National Climate Assessment reports and supports climate change-related research projects such as the *National Scale Modeling to Evaluate Impacts of Climate Change on Hydrology and Water Quality* project, which includes downscaled data sets from the New England coastal basin. GCRP is currently supporting a project to lay the analytical foundation for a regional long-term climate change monitoring network in the Northeast.
- The **U.S. Forest Service Northern Research Station** provides both eastern tree and bird species vulnerability projections through their on-line "Climate Change Tree Atlas" and "Climate Change Bird Atlas" databases: http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html#

1.5 Vermont Initiatives

The current effort to address climate change issues in Vermont is preceded by several other efforts. Vermont Governor Peter Shumlin established the Climate Cabinet in 2011. The cabinet is charged with providing comprehensive leadership by coordinating climate change efforts, including the reduction of greenhouse gas emissions & reliance on fossil fuels, providing outreach and education as well as implementing climate change adaptation efforts across all state agencies and departments. One of the major initiatives of the Climate Cabinet is the development of the state's Comprehensive Energy Plan (CEP) with the Department of Public Service.

The VTrans Climate Change Action Plan has three major focus areas: 1) Reducing GHG emissions from the transportation sector, 2) Protecting Vermont's transportation infra-structure from the effects of climate change, and 3) Reducing VTrans' operational impacts on climate change. VTrans and the ANR may benefit from cooperation regarding integration of adaptation for transportation infrastructure with natural resources, especially bridges, culverts, and riparian corridors.

The ANR has published a series of Climate Change Adaptation papers addressing each of its sectors and other subjects (http://www.anr.state.vt.us/anr/climatechange/Adaptation.html). This set of papers provides a brief overview of the challenges facing the different sectors of Vermont, what programs are already in place to address those challenges, and what steps need to be taken next to continue adapting to the impacts of climate change. For example, "*Climate Change and Vermont's Waters*" (Pealer and Dunnington 2011) provides an excellent summary of potential ways that climate change may impact Vermont's water resources, lists management strategies currently employed by the Watershed Management Division that will likely play an important role in climate change adaptation and mitigation, lists additional strategies that would be helpful to implement in the future, and identifies future research needs.

The Vermont Surface Water Management Strategy describes how the Watershed Management Division (WSMD) interacts with partners to protect surface waters through management of pollutants and stressors that affect the uses and values of Vermont's surface waters (http://www.vtwaterquality.org/swms.html). The Strategy presents the Division's goals, objectives and approaches for the protection and management of Vermont's surface waters, and will help to guide the Department's future decision-making to ensure efficient, predictable, consistent and coordinated management actions. Surface waters are defined as all rivers and streams, lakes, ponds, reservoirs, and wetlands in Vermont.

The Vermont 2010 Forest Resources Plan (FRP) is a proactive, comprehensive and balanced approach to the management of Vermont's forests. It provides an assessment of conditions and trends of the forest resources in the state, discusses threats to them, and identifies priority areas to focus resources. While the Plan identifies long-term strategies for assuring that our forests are healthy and providing ecological services while meeting the economic needs of the citizens of Vermont, specific actions are identified in annual work plans. A 3-year project is underway to develop forest adaptation strategies and apply these at 3 climate change demonstration areas on state land. Specific sections on climate change adaptation, monitoring and forest management will be included in the 2015 updated Plan.

Vermont's 2005 Wildlife Action Plan (Kart et al. 2005) identifies conservation strategies designed to prevent wildlife from becoming endangered or threatened. To incorporate new knowledge and fill data gaps, fish and wildlife agencies are required to revise their Wildlife Action Plans by 2015. Using guidance prepared by the Association of Fish and Wildlife Agencies (AFWA 2012), states are incorporating climate change assessments into their updated plans. In 2012 the Vermont Department of Fish and Wildlife (VFWD) began this process. These assessments will help State agencies modify their management plans to incorporate strategies that will build resiliency, enhance ecosystem function and allow species and habitats to adapt to climate change if possible.

1.6 Stakeholder Outreach and Engagement

The ANR Climate Change Team and the Governor's Climate Cabinet are working to frame adaptation and mitigation issues to actively inform and engage Vermonters in positive and thoughtful ways. The Adaptation White Paper series developed by ANR is using scientific and technical information to form policy outlines. The Citizen Science outreach is providing valuable and locally-derived data on immediate issues such as ice fishing and sugaring season duration. The Climate Change Team is issuing regular newsletters and social media bulletins on the Agency's work.

One of the most promising aspects of the state's outreach is locally-derived and specific data on climate-related issues that immediately and directly affect Vermonters. Growing season and sugaring season lengths, plant hardiness zones, ice-out dates and ice duration data, snowfall and precipitation, and information on trout and other sport species translate "climate change" into a tangible, relatable issue with real-life implications. This approach also highlights key adaptation measures that will make a difference to the state's natural heritage and highlight how Vermonters and businesses use and manage the natural environment. By focusing on issues relevant to various stakeholders, the state has an outstanding opportunity to provide leadership on climate change adaptation, public communication, and genuine citizen engagement.

This project provides the opportunity to directly connect state employees who will benefit from working together—collapsing organizational or institutional boundaries. By providing this forum for identifying common interests and linkages, and by collaborating on key findings, this project can make new connections that may endure long after the project is completed and to each sector's lasting benefit. Tetra Tech recognizes that collaboration is essential to maximize the impact of the limited financial and natural resources. Creating and enhancing the agency network increases the likelihood that individuals will work together on adaptation and mitigation strategies, and on sharing information, to reach common aims and influence stakeholder attitudes.

1.7 Climate Change Exposure Pathways

Two workshops were held over the course of this project. The first was on vulnerability assessments, and the second was on adaptation strategies. During each workshop, participants discussed plausible sets of climate change scenarios, starting with expected climatic changes and working down conceptual pathways to vulnerabilities. In the adaptation strategies workshop, participants also discussed actions that could be taken to help to reduce adverse impacts of climate change, or ways in which to take advantage of beneficial changes.

Figure 3 illustrates a climate change exposure pathway. In this example, air temperature and extreme precipitation events are increasing. These changes lead to **exposures** of higher peak flows and flooding and higher water temperatures in rivers and streams. These exposures affect the suitability of the habitat, which becomes degraded due to physical channel disturbance and reduced dissolved oxygen. Ultimately, stream organisms that are **vulnerable** to increased temperature, decreased dissolved oxygen, and decreased habitat stability are at risk in the system.

The adaptation actions that could be implemented to avert the loss of sensitive taxa include mitigation of climate change effects, protection of floodplain and riparian vegetation, allowing natural channel adjustments through state land acquisition in the floodplain, reduction of peak flows through watershed and hydrologic management, restoration of habitat features through targeted Best Management Practices (BMP), and monitoring of habitat, temperature, and biota through the ANR and volunteer programs.

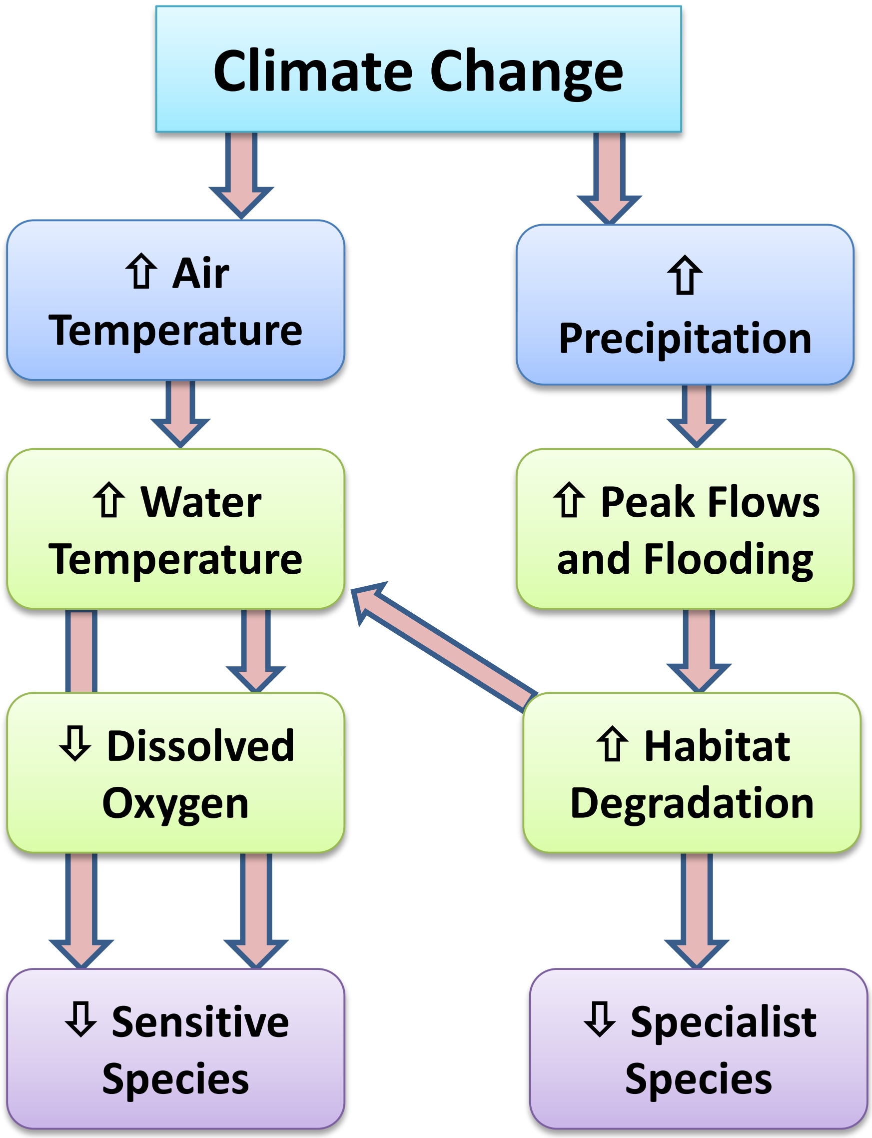

Figure 3. Conceptual diagram of climate change exposure pathways that lead to vulnerabilities in aquatic species.

2.0 EXPOSURES

2.1 Overview

The first component of vulnerability is exposure, which is defined as the amount of climate-related change a species or system is likely to experience (Glick et al. 2011a). This section provides an overview of expected changes in Vermont based on both historical climate trends and regional projections from climate models.

2.2 Historical trends

Historical trends in Vermont have been documented for many climate variables, including:

- Air temperature (annual, seasonal, monthly)
- Precipitation (annual, seasonal, monthly)
- Extreme events (extreme-heat days, intense precipitation events, droughts)
- Snow (snow cover, snow depth, snow density)
- Flow/runoff (mean annual, low, high, shifts in timing)
- Evaporation
- Soil moisture
- Ice dynamics (ice-out dates in rivers and lakes; ice cover period)
- Onset of spring (lilac leaf out dates; sugar maple leaf out dates)
- Length of growing season (freeze dates, sugar maple growing season)

Summaries of historic trends in the aforementioned variables for Vermont (where available) and for the Northeast are described below. The Vermont-based analyses are based on data from its network of weather stations. There are currently more than 200 weather stations in Vermont, over 100 of which are active (this number includes volunteer stations). An inventory of these weather stations can be found in Appendix 2A.

Historic Temperature Trends

During the past fifty years, there has been a consistent pattern of warming in Vermont (Betts 2011a, Betts 2011b). From 1960-2008, mean annual air temperature at four of Vermont's long-term weather stations (Burlington, Cavendish, Enosburg Falls, St. Johnsbury) has been increasing at 0.28 °C (0.5 °F) per decade, with steeper rates of increase in recent decades. Seasonal differences are evident, with mean winter temperatures rising fastest (0.5±0.16 °C (0.91±028 °F) per decade). The summer trend is 0.23±0.07 °C (0.4±0.12 °F) per decade (Betts et al. 2011a). Warming trends have also been documented on Mount Mansfield (Wright 2009) (Appendix 2B). The warming trends seen in Vermont are consistent with regional trends (Trombulak and Wolfe 2004, Hayhoe et al. 2007, UCS 2006a).

There has also been an increase in the number of extremely hot (maximum temperatures greater than 90°F) days in summer, and the number of extremely cold temperature days has decreased (DeGaetano and Allen 2002, Hansen et al. 2012, UCS 2006a).

While trends in air temperature have been well-documented, the same cannot be said for water or soil temperatures. There is a lack of long-term continuous water temperature data in Vermont, and none of the real-time USGS Daily Streamflow Network gages in Vermont are currently recording water temperature (USGS 2012). A regional effort is currently underway to compile water temperature records in the Northeast and put the locations in an interactive Google Earth map interface (Dave Armstrong USGS, personal communication 2012). Two soil climate stations were installed in 2000 by the NRCS in forests in Underhill and Sunderland to record soil temperature and moisture conditions at 5 depths, in addition to other related meteorology (http://www.wcc.nrcs.usda.gov/scan/Vermont/vermont.html).

Historic Precipitation Trends

Trends in annual precipitation are highly variable but historical records do show a consistent long-term trend in annual precipitation towards overall wetter conditions in the Northeast (Karl et al. 2009, Hayhoe et al. 2007, Keim et al. 2005). In Vermont, precipitation has increased by 15-20% in the past fifty years, with increasing trends throughout much of the year (Betts 2011a). Increases in heavy precipitation (greater than 2 in. in less than 48 h) have been observed across much of the Northeast in recent decades (Hayhoe et al. 2007, Wake and Markham 2005, UCS 2006a, Karl et al. 2009). Over the last 50 years, there has been a 67% increase in the amount of rain falling during very heavy precipitation events in the Northeast (Karl et al. 2009).

Historic Snow Trends

There is a trend towards reduced snowpack and increased snow density (UCS 2006a, Hodgkins et al. 2006a, Huntington et al. 2004, Karl et al. 2009). In Maine, a decrease in average March/April snowpack depth has been documented (Hodgkins and Dudley 2006a).

Historic Streamflow Trends

A list of USGS gages in Vermont, with spatial location (latitude/longitude), status (active/inactive) and period of record can be found in Appendix 2C. The current status of some gages is uncertain due to funding issues, but as of fall 2012, there are about 50 active gages in Vermont.

In the Northeast, there has been a clear trend towards earlier snowmelt runoff/spring peak flow and earlier center-of-volume runoff dates (Dudley and Hodgkins 2002, Hodgkins et al. 2002, Hodgkins and Dudley 2006a, Hodgkins and Dudley 2006b, Huntington et al. 2004, Hodgkins et al. 2003, Hodgkins et al. 2005a, Hodgkins et al. 2009). Advances of 1–2 weeks in the date of peak streamflow have been observed over the northern part of the Northeast, with most of the change occurring from 1970 to 2000 (Hodgkins et al. 2003, 2005a).

Based on studies in Maine, there have been few significant changes during the last century in the magnitude, timing, or duration of low streamflows (Dudley and Hodgkins 2005, Hodgkins et al. 2005b) or in total annual runoff volume (Hodgkins and Dudley 2005, Dudley and Hodgkins

2002). At some streamflow-gaging stations in Maine, annual peak flows have increased significantly during the last 50 to 100 years (Hodgkins and Dudley 2005, Collins 2009).

Historic Trends in Ice Dynamics

The duration of ice on rivers and lakes has been decreasing, with later freezing dates and earlier ice-out dates (Betts 2011a, Magnuson et al. 2000, Dudley and Hodgkins 2002, Hodgkins et al. 2002, Hodgkins et al. 2005c, UCS 2006a). The trends in the fall onset of ice are significant at fewer stations than that observed for ice-off dates (Dudley and Hodgkins 2002). Excluding Lake Champlain, ice-out data are available for 17 of Vermont's lakes and ponds, with the oldest record dating back to 1933. Trend plots for these 17 lakes and ponds can be found in Appendix 2D. Most of these data are collected by citizen scientists.

Historic Trends in Extreme Events

Extreme weather events have become more frequent and intense during the past 40 to 50 years, and the destructive energy of Atlantic hurricanes has increased in recent decades (Karl et al. 2009).

Historic Trends in Length of Growing Season/Onset of spring

The winter season has been shrinking and becoming less severe (Betts 2011b). On average, the last spring freeze has come earlier and the first fall freeze has come later; thus, the freeze period has gotten shorter and the growing season has gotten longer in Vermont (Betts 2011a, UCS 2006a). The retreat of spring freeze dates is the primary cause of the lengthening growing season (vs. the autumn first freeze) (Schwartz et al. 2006). Forest monitoring of sugar maples in spring and fall shows a lengthening of the growing season in Vermont, and from 1990 to 2006. The average length of the growing season, from budbreak to leaf drop, was 186 days in 2012, 16 days longer than the long term average (personal communication – Sandy Wilmot). Eight of the last 11 years have had longer than normal growing seasons. Vermont has gone from mostly USDA winter hardiness zone 4 to mostly zone 5 (USDA 2012).

Appendix 2E contains a list of additional resources, along with some more detailed results for the parameters described above. In addition, temperature and precipitation trend plots generated using The Nature Conservancy's *Climate Wizard* (Girvetz et al. 2009) are included in Appendix 2F.

2.3 Future climatic projections

Computer models cannot predict the future exactly, but there have been major advances in the development and use of models over the last 20 years, and current models give us a reliable guide to the broad direction and range of likely changes in temperature and precipitation. Future projections vary depending on what model/s and emissions scenarios (Nakicenovic et al. 2000) are being used, what timeframe (e.g., mid vs. late century) is being evaluated, and what geographic area is being targeted.

Most of the projection data used in this project came from 3 sources: the 2006 Northeast Climate Impacts Assessment (NECIA) (UCS 2006a); a journal article on past and future changes in climate and hydrologic indicators in the Northeast (Hayhoe et al. 2007); and a report prepared for the U.S. Global Change Research Program on climate change impacts in the United States (Karl et al. 2009). Projection data from these sources are consistent with those being used by other Northeastern states. . Some states, like Maine and New York, have done additional state-specific analyses on climatic projections (Jacobsen et al. 2009, New York City Panel on Climate Change 2009, Rosenzweig et al. 2011). Updated projection data will become available later this year with the release of the 2013 National Climate Assessment report (NCADAC 2013).

Projected trends for the Northeast are summarized below. Most are continuations of the historic trends described in the previous section.
Table 1 contains a synopsis of these projections.

Projected Temperature Trends

Temperatures are projected to continue increasing over time (UCS 2006a, Hayhoe et al. 2007, Karl et al. 2009). Based on averaged model-projected changes, mean annual temperature are projected to increase from 3.7°F (lower emissions) to 5.8°F (higher emissions) by mid-century (2040-2069) and 5.0°F (lower emissions) to 9.5°F by the end of the century (2070-2099) compared to a 1961-1990 baseline modeled average (UCS 2006a). Trend rates will differ across seasons, with larger temperature increases occurring in winter versus summer (UCS 2006a). By mid-century (2040-2069), mean winter temperatures are projected to increase by 4.3°F (lower emissions) to 6.1°F (higher emissions) and by the latter part of the century (2070-2099), 5.8°F (lower emissions) to 9.8°F (UCS 2006a). Increases in mean summer temperatures are projected to range from 3.8°F (lower emissions) to 6.4°F (higher emissions) by mid-century (2040-2069) and 5.1°F (lower emissions) to 10.6°F by the end of the century (2070-2099) (UCS 2006a). There will be more frequent extreme-heat days (maximum temperatures greater than 90°F) (UCS 2006a, Karl et al. 2009).

Projected Precipitation Trends

Total precipitation in Vermont is expected to increase in all seasons except summer. By the end of the century, projected increases under the higher emissions scenario are about 15% in winter, 10% in spring, 5% in fall, and no change in summer (Karl et al. 2009, Betts 2011b). Confidence in projected changes is higher for winter and spring than for summer and fall (Karl et al. 2009). Frequency of heavy precipitation events is likely to increase in all seasons, with the heaviest precipitation events occurring in the summer season (Karl et al. 2009).

Projected Snow Trends

There will be less winter precipitation falling as snow and more as rain (UCS 2006a, Karl et al. 2009). The duration and extent of snow cover will continue to decrease (UCS 2006a, Hayhoe et al. 2007, Karl et al. 2009). Vermont's snow season could be cut by more than half by late-century under the high emissions scenario (vs. roughly one-third under the low emissions scenario) (UCS 2006b). Both high and low emissions scenarios show large reductions in the length of the snow season in winter/early spring, with reductions in the number of snow days projected to range from 25 (lower emissions) to50%(higher emissions) by the end of the century (2070–2099) (Hayhoe et al. 2007). There will continue to be an increase in snow density as snow becomes wetter or more "slushy" (UCS 2006b, Karl et al. 2009). Multiple melt events in the winter could lead to possible flooding (Betts 2011b).

Projected Streamflow Trends

More high-flow and low-flow events are projected to occur annually (Hayhoe et al. 2007). Peak streamflow in spring is projected to continue to occur earlier in the year, with further advances of 5–8 days by mid-century and up to 15 days by the end of the century (Hayhoe et al. 2007). There will be a general tendency towards more streamflow in winter and spring, and less in summer and fall. This translates into higher winter high flow events and lower summer low flows (Hayhoe et al. 2007). There are projected to be reduced summer streamflows due to declining springtime snowpack and rises in temperatures and evaporation (Karl et al. 2009, Hayhoe et al. 2007). Projected future changes in low-flow amounts and duration differ significantly between emissions scenarios (Hayhoe et al. 2007). There will also be an increased likelihood of high flow events in the winter, particularly under the higher-emissions scenario, which implies a greater risk of flooding (UCS 2006a).

Table 1. Summary of model-projected changes in temperature, hydrology, extreme events and phenology.

	Parameter	Trend	Projections (range = low to high emissions scenario)
Temperature	Annual temperature	Increase	By mid-century (2040-2069), average projected increases range from 3.7 to 5.8°F compared to 1961-1990 baseline modeled average; by end of century (2070-2099), projected increases range from 5.0 to 9.5°F (UCS 2006a).
	Seasonal temperature	Increase	**Winter**: by mid-century (2040-2069), projected increases range from 4.3 to 6.1°F compared to 1961-1990 baseline modeled average; by end of century (2070-2099), projected increases range from 5.8 to 9.8°F (UCS 2006a). **Summer**: by mid-century (2040-2069), projected increases range from 3.8 to 6.4°F compared to 1961-1990 baseline modeled average; by end of century (2070-2099), projected increases range from 5.1 to 10.6°F (UCS 2006a).
	# Hot days	Increase	By mid-century, models project 20 to 30 days per year (lower emissions) or 30 to 60 days per year (higher emissions) over 90˚F; by end of the century, most northeastern cities are projected to experience over 60 days each year with temperatures over 90˚F (higher emissions) (UCS 2006a).
	# Cold days	Decrease	Reduction in days with cold (<0° F) temperatures (Karl et al. 2009)
Hydrology	Annual precipitation	Increase	By end of century, projected total increase of 10% (about 4 inches per year) (UCS 2006a)
	Seasonal precipitation	Variable	More winter rain, less snow; by the end of the century, projected increases under the higher emissions scenario are about 15% in winter, 10% in spring, 5% in fall, and no change in summer (Karl et al. 2009, Betts 2011b)
	Heavy rainfall events	Increase	More frequent and intense (UCS 2006a)

	Soil moisture	Decrease	Reduction in soil moisture and increase in evaporation rates in the summer (UCS 2006a)
	Snow	Decrease	Vermont's snow season could decrease by more than half by late-century under the high emissions scenario or roughly one-third under the low emissions scenario (UCS 2006b).
	Spring flows	Earlier, reduced volume	Earlier snowmelt, earlier peak streamflows in spring with reduced volume; peak spring flows could occur 5–8 days earlier by mid-century and up to 15 days earlier by the end of the century (Hayhoe et al. 2007)
	Summer low flows	Increase	Extended summer low-flow periods; projected changes differ significantly between emissions scenarios (Hayhoe et al. 2007)
	Ice dynamics	Changing	Less ice cover, reduced ice thickness (UCS 2006b)
	Variability	Increase	More high-flow events and more low-flow events over the course of the year (Hayhoe et al. 2007)
Extreme events	Flood events	Increase	More likely, particularly in winter and particularly under the high emissions scenario (UCS 2006a)
	# of Short-term droughts	Increase	By mid-century, there are projected to be more frequent short-term droughts (an average of two every three years) under both high and low emissions scenarios, with a slightly higher frequency under the higher-emissions scenario (UCS 2006a)
	Storms	Increase	More frequent and intense (UCS 2006a)
	Fire	Increase	More likely (UCS 2006a)
Phenology	Growing season	Increase	By mid-century the growing season may be 2–4 weeks longer than the 1961–1990 reference period, and by end-of-century (2080–2099), it may be extended by an average of 4 weeks (lower emissions) to 6 weeks (higher emissions) (Hayhoe et al. 2007)
	Onset of spring	Earlier	By end of century, key harbingers of spring are expected to arrive 1-2 weeks earlier under a lower emissions scenario and almost 3 weeks earlier under a higher emissions scenario (UCS 2006a)
	Onset of fall	Later	By end of century, could arrive 2 weeks later under a lower emissions scenario or 3 weeks later under a higher emissions scenario (UCS 2006a)
	Biological interactions	Changing	Could potentially be disrupted (Staudinger et al. 2012)

<u>Projected Trends in Ice Dynamics</u>

The trend towards decreasing duration of ice on rivers and lakes is projected to continue (UCS 2006b, Karl et al. 2009).

<u>Projected Trends in Extreme Events</u>

The intensity of hurricanes is likely to increase this century (Karl et al. 2009). By mid-century, there are projected to be more frequent short-term droughts (an average of two every three years) under both high and low emissions scenarios, with a slightly higher frequency under the higher-emissions scenario (UCS 2006a). This is because rising temperatures will increase evaporation rates and reduce soil moisture in summer. By the end of the century, short-term droughts under the higher-emissions scenario may be as frequent as once per year in parts of the Northeast (UCS 2006a). Only a slight increase in drought risk is expected under the lower-emissions scenario (UCS 2006a). As soil moisture is depleted and vegetation becomes increasingly water stressed, the risk of wildfires will increase (UCS 2006a, Brown et al. 2004, Amiro et al. 2001).

Projected Trends in Length of Growing Season/Onset of Spring

By mid-century the growing season may be 2–4 weeks longer than the 1961–1990 reference period, and by end-of-century (2080–2099), the growing season may be extended by an average of 4 weeks under the lower emissions scenario and 6 weeks under the higher emissions scenarios (Hayhoe et al. 2007). If current high emissions continue, Vermont's summer climate by 2080 will feel similar to the climate of northwest Georgia for the period 1961-1990 (Figure 4) (UCS 2006b). However, if emissions are greatly reduced, the climate of Vermont will more closely resemble the climate of southeastern Ohio (UCS 2006b).

Appendix 2G contains additional results for all of these parameters. In addition, early, mid and late-century projections for temperature and precipitation under high and low emissions scenarios were generated for 15 different models using The Nature Conservancy's Climate Wizard tool. Tables with these results can be found in Appendix 2H.

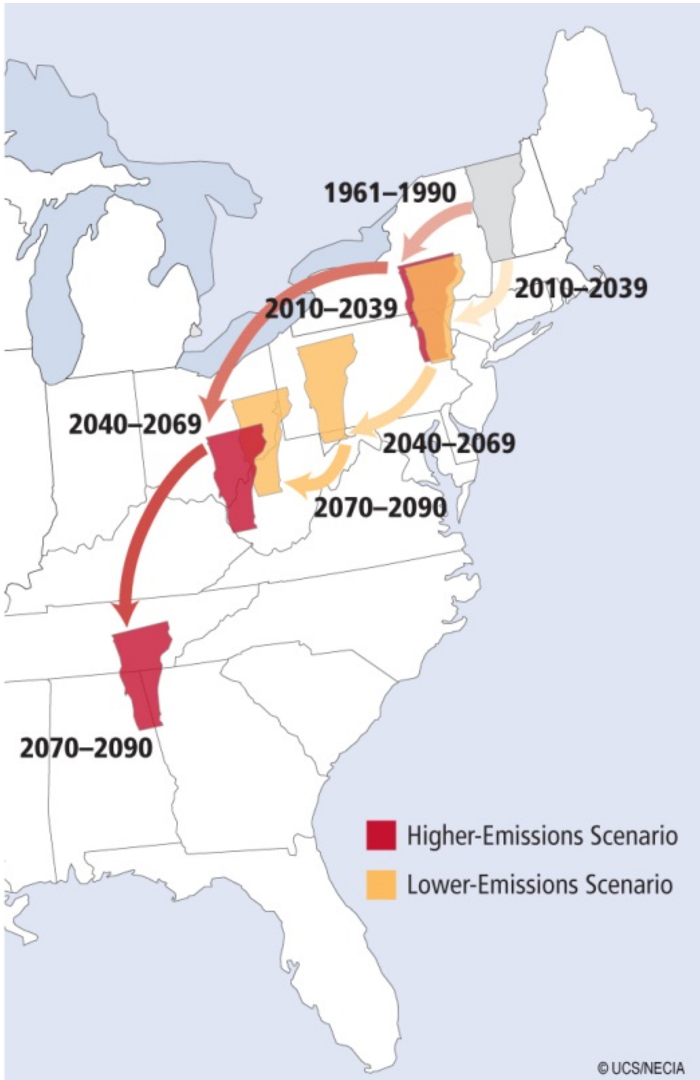

Figure 4. This map from the Northeast Climate Impacts Assessment (UCS NECIA 2006b) gives a visualization of what summers in Vermont will feel like over the course of this century under lower- and higher-emissions scenarios. If current high emissions continue, Vermont's summer climate by 2080 will feel similar to the climate of northwest Georgia for the period 1961-1990. However, if emissions are greatly reduced, the climate of Vermont will more closely resemble the climate of southeastern Ohio (UCS NECIA 2006b).

2.4 Mapping

Mapping exercises were performed to identify potential exposure ‘hot spots’ in Vermont. These are areas that have shown or are projected to experience the greatest amount of change in temperature and precipitation. Figure 5 shows baseline (1961-1990) historic patterns in mean annual air temperature and precipitation, overlaid with delineations of Vermont’s biophysical regions (Thompson and Sorenson 2000). Western (Champlain Valley and Taconic Mountains) and the southeastern corner of Vermont have the warmest mean annual temperatures, while the Northeastern Highlands and higher elevation areas like the Northern Vermont Piedmont experience the coolest annual temperatures (Figure 5). The greatest amount of precipitation falls along the Green Mountains, which run along the central ‘spine’ of Vermont, while areas in western (in particular Champlain Valley) and eastern Vermont have the lowest amounts of mean annual precipitation.

Future projected temperature patterns differ very little across the state. Mid-century projections show slightly greater changes occurring in the northern half of the state during the winter (Figure 6A). Slightly greater increases in mean annual precipitation are projected to occur in the southern part of Vermont, but there is greater uncertainty in projected precipitation patterns vs. temperature patterns (Figure 6B). For more information on easy-to-use mapping interfaces like the Climate Wizard, see Appendix 2I.

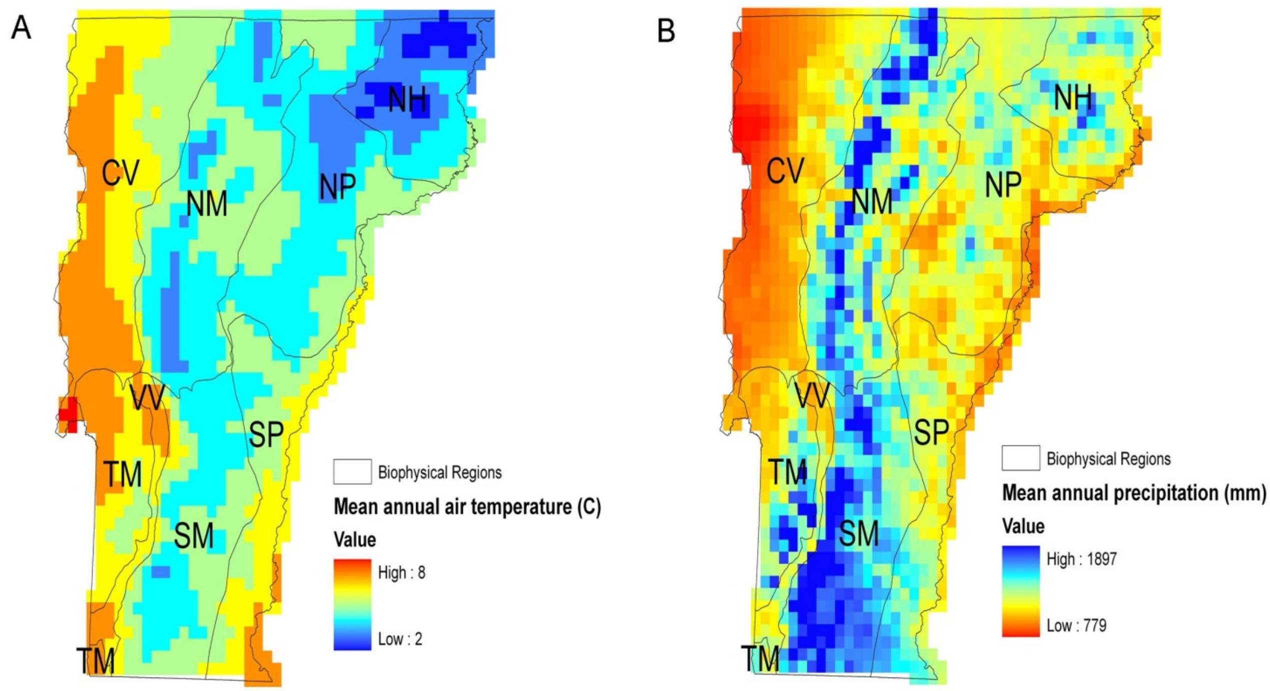

Figure 5. A) Average annual mean temperature (°C) 1961-1990; B) Average annual precipitation (mm) 1961-1990. Map produced using the ClimateWizard © University of Washington and The Nature Conservancy, 2009. Base climate data from the PRISM Group, Oregon State University, http://www.prismclimate.org. Biophysical regions are as follows: CV=Champlain Valley; TM: Taconic Mountains; VV=Vermont Valley; NM=Northern Green Mountains; SM=Southern Green Mountains; NP=Northern Vermont Piedmont; SP=Southern Vermont Piedmont; NH: Northeastern Highlands (from Thompson and Sorenson 2000).

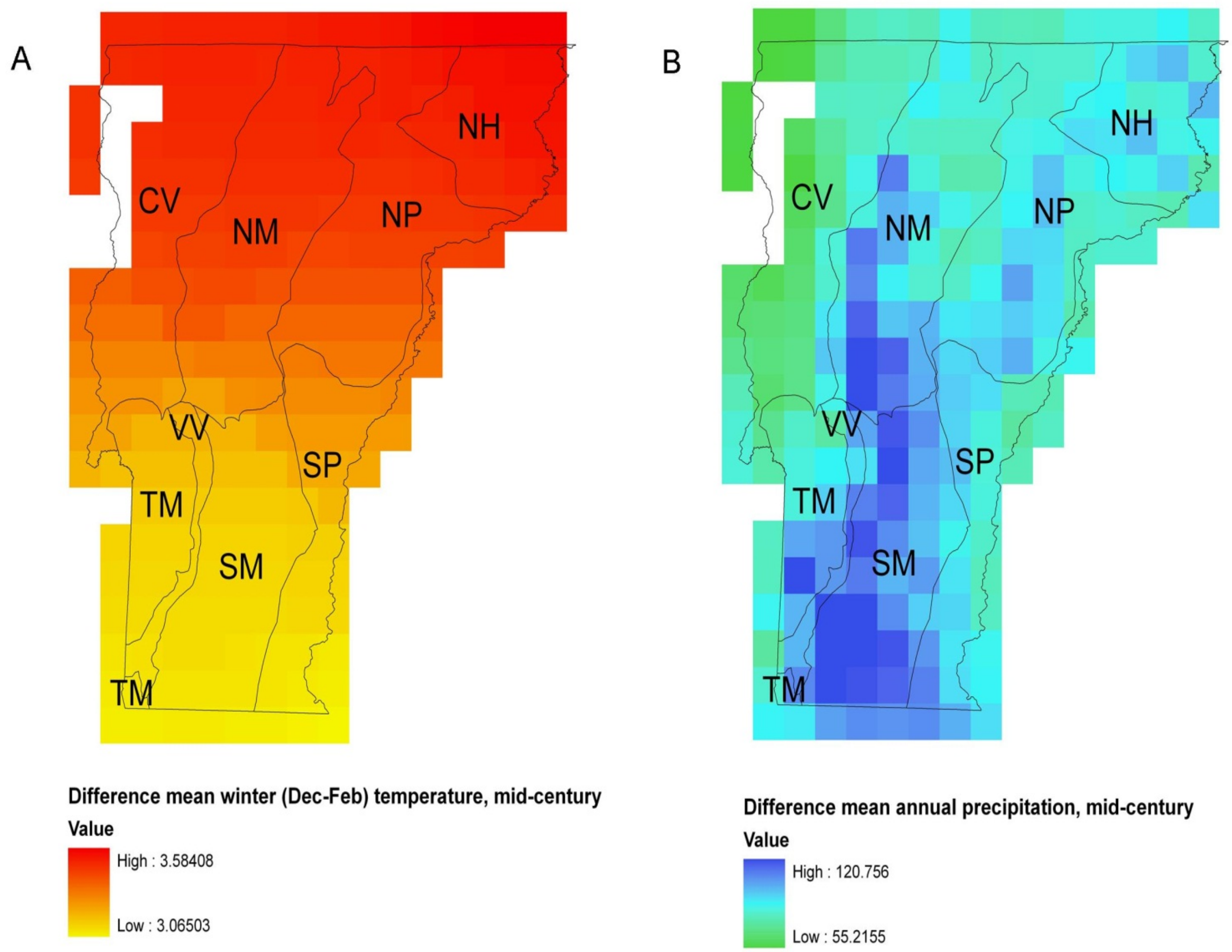

Figure 6. A) Projected mid-century departure mean winter (Dec-Feb) temperature (°C) (2040-2069 vs. 1961-1990); B) Projected mid-century departure mean annual precipitation (mm) (2040-2069 vs. 1961-1990). Maps produced using the ClimateWizard © University of Washington and The Nature Conservancy, 2009. Base climate projections downscaled by Maurer, et al. (2007). We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modeling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy. Biophysical regions are as follows: CV=Champlain Valley; TM: Taconic Mountains; VV=Vermont Valley; NM=Northern Green Mountains; SM=Southern Green Mountains; NP=Northern Vermont Piedmont; SP=Southern Vermont Piedmont; NH: Northeastern Highlands (from Thompson and Sorenson 2000).

3.0 VULNERABILITY ASSESSMENT

3.1 Approach

Vulnerability assessments are conducted to identify which species or habitats are likely to be most strongly affected by projected climatic changes and to understand why these resources are likely to be vulnerable (Glick et al. 2011a). On July 9, 2012, the Vermont ANR convened a workshop of natural resource professionals with expertise in four areas: forests and upland habitats; wetlands; streams and rivers; and lakes. This workshop was designed and intended primarily for sharing information about the progress made so far on the climate change adaptation plan, findings on climate change exposures, background on climate change exposure and adaptation planning terms, and the recommended process for completing a vulnerability assessment as part of the adaptation plan. Towards that end, a series of presentations were made in the morning for orientation. A vulnerability assessment process for documenting exposures and sensitivities was conducted in an afternoon session broken out into four groups representing the major habitat types. During these break-out sessions, each group focused discussions somewhat differently, but attempted to refine habitat units and to assign vulnerability ratings to each unit.

An expert elicitation/consensus approach was used, which is consistent with what many other states (NY, MA, NH, ME, CT) and NEAFWA have done. This approach relies on expert judgments to assess vulnerability and can range from highly formal and controlled elicitation-based models and processes to less formal. It is relatively inexpensive, flexible and rapidly applied. It requires time and active participation and is limited by the knowledge base of the participants. Also, it is iterative – people’s thoughts may change.

At the workshop, much of the discussion was focused on assessing habitats. A habitat-based approached is preferred by some because of the strong association between habitat (in particular, geology and habitat heterogeneity) and biodiversity (Anderson and Feree 2010). Habitat also offers a better organizational framework than species, which can cross multiple habitat types and can be overwhelming when assessed in large numbers. Drawbacks to focusing solely on the habitat-based approach are that there can be problematic classification and scale issues and important information conveyed by species (e.g., keystone species, compositional changes) may be missed.

Worksheets were developed to help structure the workshop discussions (examples of habitat and species worksheets can be found in Appendix 3A). When designing the worksheets, ideas and approaches used by other states and entities (e.g., Manomet & NWF 2012a, Comer et al. 2012, Whitman et al. 2010, New Hampshire Fish and Game 2012) were considered. Participants were asked to think of both negative and positive effects (direct and indirect) associated with key climate factors, reasons for these impacts, and mediating factors. Non-climatic factors and how those rate in relation to climatic factors were also discussed, but to a lesser extent. Participants were asked to assign vulnerability and confidence scores to a variety of habitats and species, using the definitions shown in Table 2 and Table 3. Although the end score was important, the reasons behind the scores are of equal or greater importance, since other researchers might reach different conclusions from similar lines of evidence.

At the end of the day, vulnerability ratings were not complete for each habitat type, but progress was made. A complete and thorough vulnerability assessment requires considerably longer than one afternoon for each of the major habitat types. Some groups were able to meet after the workshop to complete a more thorough and detailed set of vulnerability assessments; in these cases, the more comprehensive results have been integrated into this report. Workshop worksheets were supplemented with results from the regional NEAFWA assessment, other states and from relevant literature. Results from this exercise should be regarded as a work in progress and warrant closer review by experts from the Vermont ANR.

Some species-level vulnerability assessments were completed at the workshop and during follow-up meetings. Workshop participants took the following into consideration when making their assessments: habitat specificity, range, environmental or physiological tolerance, interspecific or phenological dependence, mobility and vulnerability to exotic pathogens or invasive species. Species with specialized habitat and microhabitat requirements, poor or limited opportunity to establish at new locations, highly fragmented populations and/or occur at the southern edge of their range are generally considered to be most vulnerable (Foden et al. 2008, Whitman et al. 2012, Schlesinger et al. 2011). Completed worksheets can be found in Appendix 3B.

Species are being assessed in greater detail as part of the 2015 Wildlife Action Plan updates that are currently underway. In addition to expert elicitation, Vermont Fish & Wildlife is using NatureServe's Climate Change Vulnerability Index (CCVI) to assess some species. The CCVI uses a scoring system that integrates a species' predicted exposure to climate change within an assessment area and three sets of factors associated with climate change sensitivity, each supported by published studies: 1) indirect exposure to climate change, 2) species-specific factors (including dispersal ability, temperature and precipitation sensitivity, physical habitat specificity, interspecific interactions, and genetic factors), and 3) documented response to climate change (NatureServe 2011). The ANR should also watch for a comprehensive report by Whitman et al. that contains expert elicitation assessments on 442 species (this report should be released in 2013).

Table 2. Definitions of vulnerability for habitat and species-level assessments.

<table>
<tr><th colspan="2">Vermont Workshop (timeframe: 2050)</th><th colspan="2">NatureServe Habitat Vulnerablity Assessment (Comer et al. 2012) (timeframe: 2060)</th><th colspan="2">NEAFWA (Manomet & NWF 2012a) (timeframe: unspecified)</th></tr>
<tr><td>Extremely Vulnerable</td><td>Abundance and/or range extent in Vermont extremely likely to substantially decrease (>90% loss) or disappear</td><td>Very High Vulnerability</td><td>Extremely likely to substantially decrease or disappear</td><td>Critically Vulnerable</td><td>Likely to be eliminated</td></tr>
<tr><td>Highly Vulnerable</td><td>Abundance and/or range extent in Vermont likely to decrease significantly (60-90% loss)</td><td>High Vulnerability</td><td>Likely to decrease significantly</td><td rowspan="2">Highly Vulnerable</td><td rowspan="2">Likely to be greatly reduced</td></tr>
<tr><td>Moderately Vulnerable</td><td>Abundance and/or range extent in Vermont likely to decrease (30-60% loss)</td><td>Moderate Vulnerability</td><td>Likely to decrease</td></tr>
<tr><td>Slightly Vulnerable</td><td>Available evidence does not suggest that abundance and/or range extent in Vermont will change (decrease, 15 - 30% loss)</td><td rowspan="2">Low Vulnerability</td><td rowspan="2">Presumed stable</td><td rowspan="2">Vulnerable</td><td rowspan="2">Relatively unaffected</td></tr>
<tr><td>Not Vulnerable, No Effect</td><td>Abundance and/or range extent in Vermont likely to increase or decrease by less than 15%</td></tr>
<tr><td rowspan="2">Increase Possible or Likely</td><td rowspan="2">Available evidence suggests that abundance and/or range extent in Vermont is likely to increase (>15% increase)</td><td rowspan="2">Not Vulnerable</td><td rowspan="2">Expansion likely</td><td>Less Vulnerable</td><td>Habitats that may extend their range</td></tr>
<tr><td>Least Vulnerable</td><td>Habitats that may greatly extend their range</td></tr>
<tr><td>Unknown/ Uncertain</td><td>Available evidence not available or not conclusive at this time</td><td colspan="2">Insufficient Evidence</td><td colspan="2">------</td></tr>
</table>

*at the Vermont workshop, a scoring scale more in line with the NatureServe scale was used; this was because people did not have the experience necessary to distinguish “slightly vulnerable” from “not vulnerable”, nor did they feel comfortable using a quantitative scale.

Table 3. Definitions of confidence.

Vermont Workshop		NEAFWA (Manomet & NWF 2012a)	
Low	Not very confident (0-30% certainty in vulnerability score)	Low	Approximate confidence level of <30%
Moderate	Somewhat confident (30-60% certainty in vulnerability score)	Medium	Approximate confidence level of 30-70%
High	Very confident (>60% certainty in vulnerability score)	High	Approximate confidence level of >70%

3.2 Classification

Selecting appropriate classification schemes for each habitat type was an important and challenging step. Ultimately, it was approached from a management perspective, such that some community types were 'lumped' together because they are expected to respond similarly to climate change, meaning that similar strategies could be employed when managing them.

3.2.1 VT-based classification schemes

The upland and wetlands groups assessed the natural communities described in Thompson and Sorenson 2000. Natural communities are defined as interacting assemblages of organisms, their physical environment, and the natural processes that affect them (Thompson and Sorenson 2000). At a coarser-scale, natural community types are grouped into formations. Tables with descriptions of natural community types grouped by formation can be found in Appendix 3C. These tables include patch codes, which indicate the extent to which the natural community types occur in the Vermont landscape, and state ranks, which indicate the relative rarity of natural community types and are assigned by the Vermont Natural Heritage Inventory. Descriptions of the patch codes and state ranks can be found in Table 4 and Table 5, respectively.

Table 4. Patch codes indicate the extent to which the natural community type occurs across the Vermont landscape.

Code	Description	
M	Matrix	A natural community type that is dominant in the landscape, occupying 1,000 to 100,000 contiguous acres. Matrix communities have broad ecological amplitude, occurring across a wide range of soil and bedrock types, slopes, slope aspects, and landscape positions. Regional scale processes such as climate typically determine their range and distribution.
L	Large	A natural community type that occurs in the landscape on a scale of 50 to 1,000 acres and is usually associated with a single dominant ecological process or environmental condition such as fire or hydrology.
S	Small	A natural community that occurs in the landscape as small, discrete areas typically less than 50 acres, and for some types, consistently under an acre in size. Small patch communities occur where several ecological processes and environmental conditions come together in a very precise way.

Table 5. State ranks indicate the relative rarity of natural community types and are assigned by the Vermont Natural Heritage Inventory.

S1	Very rare in the state, generally with fewer than five high quality occurrences
S2	Rare in the state, occurring at a small number of sites or occupying a small total area in the state
S3	High quality examples are uncommon in the state, but not rare; the community is restricted in distribution for reasons of climate, geology, soils, or other physical factors, or many examples have been severely altered
S4	Widespread in the state, but the number of high quality examples is low or the total acreage occupied by the community type is relatively small
S5	Common and widespread in the state, with high quality examples easily found

Several different classification schemes were considered for rivers. These included the 4 stream types used by the biomonitoring group (VT DEC 2004: small high gradient, moderate high gradient, warm water moderate gradient and slow winder); a more detailed grouping developed by TNC (TNC 2008); and groupings based on geomorphologic principles employed by the Rivers program (Milone and MacBroom 2008, Rosgen 1996, Montgomery and Buffington 1997, Schumm 1977). At the July 9th workshop, the geomorphic classification scheme/s used by the Rivers program was cross-walked with the biological classification scheme/s used by the biomonitoring group, and came up with 4 broad stream groupings: high gradient source/headwater streams; moderate gradient transfer streams; moderate gradient response streams; and low gradient response streams. Participants assessed impacts of climate change on physical processes in 3 of these stream classes: high gradient source/headwater streams; moderate gradient transfer streams; and low gradient response. Descriptions of the biological-geomorphological classification groups can be found in Appendix 3D. More work needs to be done to further refine this classification scheme. Also, it should be noted that not all streams fit into these groupings (e.g., small, low elevation streams flowing into Lake Champlain).

The Vermont Lakes Program uses a classification scheme based on size and trophic status. During the July 9th workshop, the lakes group decided to group lakes into 2 categories for assessment: unstratified and stratified lakes. New Hampshire did something similar when assessing the vulnerability of their lakes to climate change (New Hampshire Fish and Game 2012).

3.2.2 Regional classification schemes

Attempts were made to cross-walk Vermont's habitat types with those assessed by other states as well as those assessed as part of the regional NEAFWA effort. This was a difficult task because different states use different classification schemes. This was further confounded by the fact that when assessing habitats for climate change, habitats are often further grouped based on how they are expected to respond to climate change.

A regional classification scheme has been developed for terrestrial habitats (TNC/NEAFWA, 2011). Cross-walk files are available to link the regional terrestrial habitat classification systems with each state's existing scheme. A table with the regional terrestrial habitats found in Vermont can be found in Appendix 3E. The habitats assessed for the regional NEAFWA work are based on this regional scheme. To make the NEAFWA results more relevant at a state-level, the region was divided into 4 latitudinal zones, as depicted in Figure 7 (Manomet & NWF 2012a). The northern half of Vermont falls within Zone 1 and the southern half is in Zone 2 (Figure 7).

TNC has also developed a regional classification scheme for freshwater streams (Olivero and Anderson 2008). The classification groups are based on thermal class, gradient, size and geology. The Vermont-based scheme described in Appendix 3D is similar in that it is based largely on size and gradient, with thermal class and geology as secondary considerations.

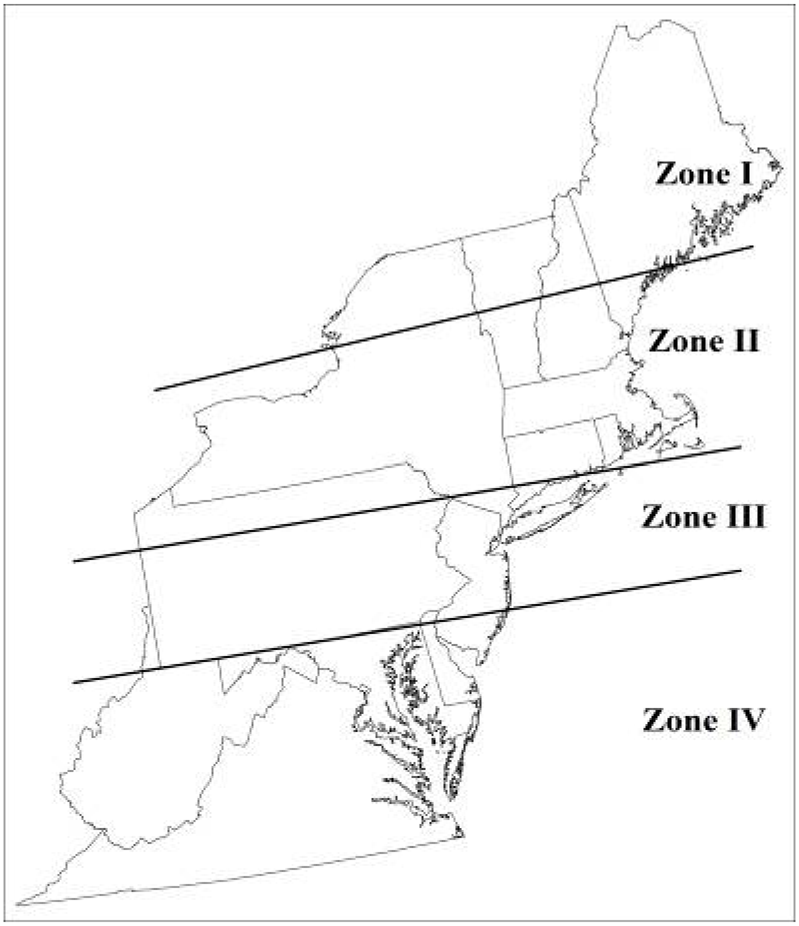

Figure 7. Latitudinal zones used in NEAFWA model application (from Manomet & NWF 2012a).

3.3 Upland forests

There are 3 upland forest formations in Vermont: spruce-fir-northern hardwood, northern hardwood and oak-pine. Descriptions of these formations along with a brief summary of their potential susceptibility to climate change can be found in Table 6. Descriptions of natural community types within these formations can be found in Appendix 3C. Table 7 through 9 show regional results (Manomet & NWF 2012a) cross-walked with Vermont's natural community types.

3.3.1 Climate change vulnerability ratings

The climate change vulnerability ratings were based primarily on regional results (Manoment & NWF 2012a), US Forest Service publications (Rustad et al. 2012, Iverson et al. 2008, Prasad et al. 2007), results from other states (

Table 10) and results from an expert elicitation exercise on tree species by a working group in Vermont Forest & Parks (in progress). During the July 9th workshop, only the spruce-fir-northern hardwood formation was assessed (Appendix 3F). Although these results were utilized, more weight was placed on the sources cited above because they are more comprehensive. Results presented here warrant closer review by experts in Vermont and should be regarded as a first step, not a final product.

Results anticipated by 2050 are as follows:

- **Most likely to be negatively affected (high confidence)**:
  - high elevation spruce-fir forests in southern Vermont
  - species associated with montane forests, like the Bicknell's thrush

- **Most likely to benefit (high confidence)**:
  - oak-pine forests and associated species
  - pests that were previously limited by winter temperatures (e.g., hemlock woolly adelgid)
  - non-native invasive plants, especially Asiatic bittersweet

Northern hardwood forests are expected to be less vulnerable to climate change than the montane spruce-fir forests, but abundance and compositional changes are expected to occur within this formation, and these changes are likely to be more evident in southern versus northern Vermont (Manomet and NWF 2012a). Distributions of montane, northern hardwood and oak-pine forests are shown in Figure 8.

Table 6. Descriptions of Vermont's upland forest formations (Thompson and Sorenson 2000) and their potential susceptibility to climate change. Natural community types within these formations are described in Appendix 3C.

Formation	Description	Potential Susceptibility to Climate Change
Spruce-Fir-Northern Hardwood Forests	Forests of this formation characterize Vermont's coldest regions. At higher elevations and in low, cold, moist areas, red spruce and balsam fir may dominate the canopy. Warmer or better drained sites have significant amounts of hardwoods (yellow birch, sugar maple, and beech) along with softwoods in the canopy. Human or natural disturbance can also lead to temporary dominance by hardwood species.	Found in colder regions of Vermont with abundant precipitation. Many component species are at the southern limit of their ranges in Vermont. Snow pack and soil saturation are important climate factors.
Northern Hardwood Forests	Forests of this formation are best developed at Vermont's middle elevations and forests of this formation are widespread in the state. Beech, sugar maple, and yellow birch are the prominent tree species, but hemlock, red oak, red maple and white pine can be common as well, and red spruce makes an occasional appearance. These are the dominant communities in nearly all biophysical regions, excepting the highest elevations of the Green Mountains and the lowest elevations in the Champlain Valley.	The dominant forests in Vermont with component species generally widespread in the community's range. Sugar maple is a keystone species and sensitive to site conditions. Climate related changes in soil organic matter, available moisture, available nutrients and soil temperature may lead to general sugar maple decline and loss of associated species.
Oak-Pine-Northern Hardwood Forests	Forests of this formation are best developed in the warmer regions of Vermont - the southern Vermont Piedmont, Champlain Valley, and the lower elevations in the Taconic Mountains. This formation is typically found on dry hilltops, surrounded by lower slopes of forests in the Northern Hardwood Formation. In this formation, hardwoods such as sugar maple, beech, and yellow birch are common, but warmer climate species such as red oak, shagbark hickory and white oak can be present in significant numbers. White pine is a prominent part of this formation.	Found in the warmer and drier regions of Vermont. Many component species are at the northern limit of their ranges in Vermont.

Table 7. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Spruce-Fir-Northern Hardwood Forest formation. During the vulnerability workshop, participants rated this formation as moderately vulnerable, with medium confidence. Descriptions of the natural community types can be found in Appendix 3C. Vuln=vulnerability; Conf=confidence.

Natural Community Types	VT Patch Size	VT State Rank	NETWHCS Habitat System	NEAFWA			
				Zone 1 (N)		Zone 2 (S)	
				Vuln	Conf	Vuln	Conf
Subalpine Krummholz	S-L	S1	Acadian-Appalachian Subalpine Woodland and Heath-Krummholz	--	--	--	--
Montane Spruce-Fir	M	S3	Acadian-Appalachian Montane Spruce-Fir Forest	Relatively unaffected	High	Highly Vuln	High
Montane Yellow Birch-Red Spruce	M	S3					
Lowland Spruce-Fir	L-M	S3	Acadian Low-Elevation Spruce-Fir Forest and Flats	--	--	--	--
			Acadian Sub-Boreal Spruce Barrens	--	--	--	--
Red Spruce-Northern Hardwood	M	S4	Laurentian-Acadian Northern Hardwoods Forest	Less Vuln	High	Relatively unaffected	High
Red Spruce-Heath Rocky Ridge	S-L	S3	Northern Appalachian-Acadian Rocky Heath Outcrop	--	--	--	--
Boreal Talus Woodland	S	S3	Laurentian-Acadian Acidic Cliff and Talus	--	--	--	--
Cold-Air Talus Woodland	S	S1	Laurentian-Acadian Acidic Cliff and Talus	--	--	--	--

Table 8. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Northern Hardwood Forest formation. During the vulnerability workshop, participants did not have time to rate this formation. Descriptions of the natural community types can be found in Appendix 3C.

Natural Community Types	VT Patch Size	VT State Rank	NETWHCS Habitat System	NEAFWA			
				Zone 1 (N)		Zone 2 (S)	
				Vuln	Conf	Vuln	Conf
Northern Hardwood Forest	M	S5	Laurentian-Acadian Northern Hardwoods Forest	Less Vuln	High	Relatively unaffected	High
Rich Northern Hardwood Forest	S-L	S4					
Northern Hardwood Talus Woodland	S	S3					
Mesic Red Oak-Northern Hardwood Forest	L	S4	Appalachian (Hemlock)-Northern Hardwood Forest	--	--	--	--
Hemlock-Northern Hardwood Forest	L-M	S4					
Hemlock Forest	S	S4	Laurentian-Acadian Pine-Hemlock-Hardwood Forest	--	--	--	--
Temperate Hemlock Forest	S-L	S4	--	--	--	--	--

Table 9. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Oak-Pine Forest formation. During the vulnerabilityworkshop, participants did not have time to rate this formation. Descriptions of the natural community types can be found in Appendix 3C.

<table>
<tr><th rowspan="3">Natural Community Types</th><th rowspan="3">VT Patch Size</th><th rowspan="3">VT Patch Size</th><th rowspan="3">VT State Rank</th><th rowspan="3">NETWHCS Habitat System</th><th colspan="4">NEAFWA</th></tr>
<tr><th colspan="2">Zone 1 (N)</th><th colspan="2">Zone 2 (S)</th></tr>
<tr><th>Vuln</th><th>Conf</th><th>Vuln</th><th>Conf</th></tr>
<tr><td rowspan="3">Northern Dry Rocky Forests and Woodlands</td><td>Red Pine Forest or Woodland</td><td>S</td><td>S2</td><td>Laurentian-Acadian Northern Pine-(Oak) Forest</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Limestone Bluff Cedar-Pine</td><td>S</td><td>S2</td><td>Laurentian-Acadian Calcareous Rocky Outcrop</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Transition Hardwood Talus Woodland</td><td>S</td><td>S3</td><td rowspan="4">Central Appalachian Pine-Oak Rocky Woodland</td><td rowspan="4">Least Vulnerable</td><td rowspan="4">High</td><td rowspan="4">Least Vulnerable</td><td rowspan="4">High</td></tr>
<tr><td rowspan="5">Southern Dry Rocky Forests and Woodlands</td><td>Red Cedar Woodland</td><td>S</td><td>S2</td></tr>
<tr><td>Dry Oak Woodland</td><td>S</td><td>S2</td></tr>
<tr><td>Pitch Pine-Oak-Heath Rocky Summit</td><td>S</td><td>S1</td></tr>
<tr><td>Dry Oak</td><td>S</td><td>S3</td><td rowspan="3">Central Appalachian Dry Oak-Pine Forest</td><td rowspan="3">Least Vulnerable</td><td rowspan="3">High</td><td rowspan="3">Least Vulnerable</td><td rowspan="3">High</td></tr>
<tr><td>Dry Oak-Hickory-Hophornbeam</td><td>S-L</td><td>S3</td></tr>
<tr><td rowspan="5">Dry Mesic Forests and Woodlands with Deeper Soil</td><td>White Pine-Red Oak-Black Oak</td><td>L</td><td>S3</td></tr>
<tr><td>Mesic Maple-Ash-Hickory-Oak</td><td>L</td><td>S3</td><td>Appalachian (Hemlock)-Northern Hardwood Forest</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Mesic Clayplain</td><td>L-M</td><td>S2</td><td>North-Central Interior Wet Flatwoods</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Sand-Over-Clay</td><td>L</td><td>S2</td><td>--</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>Pine-Oak-Heath Sandplain</td><td>L</td><td>S1</td><td>Northeastern Interior Pine Barrens</td><td>--</td><td>--</td><td>Least Vulnerable</td><td>High</td></tr>
</table>

Table 10. Results of vulnerability assessments from other states that pertain to forest habitat types.

State	Community	Vulnerability
New Hampshire (New Hampshire Fish and Game 2012) DRAFT	High-elevation spruce fir	High (possibly extreme)
	Low-elevation spruce fir	Moderate-High
	Northern-hardwood conifer	Moderate
	Hemlock-hardwood pine forest	Moderate-High (depending on latitude)
	Pine barrens Rocky ridge/talus slopes	Low-moderate Low
Maine (Whitman et al. 2010)	Mountaintop forest (including krummholz)	High
	Coniferous forest	High
	Deciduous and mixed forest	High
	Dry woodlands and barrens	Low
New York (Galbraith 2012)	Mountain spruce-fir forests	In progress
	Spruce-fir forests and flats	
	Mixed Northern Hardwoods	
	Oak-Pine Forest	
	Oak Forest	
	Pine Barrens	
Massachusetts (Manomet 2010b)	Spruce-fir forest	High
	Northern Hardwood Forest	Moderate-High
	Pitch pine scrub-oak	Low
Connecticut (2010)	Upland forest complex	Moderate

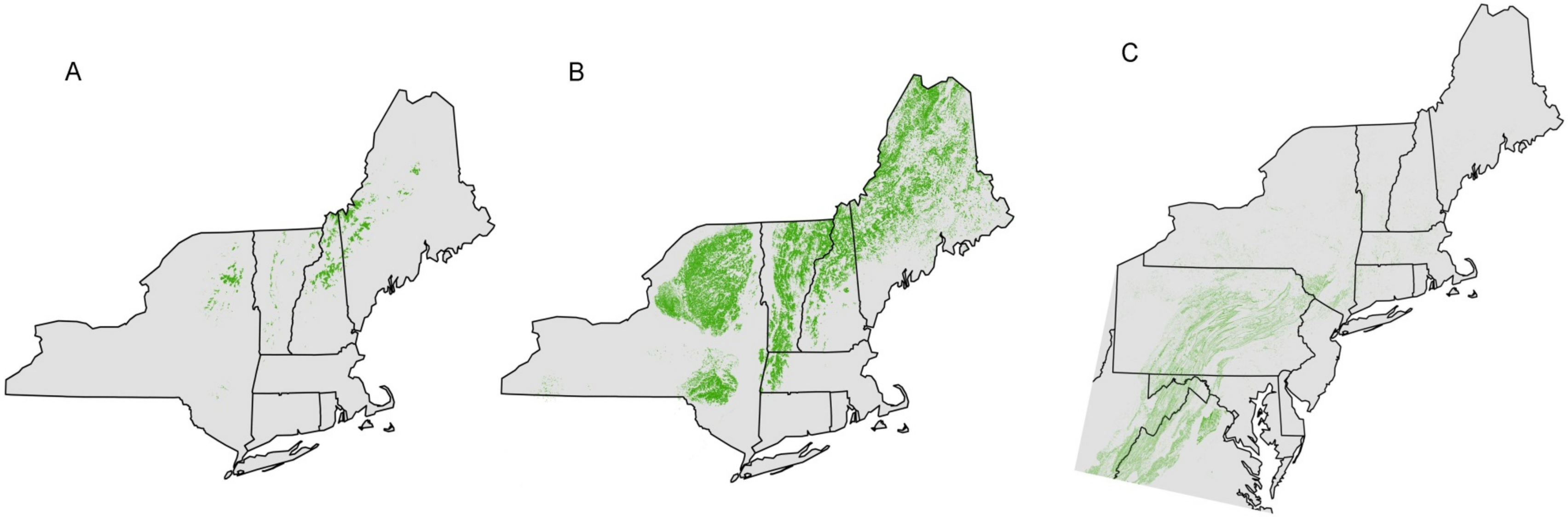

Figure **8**. Current distribution maps of A) Acadian-Appalachian Montane Spruce-Fir-Hardwood forest, which corresponds to Vermont's montane forests (Gawler et al. 2008); B) Laurentian-Acadian Northern Hardwood forest, which corresponds to Vermont's northern hardwood forests (Gawler et al. 2008); C) Central Appalachian Dry Oak-Pine forest, Central Appalachian Pine-Oak RockyWoodland, Laurentian Acadian Northern Pine (Oak) forest, which corresponds to several of Vermont's northern and southern dry rocky forests and woodlands (Gawler et al. 2008). These maps are based on GIS files from the Northeast Terrestrial Habitat Mapping Project (NEAFWA 2011).

3.3.2 Mechanisms by which climate change is expected to impact upland forests

Although the vulnerability ratings are important, it is also important to understand the mechanisms leading to the ecological effects, as this will help inform adaptation strategies. Climate change will have both direct and indirect effects on forest ecology. Table 11 provides a summary of mechanisms by which climate-related factors are expected to impact upland forests in Vermont (by necessity, in many cases these are oversimplifications of highly complex and inter-related pathways). The bulleted text below highlights commonly cited themes in the literature and vulnerability assessments that were reviewed. There is a high level of certainty in the climatic projections associated with these pathways.

- Compositional changes associated with rising temperatures/changes in thermally suitable habitat, resulting in the eventual loss of cold-adapted species and an increase in warm-adapted species.
- Increase in overwinter survival of pests, such as balsam and hemlock woolly adelgid.
- Increased physiological stress from heat and/or water limitation, resulting in increased susceptibility to pests and disease, decreased productivity and increased tree mortality.
- Increased physical damage and disturbance from extreme storm events (e.g., wind and ice), which facilitates the spread of invasive species (Rustad et al. 2012).
- Early spring thaws/late frosts can damage flowers which affect subsequent regeneration potential, and vegetation and roots which affect tree productivity.
- Increased likelihood of disease damage, as the suitability of conditions for pathogen survival, reproduction, spread, or host infection will increase as climate changes (Kliejunas 2011)

Some of the complex, interacting relationships described above are depicted in Figure 9. Additional resources describing potential impacts of climate change on forests can be found in Appendix 3G.

Table 11. Expected effects of key climate factors on upland forest habitats.

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Warming temperatures	High	Compositional changes associated with changes in thermally suitable habitat (loss of cold-adapted species and increase in warm-adapted species)	Long-term, but localized effects could occur on a shorter timescale	Orientation (north/south facing), topography/slope, elevation, latitude, soil type, geology, ability of species to migrate to suitable habitat, browsing preferences (Rodenhouse et al. 2009)
		Increase in overwinter survival of pests, such as balsam and hemlock woolly adelgid	Immediate	
		Increased physiological stress, resulting in increased susceptibility to pests and disease, decreased productivity and increased tree mortality	Immediate	
		Increased evapotranspiration, resulting in a decrease in soil moisture; moisture limitation/stress negatively impacts productivity and survival in many species	Immediate	
		Increased decomposition rate of organic material may enrich soils and make them more suitable for competitors	Long-term, but localized effects could occur on a shorter timescale	
		Decrease in winter snow pack, leading to change in deer and moose browsing patterns, which affects regeneration	Immediate	
Increase in extreme storm events (e.g., wind and ice)	High	Increased physical damage and disturbance, leading to gap formation, which facilitates the spread of invasive species	Immediate	Topography/slope, stand density, soil depth, root structure

Table 11. continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Phenology (timing)	High	Longer growing season	Immediate	
		Early spring thaws/late frosts can damage buds, blossoms & roots, which affects regeneration	Immediate	Topography
		Change in freeze/thaw cycles could disrupt regular periodicity of cone cycles	Immediate	Timber harvesting, size and age of trees
		Asynchronous changes in phenology may negatively impact some migratory species and pollinators	Immediate	
Increase in fire risk	Medium	Increased physical damage and disturbance, leading to gap formation, which facilitates the spread of invasive species	Long-term, but localized effects could occur on a shorter timescale	Topography, orientation, soil type, understory
		Loss of fire intolerant species and increase in fire tolerant species, such as red and pitch pines		
Increase in number of short-term droughts	Medium	Declines in forest productivity and tree survival associated with water limitation (Williams et al. 2013, Anderegg et al. 2012)	Long-term	Soil type (ability to retain moisture)

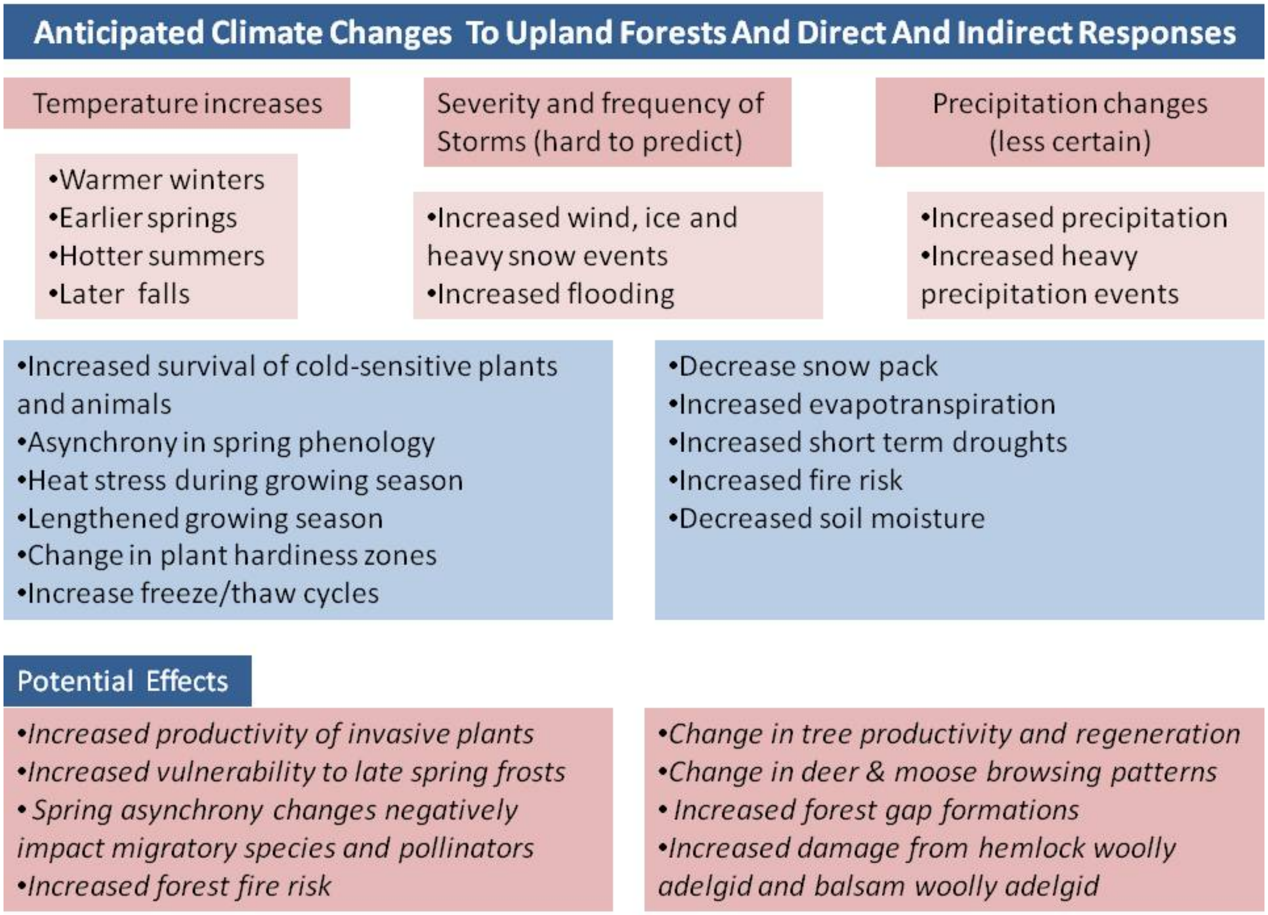

Figure 9. Depiction of some of the complex pathways by which key climatic factors can impact biology in upland forest habitats (provided by Sandy Wilmot, Vermont Forest & Parks). Additional effects can be expected on wildlife and vegetation.

3.3.3 Non-climatic stressors

It is important to consider climate change in the context of other stressors. In some cases, non-climatic stressors may pose a much larger threat than climate change; in others, climate change may exacerbate impacts from non-climatic stressors; in yet others, climate change will cause greater ecological impacts than the non-climatic factors.

The following non-climatic stressors have been identified as causing high stress to Vermont's forests:

- Air pollution (e.g., ozone, acid deposition, nitrogen deposition) (Rustad et al. 2012, Kart et al. 2005)
- Invasive species (e.g., garlic mustard, buckthorn, honeysuckle, Japanese barberry) (Rustad et al. 2012)

- Pests and pathogens (Rustad et al. 2012)
  - Introduction of Emerald ash borer (which is not as closely tied to temperature as the woolly adelgids) poses a major threat to ash survival
  - Introduction of Asian long-horned beetle could greatly impact hardwoods
  - Insect outbreak behavior in general is expected to intensify (Logan et al. 2003)
- Habitat conversion (Kart et al. 2005)
- Habitat degradation (Kart et al. 2005)

3.3.4 Major unknowns/research needs

The following were cited as major unknowns that could potentially play an important role in shaping how forests are impacted by climate change:

- Our inability to accurately project changing precipitation patterns
- Cloud cover
  - this has too many complex feedback loops for projection
  - it affects many aspects of plant productivity (e.g., photosynthesis, relative humidity, forest carbon and water cycling)
  - it is closely tied to montane spruce-fir forests, which are expected to be highly vulnerable to climate change (Thompson and Sorenson 2000).
- CO2 fertilization
  - complex feedback loops with evapotranspiration (Rustad et al. 2012)
- Nutrient cycling (Rustad et al. 2012)
- Biological interactions
- Loss of snow cover
  - uncertain as to how/if this will directly impact tree species
  - change in survival of ground-dwelling pathogens and other organisms

3.4 Wetlands

The following 5 wetland formations were assessed: open peatlands, marshes and sedge meadows, shrub swamps, hardwood swamps, softwood swamps. Seeps, vernal pools and floodplain forests were also considered in follow-up exercises. Descriptions of these formations along with a brief summary of their potential susceptibility to climate change can be found in Table 12. Descriptions of natural community types within these formations can be found in Appendix 3C. Table 13 through 17 show regional results (Manomet & NWF 2012a) cross-walked with Vermont's wetland natural community types.

3.4.1 Climate change vulnerability ratings

The climate change vulnerability ratings were based primarily on regional results (Manomet & NWF 2012a), results from other states (Table 18), literature (e.g., Winter 2000) and follow-up expert elicitation exercises by VT Fish & Wildlife. During the July 9th workshop, alluvial swamp and cattail marsh natural community types were assessed. Completed worksheets from this and the follow-up exercises can be found in Appendix 3H. Although these results were utilized, more weight was placed on the aforementioned sources because they are more comprehensive. Results presented here warrant closer review by experts in Vermont and should be regarded as a first step, not a final product.

Results anticipated by 2050 are as follows:

- **Most likely to be negatively affected**:
  - Acidic bogs, fens and peatlands (high confidence)
  - Cold-adapted species (high confidence)
  - Wetlands that depend on precipitation for their source of water (medium confidence, due to uncertainties associated with precipitation models)

- **Most likely to benefit (medium confidence)**:
  - Marsh and Sedge Meadow
  - Shrub Swamps
  - Warm-adapted species

Acidic bogs, fens and peatlands are rare in the state (Figure 10A), while freshwater marsh and shrub swamp wetlands make up a relatively large proportion of the Vermont landscape (Figure 10B) (Thompson and Sorenson 2000). Water source and the soil composition (organic versus mineral) are key factors affecting the vulnerability of wetlands to climate change. Acidic bogs and peatlands are particularly vulnerable because of their specialized habitat requirements (cold climate, short growing season, organic matter that accumulates faster than it decays). It is important to understand the relative contributions of precipitation vs. groundwater resources when assessing vulnerability, as wetlands that receive groundwater inputs are expected to be less vulnerable to changing precipitation patterns due to the buffering capacity of regional ground water flow systems (Winter 2000). Due to the uncertainties associated with precipitation models, there is a relatively high degree of uncertainty about the impacts that climate change will have on local hydrologic processes and wetlands (Manomet & NWF 2012a). Participants at the workshop generally regarded projections for increased annual precipitation as a positive and summer low flows/drought conditions as a major negative.

Table 12. Descriptions of Vermont's wetland formations (Thompson and Sorenson 2000) and their potential susceptibility to climate change. Natural community types within these formations are described in Appendix 3C.

Type	Formation	Description	Potential Susceptibility to Climate Change
Open & Shrub Wetlands	Open Peatlands	Peat-accumulating wetlands with stable water tables at or near the organic soil surface, generally lack seasonal flooding, and mosses and liverworts are consistently abundant. Trees are generally sparse or absent, except for in Black Spruce Woodland Bog and Pitch Pine Woodland Bog.	Peat accumulating wetlands are susceptible to oxidizing conditions associated with drier summers and warmer temperatures.
	Marshes and Sedge Meadows	Wetlands with standing or slowly moving water with depths that may fluctuate seasonally. The soils are primarily mineral, with well-decomposed organic mucks in some cases. Herbaceous plants are dominant.	Susceptible to changes in volume and seasonality of precipitation and snow melt.
	Wet Shores	Sparsely vegetated wetland communities that occur along the shores of rivers and lakes and are subject to seasonal flooding and scouring. The mineral soils range from mud and silt to cobble.	Susceptible to changes in frequency and duration of flooding and severity of storm events.
	Shrub Swamps	Shrub-dominated wetlands typically have significant seasonal flooding and variable soils types. Shrubs that typically dominate include speckled alder, willow, sweet gale, and buttonbush.	Varied susceptibility based on hydrologic regime.
Forested Wetlands	Hardwood Swamps	Dominated by broad-leaved deciduous trees, but may have lesser amounts of conifers. Dominant trees may be red maple, silver maple, black ash, green ash, or black gum. Soils are mineral or organic.	Depends upon source water. If source water is from ground water seepage, the seepage will moderate fluctuations in precipitation. If source water is derived from local watershed runoff, the wetlands will be susceptible to changes in volume and seasonality of precipitation and snow melt.
	Softwood Swamps	Dominated by conifers, including northern white cedar, red spruce, black spruce, balsam fir, tamarack, and hemlock. Broad-leaved deciduous trees may be present but are less abundant than conifers. Soils are mineral or organic.	
	Seeps and Vernal Pools	Typically very small and occur in depressions or at the base of slopes in upland forests. Seeps have abundant groundwater discharging at their margins and usually a lush growth of herbs. Vernal pools are depressions that fill with water in the spring and fall and typically have little herbaceous cover.	
	Floodplain Forests	Usually dominated by silver maple or sugar maple, with abundant ostrich fern or sensitive fern. Closely associated with river and lake floodplains and have exposed mineral soils of alluvial origin.	Susceptible to changes in frequency and duration of flooding and severity of storm events.

Table 13. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Open Peatlands formation.

Natural Community Types	VT Patch Size	VT State Rank	VT		NETWHCS Habitat System	NEAFWA			
						Zone 1 (N)		Zone 2 (S)	
			Vuln	Conf		Vuln	Conf	Vuln	Conf
Dwarf Shrub Bog	S	S2	Slightly vuln if groundwater fed; moderately vuln if precipitation dependent	Medium	Boreal-Laurentian Bog/ North-Central Interior and Appalachian Acidic Peatland	Highly vuln	High	Highly vuln	High
Black Spruce Woodland Bog	S	S2			Boreal-Laurentian Bog				
Pitch Pine Woodland Bog	S	S1			North-Central Interior and Appalachian Acidic Peatland				
Alpine Peatland	S	S1			Acadian-Appalachian Subalpine Woodland and Heath-Krummholz	--	--	--	--
Poor Fen	S	S2			Boreal-Laurentian-Acadian Acidic Basin Fen	Highly vuln	High	Highly vuln	High
Intermediate Fen (ground water moderation)	S	S2			Laurentian-Acadian Alkaline Fen	--	--	--	--
Rich Fen (ground water moderation)	S	S2			North-Central Appalachian Seepage Fen	--	--	--	--

Table 14. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Marsh and Sedge Meadow formation.

Natural Community Types	VT Patch Size	VT State Rank	VT		NETWHCS Habitat System	NEAFWA			
						Zone 1 (N)		Zone 2 (S)	
			Vuln	Conf		Vuln	Conf	Vuln	Conf
Shallow Emergent Marsh	S	S4	Moderate	Medium	Laurentian-Acadian Freshwater Marsh	Less Vuln	Medium	Less Vuln	Medium
Cattail Marsh	S-L	S4							
Deep Broadleaf Marsh	S	S4							
Wild Rice Marsh	S	S3							
Deep Bulrush Marsh	S-L	S4							
Sedge Meadow	S	S4			Laurentian-Acadian Wet Meadow-Shrub Swamp	Less Vuln	Medium	Less Vuln	Medium

Table 15. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008)and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Shrub Swamps formation.

Natural Community Types	VT Patch Size	VT State Rank	VT		NETWHCS Habitat System	NEAFWA			
						Zone 1 (N)		Zone 2 (S)	
			Vuln	Conf		Vuln	Conf	Vuln	Conf
Alluvial Shrub Swamp	L	S3	Moderate	Medium	Central Appalachian Stream and Riparian/ Laurentian-Acadian Floodplain Systems				
Alder Swamp	L	S5			Laurentian-Acadian Wet Meadow-Shrub Swamp	Less Vuln	Medium	Less Vuln	Medium
Sweet Gale Shoreline Swamp	S	S3			Boreal-Laurentian-Acadian Acidic Basin Fen	Highly vuln	High	Highly vuln	High
Buttonbush Swamp	S	S2							
Buttonbush Basin Swamp	S	S2							

Table 16. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Basin Swamps and Wetlands formation.

Natural Community Types	VT Patch Size	VT State Rank	VT		NETWHCS Habitat System	NEAFWA			
						Zone 1 (N)		Zone 2 (S)	
			Vuln	Conf		Vuln	Conf	Vuln	Conf
Red Maple-Sphagnum Acidic Basin Swamp	S	S3	Moderate	Medium	Northern Appalachian-Acadian Conifer-Hardwood Acidic Swamp	--	--	--	--
Spruce-Fir-Tamarack Swamp	L	S3			Boreal-Laurentian Conifer Acidic Swamp	--	--	--	--
Black Spruce Swamp	S	S2				--	--	--	--
Hemlock-Sphagnum Acidic Basin Swamp	S	S2			North-Central Appalachian Acidic Swamp	--	--	--	--
Red Spruce-Cinnamon Fern Swamp	S	S3			--	--	--	--	--
Red Maple-Black Gum Swamp	S	S2			--	--	--	--	--
Red Maple-White Pine-Huckleberry Swamp	S	S1			--	--	--	--	--

Table 17. Cross-walk of the Northeast Terrestrial Wildlife Habitat Classification System (NETWHCS) (Gawler et al. 2008) and NEAFWA results (Manomet & NWF 2012a) with natural community types from Vermont's Ground Water Seepage and Flooded Swamps formation.

Natural Community Types	VT Patch Size	VT State Rank	VT		NETWHCS Habitat System	NEAFWA			
						Zone 1 (N)		Zone 2 (S)	
			Vuln	Conf		Vuln	Conf	Vuln	Conf
Northern White Cedar Swamp	S	S3	Slightly vulnerable	Medium	Laurentian-Acadian Alkaline Conifer-Hardwood Swamp/ Acadian-Appalachian Conifer Seepage Forest	--	--	--	--
Red Maple-Black Ash Seepage Swamp	S-L	S4			Laurentian-Acadian Alkaline Conifer-Hardwood Swamp	--	--	--	--
Red Maple-Northern White Cedar Swamp	L	S3							
Calcareous Red Maple-Tamarack Swamp	S	S2			North-Central Interior and Appalachian Rich Swamp	--	--	--	--
Red or Silver Maple-Green Ash Swamp	L	S3			--	--	--	--	--
Hemlock-Balsam Fir-Black Ash Seepage Swamp	S	S3			--	--	--	--	--

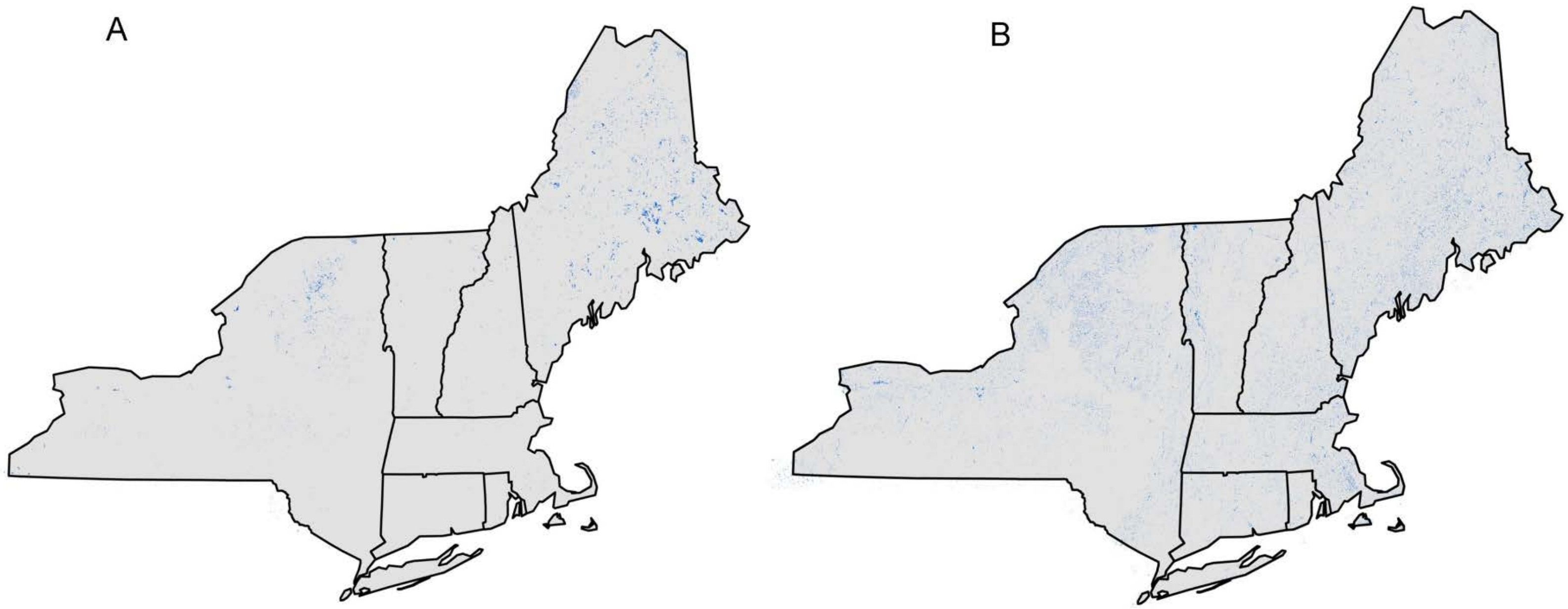

Figure **10**. Current distribution maps of A) North Central Interior and Appalachian Acidic Peatland and Boreal-Laurentian Bog, Boreal-Laurentian-Acadian Acidic Basin Fen, which corresponds with several of Vermont's open peatland natural community types (Gawler et al. 2008); and B) Laurentian-Acadian Wet Meadow Shrub Swamp and Laurentian-Acadian Freshwater Marsh, which corresponds with several of Vermont's marsh and sedge meadows and shrub swamp natural community types (Gawler et al. 2008). These maps are based on GIS files from the Northeast Terrestrial Habitat Mapping Project (NEAFWA 2011).

Table 18. Results of vulnerability assessments from other states that pertain to wetland habitat types.

State	Community	Vulnerability
New Hampshire (New Hampshire Fish and Game 2012) DRAFT	Marsh/shrub wetlands	Low
	Peatlands	Moderate-high
	Northern swamps	Moderate-high
	Temperate swamps	Low-moderate
	Floodplain forests	Moderate-high
	Vernal pools	High
Maine (Whitman et al. 2010)	Emergent marsh and wet meadows	Moderate
	Shrub-scrub wetland	Moderate
	Peatlands	High
	Forested wetland	Moderate
New York (Galbraith 2012)	Mixed hardwood swamp	In progress
	Hardwood swamp	
	Conifer forest swamp	
	Northern white cedar	
	Boreal forested peatland	
	Open acidic peatlands	
	Open alkaline peatlands	
	Freshwater marsh	
	Wet meadow/shrub swamp	
Massachusetts (Manomet 2010b)	Emergent marsh	Moderate-high
	Shrub swamp	Relatively unaffected (slight increase or decrease possible)
	Spruce-fir boreal swamp	High-critically high
	Hardwood swamp	No effect-moderate
	Riparian forest	Moderate
	Vernal pools	Low-moderate
Connecticut (2010)	Forested swamps	High
	Bogs and fens	Low
	Herbaceous freshwater wetlands	High

3.4.2 Mechanisms by which climate change is expected to impact wetlands

Although the vulnerability ratings are important, it is also important to understand the mechanisms leading to the ecological effects, as this will help inform adaptation strategies. Table 19 provides a summary of mechanisms by which climate-related factors are expected to impact wetlands in Vermont. The bulleted text below highlights commonly cited themes in the literature and vulnerability assessments that were reviewed. There is a high level of certainty in the climatic projections associated with these pathways.

- Compositional changes associated with rising temperatures/changes in thermally suitable habitat, resulting in the eventual loss of cold-adapted species and an increase in warm-adapted species.
- Increase in overwinter survival of pests, such as the hemlock woolly adelgid.
- Increased physiological stress from heat and/or water limitation, resulting in increased susceptibility to pests and disease, decreased productivity and increased mortality.
- Increased physical damage and disturbance from extreme storm events (e.g., wind and ice), which facilitates the spread of invasive species
- Increased decomposition rate of peatlands/organic material, which, in combination with drier soils and a longer growing season, could lead to significant changes in overall species composition of peatlands and the eventual conversion to a different habitat type (e.g.,. replacement by more forested wetlands or non-wetland habitats)

The following pathways are precipitation-dependent, thus they are more uncertain:

- Shortening or lengthening of effective hydroperiods, which impacts amphibian breeding success (lengthening would be beneficial; shortening would be detrimental)
- Changes in duration and seasonality of flooding; eventually this could lead to localized shifts in vegetation composition and structure (Whitman et al. 2010)

Some of the complex pathways by which warming temperatures can impact peatland habitats are depicted in the conceptual diagram in Appendix 3I. Additional resources describing potential impacts of climate change on wetlands can be found in Appendix 3J.

Table 19. Expected effects of key climate factors on wetland habitats.

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Warming temperatures	High	Compositional changes associated with changes in thermally suitable habitat (loss of cold-adapted species and increase in warm-adapted species)	Long-term, but localized effects could occur on a shorter timescale	Orientation (north/south facing), elevation, latitude, topography/slope, groundwater influence, water depth size and connectivity of wetland, localized factors (e.g., surrounding land use, buffers)
		Increase in overwinter survival of hemlock woolly adelgid	Immediate	
		Increased physiological stress, resulting in increased susceptibility to pests and disease, decreased productivity and increased mortality	Immediate	
		Increased evapotranspiration, resulting in a decrease in soil moisture; this could result in the loss of species that require permanent soil saturation and immersion	Immediate	
		Increased decomposition rate of peatlands/organic material, which, in combination with drier soils and a longer growing season, could lead to significant changes in overall species composition of peatlands and the eventual conversion to a different habitat type (e.g., replacement by more forested wetlands or non-wetland habitats)	Long-term, but localized effects could occur on a shorter timescale	
Increase in extreme storm events (e.g., wind and ice)	High	Increased physical damage and disturbance (swamps in particular are susceptible to windthrow because trees in these habitats tend to be shallowly rooted (New Hampshire Fish and Game 2012 - draft)); this leads to gap formation, which facilitates the spread of invasive species	Immediate	Topography/slope, soil depth, root structure

Table 3-19. Continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Phenology (timing)	High	Longer growing season	Immediate	
		Asynchronous changes in phenology may negatively impact some migratory species and pollinators	Immediate	
		Change in freeze/thaw cycles could disrupt amphibian breeding cycles and impact breeding success	Immediate	
Increase in number of short-term droughts	Medium	Moisture limitation/stress negatively impacts productivity and survival in many species; precipitation-dependent wetlands (and associated species) will be particularly vulnerable	Long-term, but localized effects could occur on a shorter timescale	Ability of soils to retain moisture, groundwater discharge, water depth (shallower water communities are believed to be more vulnerable), size and connectivity of wetland, localized factors (e.g., surrounding land use, buffers), topography/slope
Increase in fire risk	Medium	Fire could erode peat beds and expose mineral substrates, which could favor more tree growth (NEAFWA 2012 draft)	Long-term, but localized effects could occur on a shorter timescale	
Changing precipitation patterns	Medium	Changes in duration and seasonality of flooding; eventually this could lead to localized shifts in vegetation composition and structure (e.g., longer durations of immersion could result in the replacement of shrub swamp by emergent wetlands) (Whitman et al. 2010)	Immediate	
		Could shorten or lengthen effective hydroperiods, which impacts amphibian breeding success (lengthening would be beneficial; shortening would be detrimental)	Immediate	

3.4.3 Non-climatic stressors

Non-climatic, "traditional" stressors (e.g., habitat loss and fragmentation) are expected to pose a greater threat to freshwater marshes and shrub swamps than climate change (Manomet & NWF 2012a). The 2005 Vermont Wildlife Action Plan notes that habitat alterations, degradation and conversion can be harmful to amphibians, which rely on connectivity/movement corridors to get to and from breeding, feeding, and seasonal habitats (Kart et al. 2005). It is possible that beavers, which are expanding their range, may mediate some climate-related impacts (Appendix 3B).

3.4.4 Major unknowns/research needs

The following were cited as major unknowns that could potentially play an important role in shaping how wetlands are impacted by climate change:

- Our inability to accurately project changing precipitation patterns
- Hydrology of wetlands (groundwater-surface water interactions)
- Nutrient cycling/chemistry (will fens stay alkaline?)
- Cloud cover
- CO2 fertilization
- Biological interactions
- Impact of changing ice dynamics

3.5 Rivers

At the workshop, assessments of the impacts of climate change on physical processes were made for three stream types: high gradient/high elevation/headwater, moderate gradient and low gradient. As described in Section 3.2.1, these stream types represent a merging of geomorphic and biological classification schemes (for more details, see Appendix 3D). While this classification scheme may be adequate for assessing impacts of climate change on physical processes, it may not adequately account for biological considerations. During a follow-up expert elicitation exercise, a group from VT Fish & Wildlife assessments felt that small streams should be split into at least 3 classes when assessing biology: Lake Champlain (high pH and ANC), low gradient marsh and high gradient/coldwater/high elevation (Appendix 3K). More work will need to be done to reach agreement on appropriate stream classification/s to use in light of climate change.

3.5.1 Climate change vulnerability ratings

Our climate change vulnerability ratings were based primarily on regional results (U.S. EPA2013a, in progress), results from other states (Table 20), literature and expert elicitation. During the July 9th workshop, the effects of climate change on the following physical stream processes were assessed for the 3 stream types:

- Stream, Riparian, and Floodplain Connectivity
- Sediment Regime

- Hydrologic Regime
- Temperature Regime
- Large Wood and Organics Regime

Appendix 3J contains the completed worksheets, along with a follow-up assessment by a group from VT Fish & Wildlife on ecological impacts of climate change on small streams. Although all of these results were utilized, more weight was placed on the sources cited above because they are more comprehensive and capture additional aspects of how climate change is likely to impact stream ecology. Results presented here warrant closer review by experts in Vermont and should be regarded as a first step, not a final product.

- **Most likely to be negatively affected**:
  - Coldwater habitats with the following types of natural characteristics will likely be most vulnerable to increasing temperatures:
    - poor shading
    - south-facing
    - little or no groundwater influence
    - low to mid elevation streams with poor connectivity
    - located in southern Vermont (latitudinal influence) or the Champlain Valley, which is warmer and drier than other parts of the state (Figure 11)
  - Small to medium-sized streams with little or no groundwater influence will likely be most vulnerable to extended summer low flow periods and drought
  - Flat low elevation streams are likely to warm faster than streams with steep gradients (Loarie et al. 2009, Isaak and Rieman 2013)
  - Streams in steep catchments with low capacity to absorb water (e.g., via floodplains, wetlands, open water) will likely be most vulnerable to flooding
  - Cold water species like brook trout, slimy sculpin, eastern pearlshell mussel, Appalachian brook crayfish and coldwater macroinvertebrates (Appendix 3L).

- **Most likely to benefit (high confidence)**:
  - Warm-adapted species
  - Invasive species like Japanese knotweed (*Fallopia japonica*)
  - Species that have a high capacity to adapt to high levels of disturbance

All streams will be affected by climate change because stream processes are closely tied to temperature and hydrology, but coldwater habitat in particular is expected to be highly vulnerable to climate change (Table 20). Based on Olivero and Anderson's 2008 regional freshwater aquatic habitat classification scheme, Vermont's streams are mostly cold and coolwater (Figure 12). When assessing the vulnerability of coldwater habitats to climate change, it is important to remember that localized factors such as groundwater influence, stream shading and stream size can mediate increases in water temperature associated with increasing air temperatures (Manomet & NWF 2012b).

It is also important to consider actual temperature values and how these relate to thermal tolerance limits of aquatic organisms (where such information is available). Regional thermal tolerance values are now available for more than 300 aquatic macroinvertebrates (U.S.

EPA2013a, in progress) (Appendix L). It seems likely that more organisms will be closer to their thermal tolerance limits in transitional coolwater versus the coldest coldwater streams; thus greater compositional changes may occur in these transitional areas.

Table 20. Results of vulnerability assessments from other states that pertain to running waters.

State	Community	Vulnerability
Manomet & NWF 2012b	Coldwater fish habitat	Not rated
New Hampshire (New Hampshire Fish and Game 2012)	River shores	Moderate-high
	Warm rivers	Low
	Cold rivers	High
Maine (Whitman et al. 2010)	Rivers and streams	High
Massachusetts (Manomet 2010b)	Coldwater rivers and streams	High
Connecticut (2010)	Coldwater streams and associated riparian zones	High
	Major rivers and associated riparian zones	High
	Warm water streams and associated riparian zones	Medium

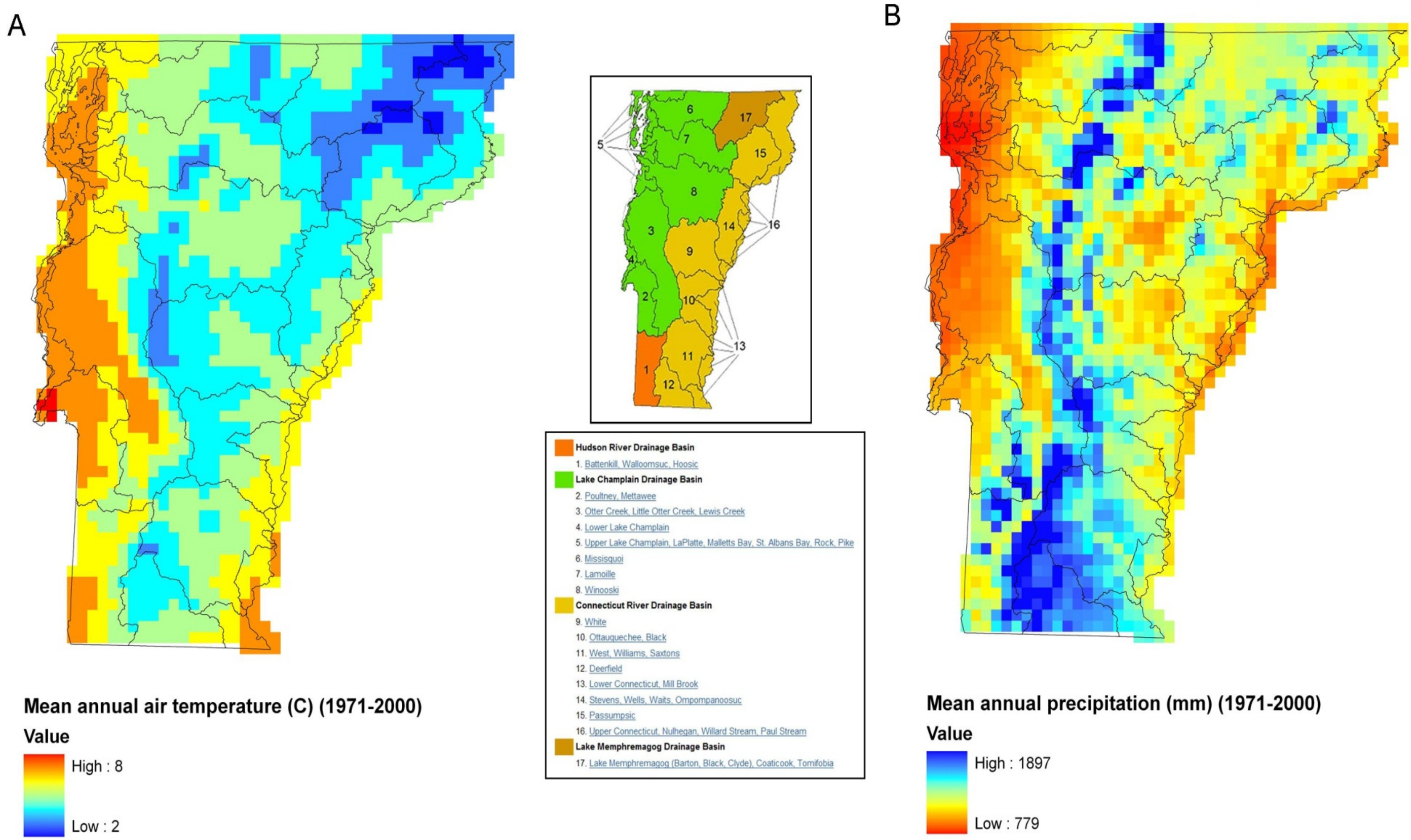

Figure 11. Maps of (A) PRISM mean annual air temperature (°C) (1971-2000) and (B) PRISM mean annual precipitation (mm) in Vermont DEC's 17 watershed planning basins (VT DEC 2013).

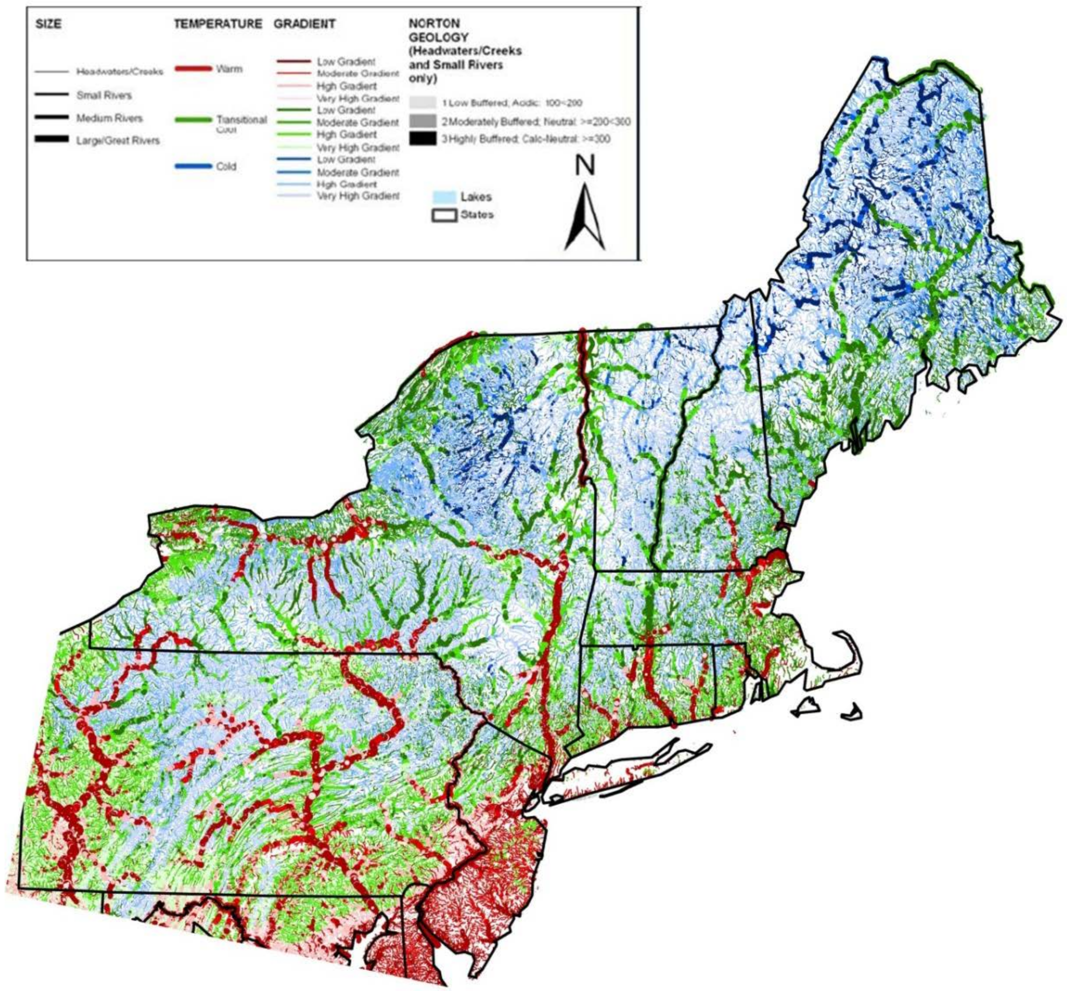

Figure 12. Map of the regional aquatic freshwater classification scheme, which is based on stream size, gradient, geology and temperature (Olivero and Anderson 2008).

It is also important to evaluate flow conditions in combination with temperature, especially when hotter than normal temperatures occur in combination with drought (low flow) conditions (Van Vliet et al. 2011). This is one of the scenarios that U.S. EPA and Tetra Tech evaluated when conducting a vulnerability assessment of watersheds in the Northeast (Figure **13**). Results indicate that streams in the Champlain Valley may be more vulnerable to a low flow/warming temperature scenario, mainly because this area is warmer and drier than other parts of the state (Figure 11). In regards to baseflow, Vermont generally rates in the middle when compared to other Northeastern states (Figure 14), with some exceptions, like the Battenkill and Dog, which are known for their strong groundwater influence.

U.S. EPA and Tetra Tech also evaluated a scenario of increased peak flow events. Patterns of peak flows are complex over space and time, and no spatially explicit modeling projections are available for this exposure. Because of these data limitations, each catchment was assumed to have an equal chance of being exposed to extreme high flows, which can occur at any time of the year. Parameters related to water input and water storage capacity were evaluated. These included mean (terrestrial) slope of the catchment (Figure 15A), percent open water and wetland (Figure 15B). Percent non-developed floodplain was also evaluated (Figure 16). Results indicate that Vermont is generally more vulnerable than other Northeastern states to flood events, based on topography and land cover. Intact floodplains can help dampen the impacts of flood events, as was demonstrated along Otter Creek during Irene (VANR 2011).

Vulnerability to shifts in the timing of winter/spring runoff was also assessed. Snow water equivalent (SWE)[1] projections (Hayhoe et al. 2007) were used to identify areas where the rain/snow line is expected to shift by the greatest amount. It was hypothesized that this will likely correspond with areas of greatest change in the timing and amount of spring runoff, and that aspect/orientation will play an important role as well. Based on the results, south-facing watersheds in southeastern and central Vermont are likely going to experience (or may already be experiencing) the greatest amount of change (Figure 17).

[1] SWE is the amount of water contained within the snowpack. It can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instantaneously

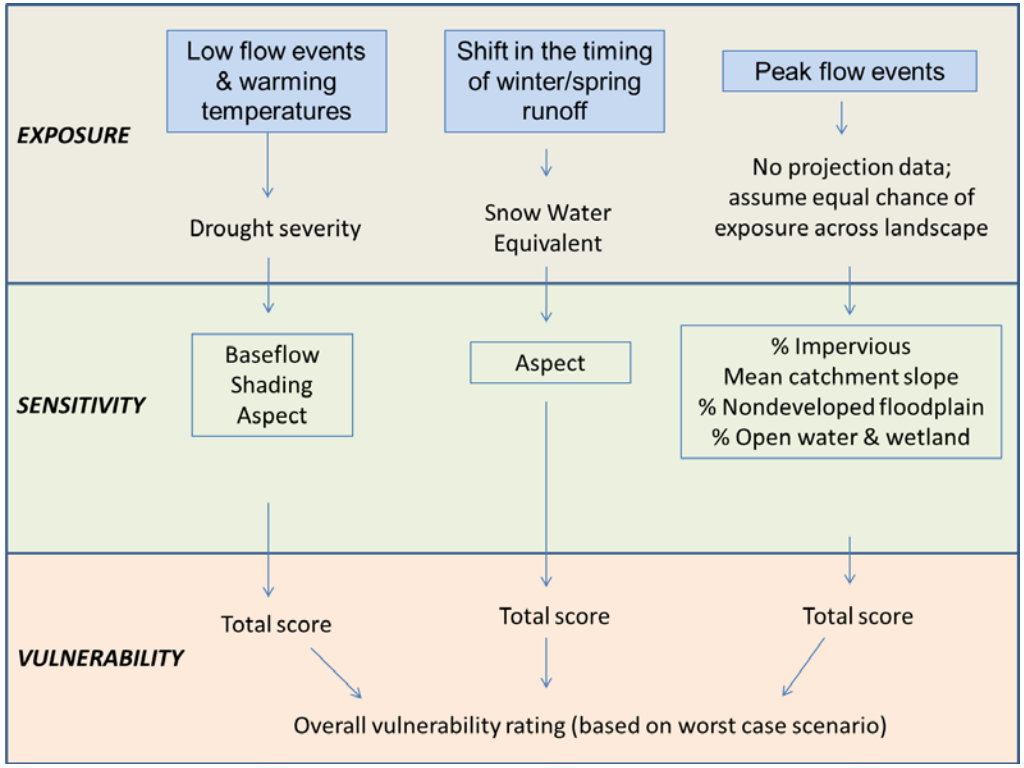
EXPOSURE
Low flow events & warming temperatures
Shift in the timing of winter/spring runoff
Peak flow events
Drought severity
Snow Water Equivalent
No projection data; assume equal chance of exposure across landscape
SENSITIVITY
Baseflow
Shading
Aspect
Aspect
% Impervious
Mean catchment slope
% Nondeveloped floodplain
% Open water & wetland
VULNERABILITY
Total score
Total score
Total score
Overall vulnerability rating (based on worst case scenario)

Figure **13**. Flow diagram showing the different sets of exposure and sensitivity variables that were considered in U.S. EPA's watershed-level

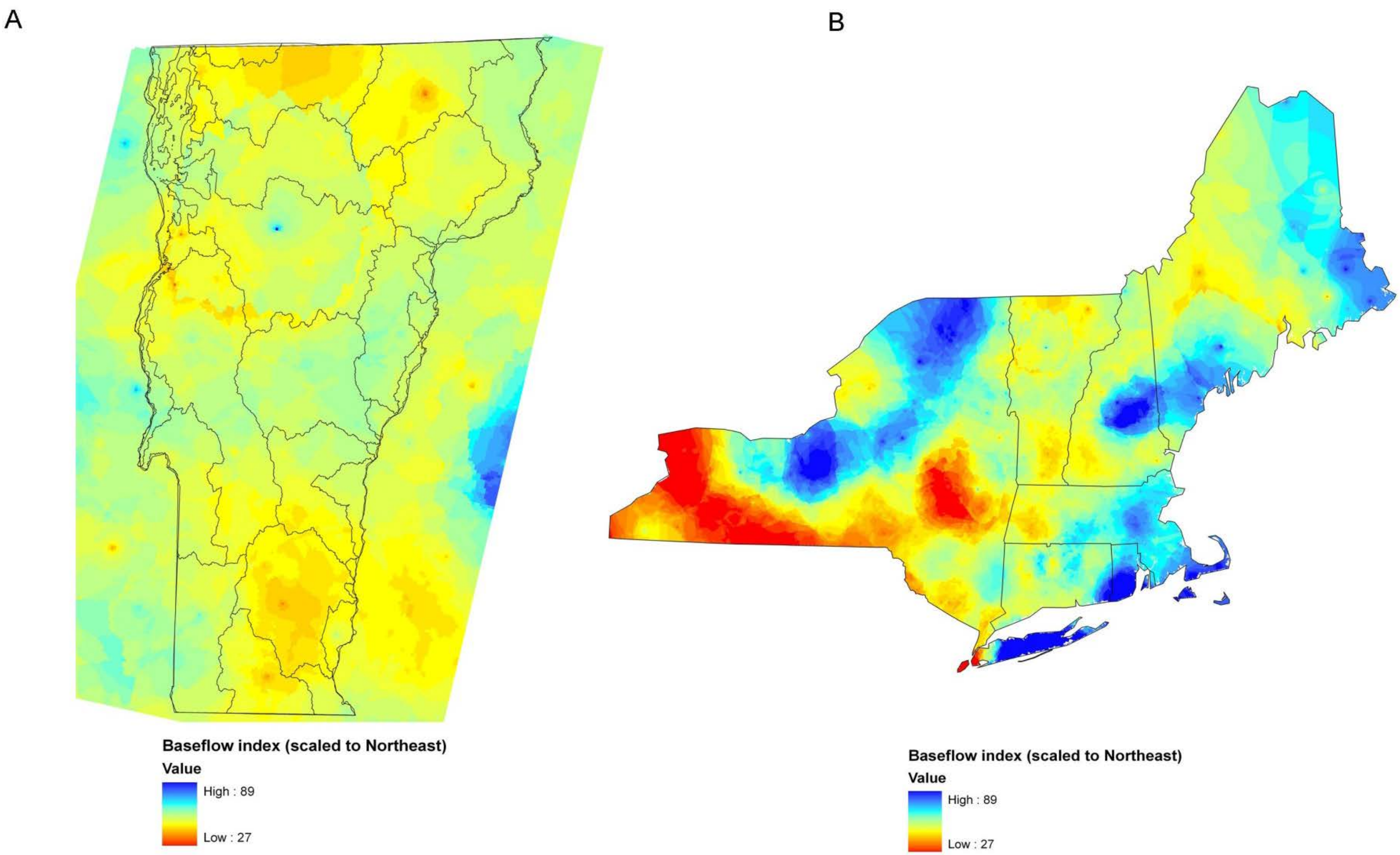

Figure 14. Baseflow index (source: Wolock 2003) in (A) Vermont DEC's 17 watershed planning basins (VT DEC 2013) and (B) the Northeast.

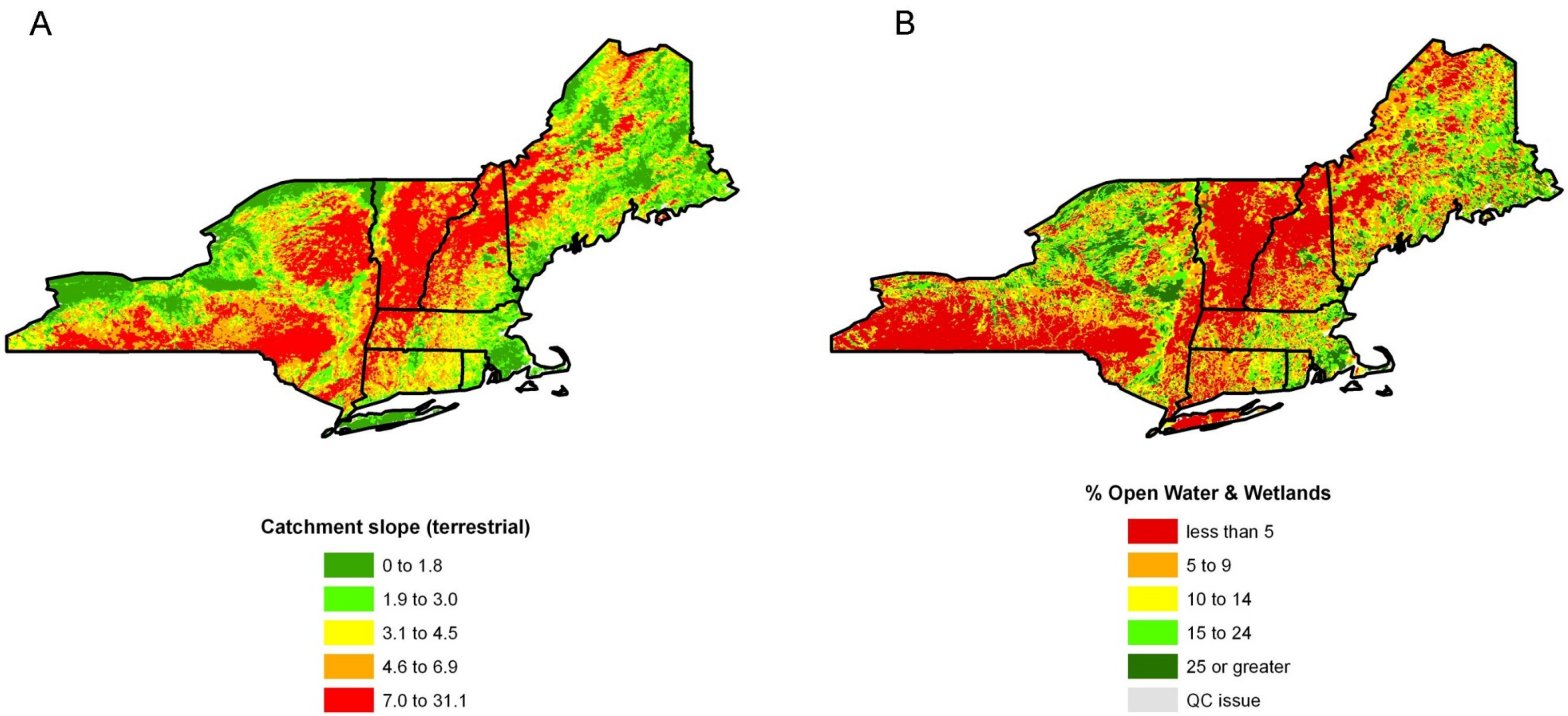

Figure 15. Map of: A) mean local catchment slope as calculated by TNC from the USGS NED 30m digital elevation model (http://ned.usgs.gov/) (source: Olivero and Anderson 2008); and B) % open water and wetlands (source: NLCD 2001 land cover data associated with NHDPlus catchments (local+upstream) (Horizon Systems 2012)).

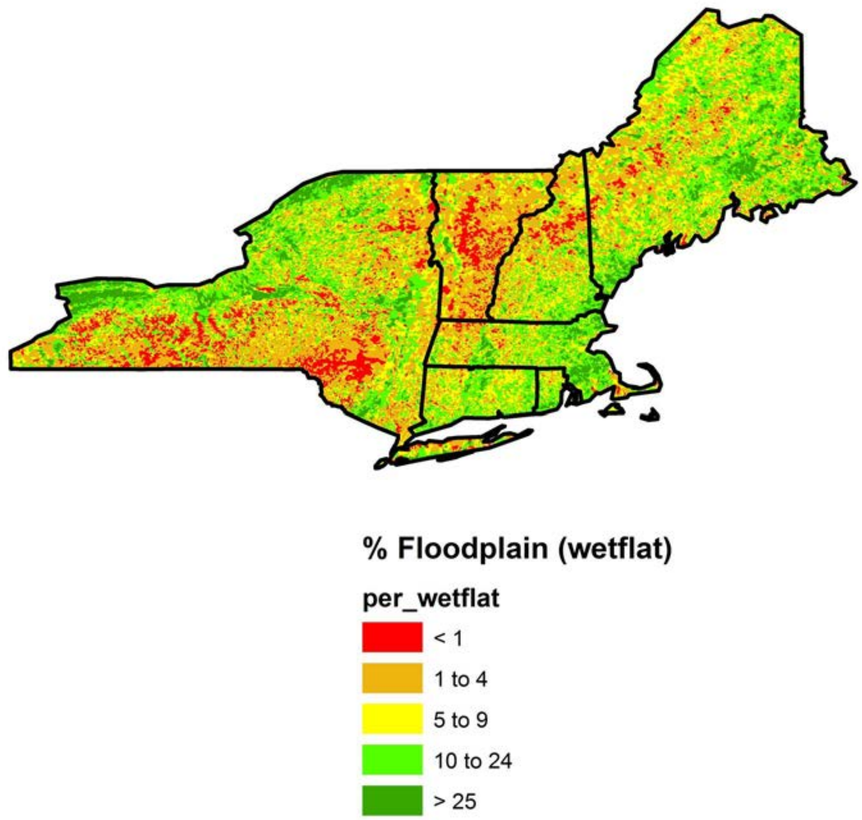

Figure 16. Percent floodplain (wet-flat) in NHDPlus local catchments (source: active river area GIS layer (Smith et al. 2008)).

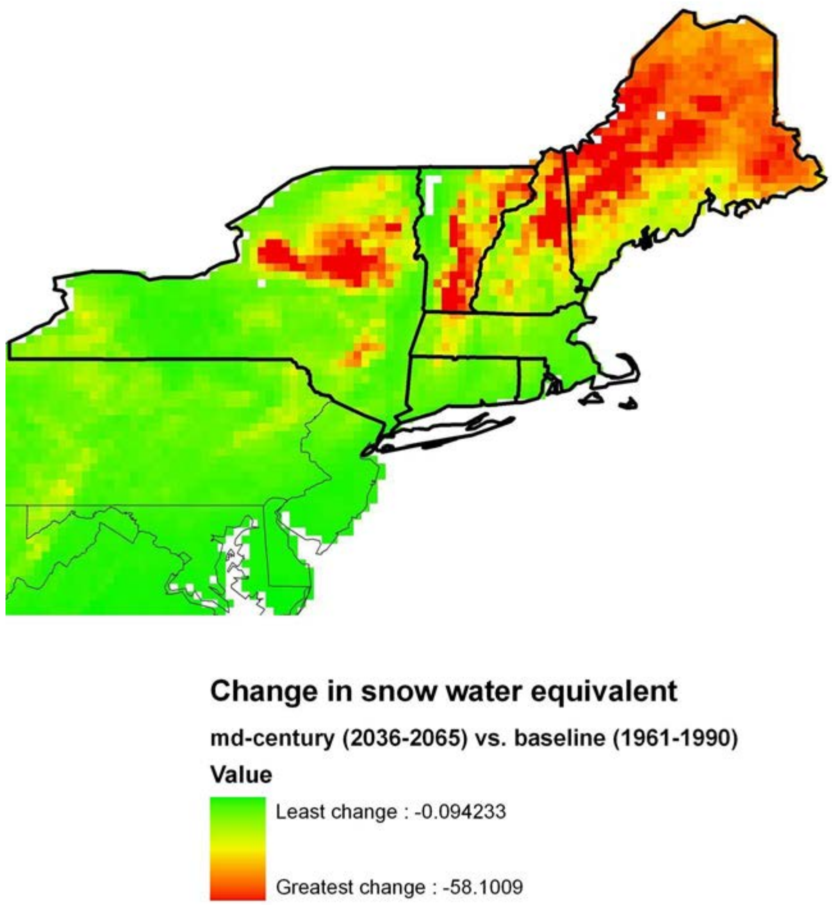

Figure 17. Map of projected change in snow water equivalent [(2036-2065)-(1961-1990), under the high (a1) emissions scenario; average of HadCM3 and PCM models]. Data provided by Justin Sheffield, Princeton University.

3.5.2 Mechanisms by which climate change is expected to impact rivers

Although the vulnerability ratings are important, it is also important to understand the mechanisms leading to the ecological effects, as this will help inform adaptation strategies. Table 21 provides a summary of mechanisms by which climate-related factors are expected to impact running waters in Vermont. In addition, a summary of expected effects of key climate factors on physical processes that shape stream ecosystems can be found in Table 22. This is based largely on input that was received during the July 9th workshop. Climate change can influence thermal and hydrologic regimes via a number of complex pathways. The bulleted text below highlights several commonly cited themes in the literature and vulnerability assessments that were reviewed.

- Compositional changes associated with rising temperatures/changes in thermally suitable habitat, resulting in the eventual loss of cold-adapted species and an increase in warm-adapted species.
- Increased physiological stress from heat and/or water limitation, resulting in increased susceptibility to pests and disease, decreased productivity and increased mortality.
- Increased physical damage and disturbance from extreme storm events (e.g., wind and ice), which facilitates the spread of invasive species.

The following pathways related to extended summer low flow conditions are affected in part by precipitation, thus they are more uncertain:

- Reduction in amount of wetted habitat (edge habitat in particular), which leads to more predation and more competition for limited resources.
- Reduced dissolved oxygen (particular when low flow conditions occur in combination with warm temperatures) which causes physiological stress and in some instances, mortality.
- Decrease in water quality due to concentration of toxins.

The timing of flow events is critical ecologically because the life cycles of many aquatic and riparian species are timed to either avoid or exploit flows of variable magnitudes (Poff et al. 1997). Figure 18 depicts the close link between salmon life cycle events and annual flow cycle in Maine. Conceptual diagrams depicting additional pathways by which climate change can impact streams can be found in Appendix 3M, and additional resources describing potential impacts of climate change on rivers can be found in Appendix 3N.

Table 21. Expected effects of key climate factors on running waters. Sensitivity factors are factors that will lessen or worsen the degree of impact. Some are naturally occurring and cannot be altered (e.g., elevation, latitude), while others can be influenced by human factors (e.g., shading/riparian buffer).

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors (+/-)
Warming temperatures	High	Loss of cold water (in-stream) habitat, resulting in compositional changes (loss of cold-adapted species like brook trout, slimy sculpin and eastern pearlshell) and increase in warm-adapted species).	Long-term, but localized effects could occur on a shorter timescale	Orientation (north/south facing), topography/slope, latitude, elevation, groundwater influence, shading, watershed size, color, localized factors (e.g., surrounding land use), connectivity (ability for organisms to disperse locally and regionally), availability of refugia, warming from human constructed impoundments
		Increase in overwinter survival of hemlock woolly adelgid, resulting in loss of riparian shading	Immediate	
		Increased physiological stress, resulting in increased susceptibility to pests and disease, decreased productivity and increased mortality	Immediate	
		Increased evapotranspiration, resulting in a decrease in soil moisture in riparian areas (and potentially in a decrease in the water table); certain organisms are particularly vulnerable to moisture limitations	Immediate	
		Complex, interacting changes in stream productivity (primary productivity, respiration, decomposition) and function	Immediate	
		Changing metabolic rates, physiology, and life-history traits of aquatic species	Immediate	

Table 3-21. Continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Extended summer low flows/increase in short-term droughts	Medium	Reduction in amount of wetted habitat (edge habitat in particular), which leads to more predation and more competition for limited resources	Immediate to long-term	Groundwater, watershed size, underlying geology, type and size of tributary streams, degree of channel alteration, surrounding land use (e.g., impervious cover)
		Loss of connectivity with the riparian zone and potentially within the channel (e.g., channel-pools may become disconnected from riffles due to drying), which affects inputs into the stream (e.g., large woody debris, leaf litter) and processing of those inputs		
		Increased accumulation of fine sediments in the channel, which could impact species with life stages that are sensitive to sedimentation (e.g., eggs and larvae of many invertebrates and fish require flushing flows to remove and transport fine sediments that would otherwise fill the interstitial spaces in productive gravel habitats (Poff et al. 1997))	Immediate to long-term	Groundwater, watershed size, underlying geology, type and size of tributary streams, degree of channel alteration, surrounding land use (e.g., impervious cover), effluent from waste water treatment plants
		Reduced dissolved oxygen (particular when low flow conditions occur in combination with warm temperatures) which causes physiological stress and in some instances, mortality		
		Changes in algal dynamics (e.g., composition, frequency of blooms (more blooms are likely to occur when low flow conditions occur in combination with warm temperatures), which affects dissolved oxygen dynamics (e.g., diurnal flux)		
		Decrease in water quality due to increased concentration of pollutants and toxins (e.g., from waste water); also, changing temperature and flow conditions can affect the toxicity of some substances (e.g., ammonia)		

Table 3-21. Continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Increase in heavy rainfall events & flooding	High	Increased mortality (some organisms, like mussels, could be physically crushed, buried and/or dislodged into the riparian area)	Immediate	Availability of refugia, infiltration/capacity of catchment to absorb water (e.g., open water and wetlands, accessibility of floodplain), topography/slope, watershed size, erodibility of soils, soil saturation, bedrock control, vegetation, localized factors (i.e. surrounding land use (e.g., impervious surface, degree of encroachment, buffers)), timing of events relative to phenology, location of and design of infrastructure (e.g., culvets, bridges), human maladaptive response (i.e. instream channel manipulation following floods)
		Scour could negatively impact long-lived species that are slow to recolonize (e.g., mussels, mosses); impacts on fish and macroinvertebrates would be shorter-lived (e.g., 1-year)	Immediate	
		Facilitates spread of invasive species like knotweed	Immediate	
		Natural channel/geomorphic adjustments (i.e. channel widening, channel incision) could be beneficial or detrimental to aquatic habitat , depending on the organism and localized conditions (e.g., channel widening could lead to a decrease in riparian shading and LWD input; in the short term, channel incision could decrease the frequency of floodplain access during moderate flood events, resulting in higher power/scouring flooding and longer intervals between disturbance events that maintain floodplain/riparian habitats). Depending on the pace of climate changes and if/when climate re-stabilizes, rivers may eventually complete an adjustment process, leading to a less erosive, more stable form that includes beneficial floodplain access. Timeframe: immediate to long term.	Immediate	
		Increase in large woody debris inputs, which could be beneficial or detrimental, depending on the organism and localized conditions (Langford et al. 2012)	Immediate	
		Changes in water quality; these could be detrimental in some cases (i.e. more stormwater runoff means more nutrient, sediment and toxin loading flowing into receiving lakes) and beneficial in others (e.g., more dilution, flushing of sediments, benthic algae could benefit).	Immediate	

Table 3-21. Continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Increase in heavy rainfall events & flooding	High	Mobilization of legacy sediments, thus impacting sediment and hydrologic regimes	Immediate	Infiltration, refugia, erodibility, topography, slope
		As channels widen in response to water and sediment inputs, waters will become shallower	Immediate	
Increase in wind and ice storms	High	Increased physical damage and disturbance to riparian zone, which facilitates the spread of invasive species	Immediate	Topography/slope, soil depth, root structure, timing of storm relative to forest phenology
		Increase in large woody debris inputs (could be beneficial or detrimental, depending on the organism and localized conditions (Langford et al. 2012))		
Phenology (timing)	High	Earlier spring runoff in combination with warmer spring temperatures impact aquatic insect emergence, breeding cycles and migration	Immediate	
		Asynchronous changes in phenology may negatively impact some species	Immediate	
		Changes in timing of leaf off (and also potentially in the species of trees contributing leaf litter) will affect organisms that process leaf litter, and also affect impacts from storm events (i.e fewer leaves means that water will be delivered to the channel faster; more leaves means more trees will break crowns under heavy snow/ice loads)	Immediate	

Table 22. Expected effects of key climate factors on physical processes that shape stream ecosystems (adapted from Milone & MacBroom, Inc. 2008).

Physical process	Description	Links with stream ecology	Vulnerability to key climate factors
Temperature Regime	The daily and seasonal instream water temperatures influenced by climate, riparian canopy, hydrologic regime (particularly groundwater components), and valley and stream morphology and aspect	Temperature influences metabolic rates, physiology, and life-history traits, helps to determine rates of important community processes such as nutrient cycling and productivity, and affects overall ecosystem functioning (Allen 1995, Poole and Berman 2001)	Temperature (annual, seasonal, extremes, variability), exacerbated by extended summer low flows and droughts
Hydrologic Regime	The timing, volume, and duration of flow events throughout the year and over time, which may be influenced by the climate, soils, geology, groundwater, watershed land cover, connectivity of the stream, riparian, and floodplain network, and valley and stream morphology	The life cycles of many aquatic and riparian species are timed to either avoid or exploit flows of variable magnitudes. The natural timing of high or low streamflows provides environmental cues for initiating life cycle transitions in fish, such as spawning, egg hatching, rearing, movement onto the floodplain for feeding or reproduction, or migration up-stream or downstream. Species with life stages that are sensitive to sedimentation (e.g., eggs and larvae of many invertebrates and fish) require high flushing flows to remove and transport fine sediments that would otherwise fill the interstitial spaces in productive gravel habitats (Poff et al. 1997).	All precipitation and flow-related parameters
Stream, Riparian, and Floodplain Connectivity	The unimpeded movement of materials (water, sediment, and organic material) and organisms both longitudinally up and down the watershed and vertically between the stream channel and its riparian area and floodplain	Important for refugia (e.g., from floods or high temperatures), breeding and nursery grounds, terrestrial and aquatic organism interactions and exchange of nutrients and organic matter (Elosegi et al. 2010)	Flood events could increase connectivity (which could be beneficial); extended summer low flows could result in a loss of connectivity; uncertain about impacts of changing ice dynamics

Table 3-22. Continued…

Physical process	Description	Links with stream ecology	Vulnerability to key climate factors
Sediment Regime	The size, quantity, sorting, and distribution of sediments, which may differ between stream types due to their proximity to different sediment sources, their hydrologic regime, their stream, riparian and floodplain connectivity, and valley and stream morphology	Sediment can be beneficial or detrimental to fish and aquatic macroinvertebrates by either providing or polluting habitat; this outcome depends on the timing of delivery, the volume, and the caliber of the sediment, which are contingent on the basin-specific processes and sources that generate sediment (Goode et al. 2012)	Precipitation and flow-related parameters can have direct effects; changes in temperature and hydrology that promote vegetation disturbances (e.g.,, wildfire, insect/pathogen outbreak, drought-related die off) could increase sediment yield (Goode et al. 2012)
Large Wood and Organics Regime	The diversity, quantity, and physical retention of organic material available for biological uptake and physical refugia (moderating the expenditure of energy), which may be influenced by the primary productivity within the stream channel and riparian zone, watershed and floodplain connectivity, the hydrologic regime, and the stream and valley morphology	Can provide high-quality habitat (or in some cases, food), important for hydraulic, nutrient and organic matter retention (Elosegi et al. 2010); can have conflicting effects on stream fish populations (Langford and Langford 2012)	Could see increased contributions from floods, extreme storms (e.g., ice and wind), fires; precipitation and flow-related parameters affect transport

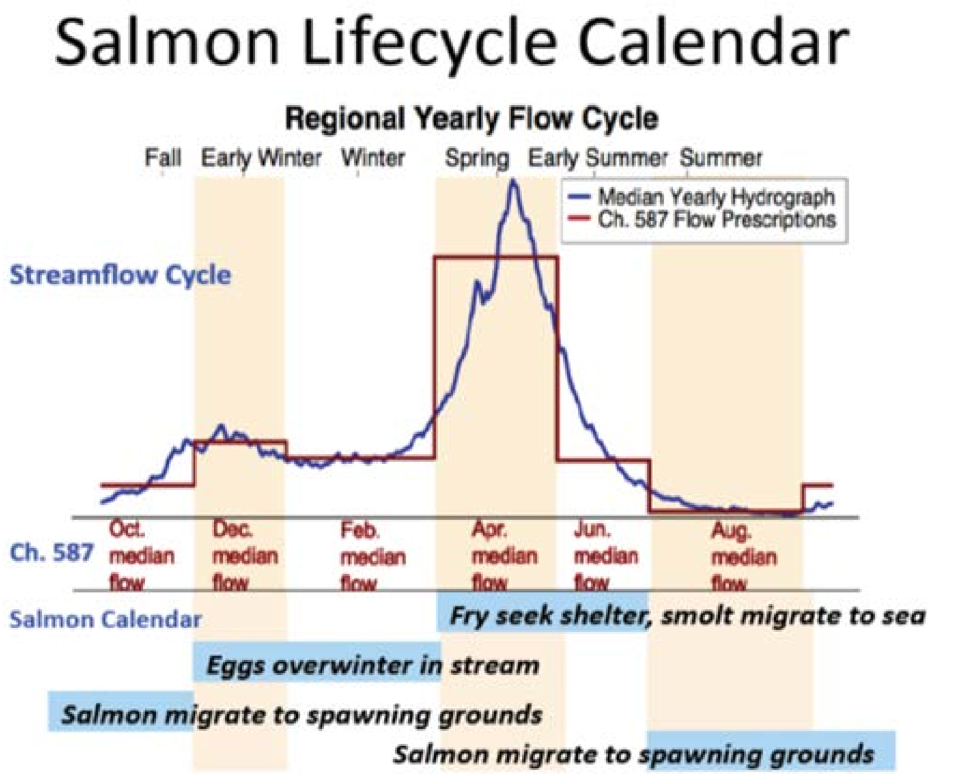

Figure 18. Salmon life cycle plotted in relation to yearly flow cycle (Ricupero 2009).

3.5.3 Non-climatic stressors

Vermont's Surface Water Management Strategy has identified and developed strategies for addressing 10 stressors that are having the greatest negative impact on Vermont's aquatic ecosystems (VT DEC 2013). These include:

- Invasive species
- Channel erosion
- Encroachment
- Land erosion
- Thermal stress (certain land uses, activities, discharges, and the physical condition of the aquatic ecosystem can influence water temperatures beyond natural variation)
- Acidity
- Toxic substances
- Flow alteration
- Non-erosion nutrients
- Pathogens

The increase in heavy rainfall events and flooding that are projected to occur with climate change are likely to exacerbate the spread of invasive species, erosion, and the influx of nutrients, sediments and toxins, and warmer air temperatures will likely worsen thermal stress. Warmer temperatures in combination with extended summer low flow periods will affect the toxicity of substances like ammonia.

Regarding impacts on hydrology, based on a case study in the Piedmont, land use effects are likely going to predominate over climate change effects under high flow scenarios, and climate change will predominate over land use under low flow scenarios (U.S. EPA 2012a). While it is not a great concern at this time, in the future, extended summer low flow conditions could be exacerbated by water withdrawals. Figure 19 shows which towns in Vermont are projected to experience the greatest percent changes in withdrawals of groundwater from 2005 to 2020 (Medalie and Horn 2010). In Vermont's Wildlife Action Plan (Kart et al. 2005), habitat alteration and degradation are identified as threats to aquatic communities. Habitat alteration/degradation following Irene have had negative impacts on fish populations (VFWD 2012).

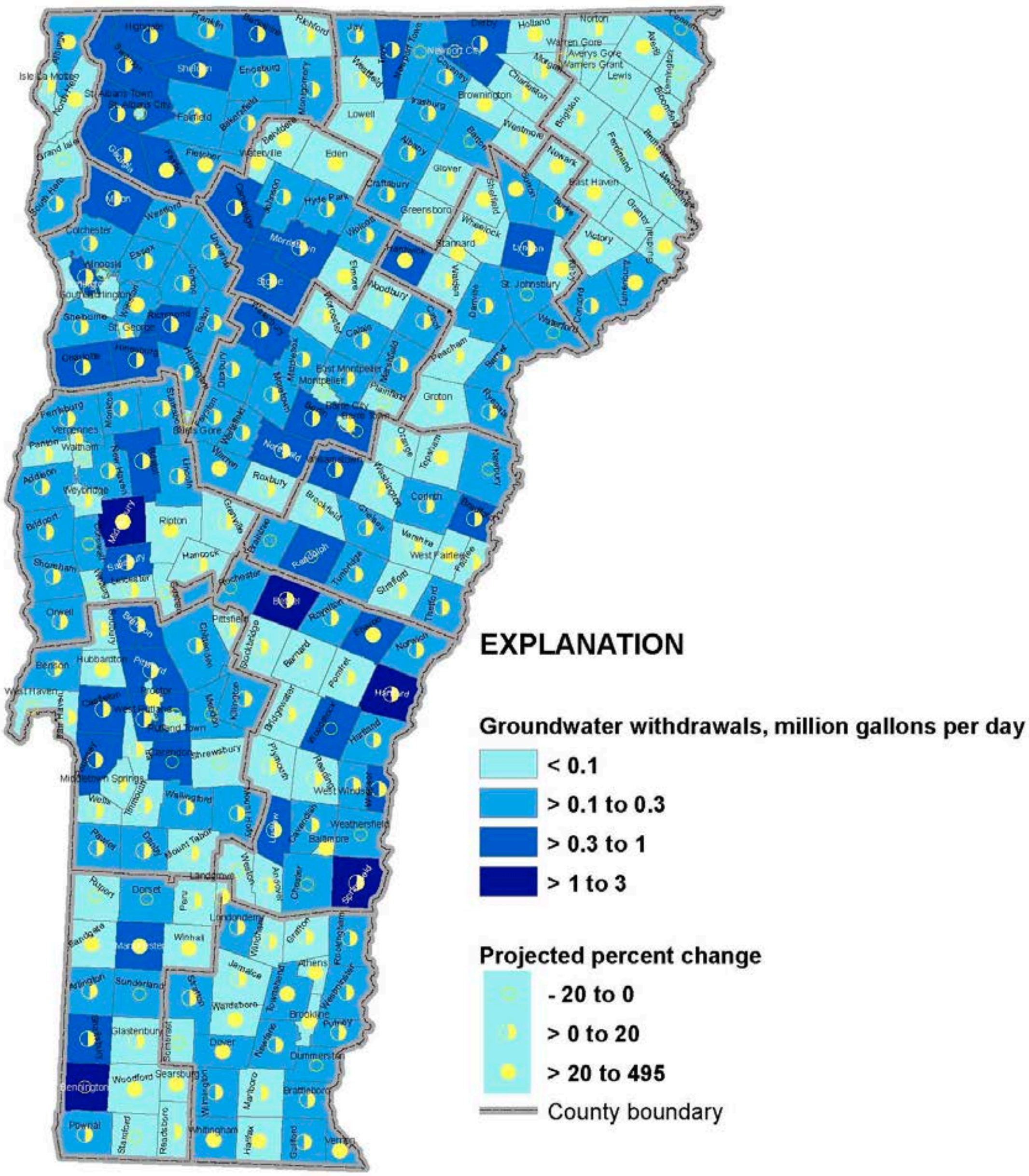

Figure 19. Withdrawals of groundwater in Vermont in 2005 and projected percent changes in withdrawals of groundwater from 2005 to 2020 (from Medalie and Horn 2010).

3.5.4 Major unknowns/research needs

The following are major unknowns and/or research needs that could potentially play an important role in shaping how rivers are impacted by climate change:

- Inability to accurately project changing precipitation patterns.
- Lack of continuous water temperature and flow data.
- Lack of understanding of groundwater-surface water interactions and the State's groundwater resources.
- Lack of understanding of how conditions from past years affect current conditions ("lag year effects").
- Lack of understanding of how changes in the timing of winter-spring streamflow will affect macroinvertebrates that are collected by biomonitoring crews during their late summer/fall index period.
- Nutrient cycling.
- Biological interactions.
- Impacts of changing ice dynamics on aquatic ecosystems.
- Impacts of changing large woody debris inputs on aquatic ecosystems.

3.6 Lakes

At the workshop, assessments of the impacts of climate change on overall lake function were made for two lake types: stratified and unstratified. This is consistent with the approach that was used by New Hampshire Fish and Game (2012). Stratified lakes develop a thermocline, which separates warm surface waters from colder, deeper water (referred to as the hypolimnion). In the winter, the temperature profile becomes more uniform, as the lakes 'turn over,' with the slightly warmer denser water shifting to the bottom, and ice usually forming on the surface. Only a subset of lakes and ponds that stratify have enough oxygenated cold water below the thermocline to provide suitable habitat for aquatic species such as lake trout (these are sometimes referred to as 2-story fisheries). These are large, deep oligotrophic or mesotrophic lakes, and include Lake Champlain.

While this classification scheme may be adequate for assessing impacts of climate change on overall lake function, it may not adequately account for biological considerations. During a follow-up expert elicitation exercise, a group from VT Fish & Wildlife used a different scheme: Dystrophic-High Elevation Acidic; Mesotrophic/Eutrophic stratified & unstratified; and Oligotrophic Lakes – stratified (Appendix 3O). More work will need to be done to reach agreement on appropriate lake classification/s to use in light of climate change.

3.6.1 Climate change vulnerability ratings

Our climate change vulnerability ratings were based primarily on results from other states (Table 23), literature and follow-up expert elicitation exercises by VT DEC. Completed worksheets from the July 9th workshop and from a follow-up exercise by VT Fish & Wildlife can be found in Appendix 3O. Results presented here warrant closer review by experts in Vermont and should be regarded as a first step, not a final product.

- **Most likely to be negatively affected**:
  - Coldwater species in smaller stratified lakes and ponds that lack extensive deep water habitat and have:
    - poor shading
    - little or no groundwater influence
    - low to mid elevation
    - located in southern Vermont (latitudinal influence) or the Champlain Valley, which is warmer and drier than other parts of the state (Figure 11)

- **Most likely to benefit**:
  - Warm-adapted species like alewives (Stager and Thill 2010)
  - Invasive species

Two factors that will strongly influence how individual lakes respond to climate change are:

- **Where the lake gets its water from -** lakes can receive water from precipitation, surface runoff (streams and rivers) and groundwater
- **Where it is positioned in the landscape -** lakes higher in the landscape receive a larger percentage of their incoming water from precipitation than lakes lower in the landscape, and thus are more sensitive to drought (Kratz et al. 2006

Table 23. Results of vulnerability assessments from other states that pertain to lake habitat types.

State	Community	Vulnerability
New Hampshire (New Hampshire Fish and Game2012)	Stratified lakes	Moderate-high (depending on size)
	Coldwater ponds	Moderate-high
Maine (Whitman et al. 2010)	Freshwater lakes and ponds	High
Massachusetts (Manomet 2010b)	Large coldwater lakes	Moderate-high
	Smaller coldwater lakes and ponds	Critically high
	Coldwater kettle ponds	Moderate
	Warmwater ponds and lakes	Likely to benefit
Connecticut (2010)	Lakes, ponds, impoundments and shorelines	Moderate

3.6.2 Mechanisms by which climate change is expected to impact lakes

Although the vulnerability ratings are important, it is also important to understand the mechanisms leading to the ecological effects, as this will help inform adaptation strategies. Climate change will have both direct and indirect effects on lakes. Table 24 provides a summary of mechanisms by which climate-related factors are expected to impact lakes in Vermont. The bulleted text below highlights commonly cited themes in the literature (e.g., Brooks and Zastrow 2002) and from the expert elicitation exercises:

- Compositional changes associated with changes in thermally suitable habitat (loss of cold-adapted species and increase in warm-adapted species)
- Increased hydrologic and nutrient loading, including increased intensity and seasonality of runoff
- Altered habitat and nursery function of littoral zones
- Longer growing seasons will allow for greater annual primary production in littoral areas, more organic matter accumulation, and greater macrophyte growth
- Increase in algal blooms, especially when warm temperatures occur in combination with low flow/low lake level and nutrient-rich conditions
- Complex changes in the food web

Predicting the effects of climate change on lakes is very challenging due to localized factors, complexities associated with stratification and mixing patterns and knowledge gaps. Some of the complex relationships between increasing temperatures and biological responses in stratified lakes and littoral habitats are depicted in conceptual diagrams in Appendix 3P. Additional resources describing potential impacts of climate change on lakes can be found in Appendix 3Q.

Table 24. Expected effects of key climate factors on lake habitats.

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Warming temperatures	High	Compositional changes associated with changes in thermally suitable habitat (loss of cold-adapted species and increase in warm-adapted species)	Long-term, but localized effects could occur on a shorter timescale	Morphometry (e.g., shape, depth), shading, flushing rate, groundwater, exposure to wind and other factors that promote mixing, cloud cover, elevation, latitude, orientation, topography/slope, soil and sediment type, contributing watershed, localized factors (e.g., impoundments, surrounding land use, buffers, boat traffic), availability of refugia
		Increase in decomposition of algae and zooplankton on the lake bottom, which could increase the chance of late season hypoxia	Immediate	
		Complex changes in the food web, changing biological interactions	Immediate	
		Increase in suitable habitat for some aquatic invasive species	Immediate	
		Altered habitat and nursery function of littoral zones	Immediate	
		Longer growing seasons will allow for greater annual primary production in littoral areas, more organic matter accumulation, greater macrophyte growth and shallowing	Immediate	
		Increase in algal blooms, especially when warm temperatures occur in combination with low flow/low lake level and nutrient-rich conditions	Immediate	
		(Stratified) Increase in average thermocline depth, resulting in the loss of cold, deep water hypolimnetic habitat and the eventual loss of cold-water species such as lake trout	Long-term, but localized effects could occur on a shorter timescale	
		(Stratified) Earlier onset of thermal stratification, which could produce greater hypolimnetic hypoxia at the end of the summer, which would cause mortality and promote greater phosphorus release from the sediments	Immediate	

Table 3-24. Continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Decrease in duration of ice and/or snow cover	High	Reduced albedo will result in greater heat absorption; in stratified lakes, this will contribute to earlier onset of thermal stratification	Immediate	Morphometry (e.g., shape, depth), shading, groundwater,cloud cover, elevation, latitude, orientation, topography/slope, contributing watershed, localized factors (e.g., surrounding land use, buffers)
Extended summer low flows/increase in short-term droughts	Medium	Lower water levels, resulting in sediment exposure and drying, which impairs littoral habitat and promotes mercury methylation; small, shallow lakes are particularly sensitive to drought	Medium to long-term, but localized effects could occur on a shorter timescale	
Increase in heavy rainfall events & flooding	High	(Large, stratified lakes) Very large flood events and associated sediment and nutrient loading could increase turbidity, reduce light penetration with both positive and negative influences on productivity, e.g., increased nutrients vs. reduced light	Immediate	Capacity to absorb water (e.g., surrounding wetlands), topography/slope, watershed size, morphometry (e.g., shape, depth), contributing watershed, shoreline substrate, localized factors (e.g., surrounding land use)
		(Small, shallow lakes) Hydrologically sensitive to individual flood events and associated sediment and nutrient loading	Immediate	
		Facilitates spread of invasive species	Immediate	
		Shoreline erosion, structural damage	Immediate	
		Large woody debris inputs could increase or decrease; potential net loss is likely to occur in poorly buffered shore areas	Immediate	
		Influx of nutrients, sediments and toxins	Immediate	
		Precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use (Haaland et al. 2010), but also may alter the ability of sunlight to inactivate parasites and pathogens in water, by absorbing ultraviolet radiation (UV) that would otherwise be an effective control (Staudinger et al. 2012)	Immediate	

Table 3-24. Continued…

Key Climate Change Factors	Confidence in projection	Ecological Effects	Timeframe	Sensitivity Factors
Increase in heavy rainfall events & flooding	High	Potential for increase in methyl mercury absorption in food chain as reservoir/lake levels are managed in response to precipitation extremes (drought and flood)	Immediate	Topography/slope, watershed size, morphometry, land use (immediately adjacent area & in contributing watershed), shoreline substrate, in-stream impoundments (and types) upstream, In-lake management practices
		More water could increase the assimilative capacity for some pollutants	Immediate	
		Sedimentation could impact reproductive and rearing/larval fish in near shore habitats	Immediate	
		Flooding can give fish access to additional backwater habitats	Immediate	
Increase in extreme storm events (e.g., wind and ice)	High	Storms with high winds could increase shoreline erosion, mainly in large lakes	Immediate	Topography/slope, watershed size, morphometry (e.g., shape, depth), contributing watershed, shoreline substrate, localized factors (e.g., surrounding land use)
Phenology (timing)	High	Warmer spring temperatures affect aquatic insect emergence, breeding cycles and migration	Immediate	
		Asynchronous changes in phenology may negatively impact some species	Immediate	
Fluctuating lake levels	High	Frequency, duration, and timing affect amphibian and reptile breeding success	Immediate	

3.6.3 Non-climatic stressors

As discussed in Section 3.5.3, Vermont's Surface Water Management Strategy has identified and developed strategies for addressing 10 stressors, several of which are likely to be exacerbated by climate change. Increased sediment and nutrient loading in Vermont's lakes is of great concern, as it could accelerate eutrophication and contribute to harmful algal blooms. Nutrient TMDLs have been developed for several of Vermont's lakes. Phosphorus is of particular concern in Lake Champlain (LCBP 2012), as are invasive species, such as zebra mussels, Eurasian milfoil, and the spiny water flea. Degradation of shoreline habitat has also been identified as a major threat to Vermont's lakes (VANR 2011).

3.6.4 Major unknowns/research needs

The following are unknowns that could potentially play an important role in shaping how lakes are impacted by climate change:

- Changes in the timing of ice-in and ice-out will have unknown implications for lake and pond ecosystems
- Cloud cover
- Mixing patterns

3.7 Habitats Not Assessed

Table 25 contains a list of vulnerability ratings assigned to habitats (natural and anthropogenically impacted) that were not assessed during this exercise. These include upland meadows, outcrops, cliffs and talus and various other habitats (e.g., grasslands, urban, early successional). Results for alpine meadows are of particular interest. Alpine meadows are extremely rare in Vermont (Thompson and Sorenson 2000). They occur in 3 locations: Mount Mansfield, Camels Hump and Mount Abraham. Based on the regional assessment, alpine meadows are highly vulnerable to climate change (Manomet & NWF 2012a). In contrast, New Hampshire assigned a rating of low vulnerability to their alpine meadow habitats based on research conducted on Mount Washington (New Hampshire Fish and Game 2012). Vermont should consider assessing some of these additional habitat types in future work.

Table 25. Results of vulnerability assessments from other states that pertain to habitats not assessed at the July 9th workshop.

State	Community	Vulnerability
New Hampshire (New Hampshire Fish and Game 2012) DRAFT	Alpine	Low
	Rocky ridge/talus slopes	Low
	Shrubland	Low
	Grassland	Low
	Caves	In progress
Maine (Whitman et al. 2010)	Alpine	High
	Shrub/early successional and regenerating forest	Low
	Cliff face and rocky outcrops (including talus)	Moderate
	Grassland/agricultural/old field	Low
	Urban/suburban	Low?
	Caves and mines	Low
New York (Galbraith 2012)	Subalpine woodland and shrub	In progress
	Plantation and disturbed land pioneer forests	
	Non-native upland forest	
	Cliff and talus	
	Rocky outcrop	
	Caves and tunnels	
	Native barrens and savanna	
	Non-native shrublands	
	Old field managed grasslands	
	Cultivated crops	
	Pasture-hay	
	Urban and recreational grasses	
	Commercial/industrial and residential	
	Residential rural	
	Surface mining	
	Powerline	
Connecticut (2010)	Early successional shrublands/forests	Low
	Rocky outcrops/summits	Low
	Talus slopes	High

4 ADAPTATION FRAMEWORK

The vulnerability section includes discussions about the habitats and types of species that are most and least vulnerable to climate change effects. The Vermont ANR can prepare for the changes associated with those vulnerabilities by planning and implementing adaptation strategies. This section describes adaptation in general, presents results of the adaptation workshop, and recommends a framework for pursuing individual strategies and an overall adaptation plan.

4.1 Climate Change Adaptation

This section was adapted from work prepared by Staudinger et al. (2012).

4.1.1 What is Climate Change Adaptation?

The Intergovernmental Panel on Climate Change (IPCC) defines adaptation in several ways, all of which include perceived climate change effects and managing natural and human systems to moderate those effects. The definitions of climate change adaption are as follows, the last of which was prepared in a special report on extreme climate events and explicitly separates processes in human and natural systems:

> Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects (IPCC, 2007b).
>
> Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2007a).
>
> In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate (IPCC 2012).

Adaptation is a process in which appropriate management responses to protect valued resources can be identified and carried out. The process happens in the midst of change and must be flexible to continuing incremental change with an intended outcome, though the ultimate outcome is uncertain. Therefore, specific adaptation goals and objectives may be established, but continual reevaluation and adjustment of adaptation approaches must be one of the management activities to accommodate ongoing environmental and climatic change and the consequences of ecological and human responses to these changes (Fazey et al. 2010).

4.1.2 Re-thinking Traditional Management Approaches

Policies, planning processes and management actions already exist to support climate change adaptation and will continue to be relevant. Many of the existing efforts of the ANR will build resiliency in natural systems and help the agency to plan for and minimize the impacts of climate change in the future. In some cases, however, the goals, objectives, or priorities of managers may change in response to current or future climate change (AWFA 2009). Because of continually changing conditions at multiple scales of space and time, the actions needed to support habitats and species may shift over time. More than in almost any other area of environmental management and policy, climate change will require the use of adaptive management: making assumptions about future conditions and how best to cope with them, monitoring the results of management actions closely, and then using the interim results to inform future decision making.

Climate change is occurring now and is predicted to continue and potentially accelerate in the future. Existing conservation efforts will be complicated in several ways because predictions are uncertain and individual, interactive, natural, and human responses are complex. Because the predictions that are being used have measurement error, uncertainty must be accepted as a part of the management process. Climatic changes have occurred and are highly likely to continue to occur, but the degrees to which changes will occur vary widely depending on model assumptions, continuance of patterns, stressor-response relationships, and many other spatial and temporal variables. The projections in climate change exposures are uncertain in the coming decades, and our knowledge of biological and ecological responses to these changes are also uncertain (Glick et al. 2011a). The capacity of habitats and species to adapt to climate change is one of the least understood aspects of climate science though it is critical in predicting changes in future environmental conditions (Donelson et al. 2011). Although it is daunting, uncertainty is not an excuse for inaction and it should simply be acknowledged as inherent to the adaptation framework.

The temporal dimension to climate-change adaptation is also a critical part of the framework. Traditional natural resource management has been 'retrospective' – utilizing knowledge of past and current conditions to inform today's management actions. However, managers are now being asked to operate in a system where the future will not resemble the past in some very basic ways and such retrospective planning may no longer be effective. The typical priority setting for 5-15 year management plans will still be required, but in addition, managers need to ask "Where are we going, and by when?" Those projections must be translated into actions to be taken in the near-term, or medium-term, or longer term, including monitoring activities for long term readjustments (AWFA 2009). A dilemma facing resource managers is the need to balance near-term goals for protecting and restoring species and ecosystems with longer-term goals for sustaining functional ecological systems in the face of climate change.

Some of the longer term considerations for managers include incorporation of shifting baselines into their plans. While traditional goals have been maintaining an existing desired condition, or restoring species or habitats to some desired historical state (Craig 2010), now the historical reference points should be used with caution in the goal setting process (Millar et al. 2007). Rapid changes now underway will make efforts to restore or maintain historical conditions increasingly difficult. In the words of Milly et al. 2008), "Stationarity is dead". In the future natural systems will fluctuate within a background of variability that is no longer stable.

One aspect of instability in planning is the movement of species to new ranges. Conservation plans have commonly assumed a stationary climate and defined static protected areas; deer wintering areas protected by Vermont's Act 250 process are a prime example. However, fixed boundary preserves may become ineffective in protecting those species that move into unprotected areas to follow preferred climate conditions (Monzón et al. 2011, Parmesan 2006). Such shifts and realignments will make protecting species and ecosystems in their current locations difficult and in many cases impossible.

Because of projected shifts in habitats and species with climate change, the need to address resource conservation and management across political jurisdictions will challenge existing models for planning, regulation, and management. Many Federal laws and regulations are not well-prepared to address the challenges that will be posed by a shifting climatic baseline and its attendant ecological responses (Ruhl 2010). Likewise, planning in Vermont is primarily implemented at the municipal level; regional planning and conservation needed to manage more dynamic areas is a relatively undeveloped practice. Cooperation among states, municipalities, agencies, and divisions within agencies will be needed to allow for implementation of forward-looking goals that are not accommodated in existing legislation, regulations, or institutional cultures.

For some species, it may be difficult to protect the range into which they would prefer to move (Scott et al. 2005). For example, alpine species typically move upslope when temperatures warm. However, such movement is not possible for communities that are already restricted to isolated mountain peaks. Consequently, sensitive monitoring and plans to recognize and address extirpation may be required (Scott et al. 2005).

Conservation strategies typically are designed to address existing environmental stressors, such as habitat disturbance, invasion of undesirable species, pollution from common waste products and land disturbance, and overharvesting of biological resources (Wilcove et al. 1998). Ecosystems and biodiversity are already threatened by these stressors individually and interactively (Heathwaite 2010, Strayer 2010). Climate change may magnify the effects of many existing stresses on habitats and species (Staudinger et al. 2012). These multiple sources of environmental change make the task of isolating and managing climate-specific impacts challenging. However, isolating climate change impacts may not be necessary. If efforts are being made to manage the other stresses, then climate change may only increase the urgency of these efforts without requiring new efforts.

Human responses to climate change may result in increasing pressure on remaining natural areas and the connections among them. For example, climate-driven population shifts may increase population density in Vermont, which would consequently increase demands on natural recreational areas and other natural resources. Likewise, implementation of adaptation actions such as infrastructure adaptation to protect people and property or implementation of climate mitigation efforts may affect natural resources in unanticipated ways. While these causes may be unmanageable, the effects could be the responsibility of the ANR.

As climate change increasingly affects natural resources, managers will need to prioritize management actions in light of severity of effects and availability of resources. Conservation triage is the process of prioritizing the allocation of limited resources to maximize conservation returns, relative to the conservation goals, under a constrained budget (Bottrill et al. 2008). Managers will be forced to decide which of multiple conservation targets should be protected, how much intervention is possible, and if limited intervention would be effective (Hagerman et al. 2010). As West et al. (2009) stress, “even with substantial management efforts, some systems may not be able to maintain the ecological properties and services that they provide in today’s climate. For other systems or species, the cost of adaptation may far outweigh the ecological, social, or economic returns it would provide. In such cases, resources may be better invested elsewhere.”

4.1.3 Adaptation Goals and Objectives

Adaptation to climate change in the context of natural resource management is primarily about managing change (Millar et al. 2007, Link et al. 2010, West et al. 2009). In order to maintain ecosystem functioning, natural resource managers are pursuing a variety of adaptation approaches, including increasing resistance to climate change, promoting resilience, enabling ecosystem transformation, and realigning restoration and management activities to reflect changing conditions (Millar et al. 2007, AWFA 2009) (Table 26). Some combination of these approaches is likely to be needed to meet broader conservation objectives.

Table 26. Climate change adaptation management continuum (Millar et al. 2007, Glick et al. 2011a, Peterson et al. 2011, AWFA 2009)

Goal	Approach	Intent
Maintain status quo conditions, "buy time"	Increase Resistance	Retain existing ecological conditions, assist the habitat or species forestall impacts
	Promote Resilience	Buffer impacts and improve the capacity of a system to return to desired conditions after disturbance, or as a means to retain the same essential function, structure, identity, and feedbacks in an altered state (Walker et al. 2004)
	Enable Transformation	Efforts that enable or facilitate the transition of ecosystems to new functional states; proactive strategies that anticipate the nature of climate-change induced transitions and, working with these anticipated trends, include actions that facilitate transitions that are congruent with future climate conditions, while minimizing ecological disruption and undesired outcomes
Actively manage system transitions that are seen as inevitable; accepting or facilitating change	Realignment (Peterson et al. 2011)	Focus on systems that already have been disturbed beyond historical ranges of natural variability, and focuses on restoration of the system, although not necessarily to its historic or predisturbance condition

Management goals should be understood on a spectrum that starts at one end to resist changes to protect high value and climate-sensitive assets. On the other end of the spectrum, management can include actively facilitating changes and encouraging inevitable system transitions so that desirable ecological attributes are retained, rather than allowing complete collapse of ecosystem functions and services. These management ideas resemble conventional conservation management, but they are materially different in the way the concepts and actions are applied (Mawdsley et al. 2009).

Actions intended to **resist** climate change are those that forestall undesired effects of change and/or manage ecosystems so they are better able to resist changes resulting from climate change. **Resilience** actions focus on managing for viable habitats and species to increase the likelihood that these will accommodate gradual changes related to climate, and tend to return to pre-disturbance conditions. **Enabling transformation** is an intentional management action that accommodates change rather than resisting it by actively or passively facilitating ecosystems to respond as environmental changes occur. **Realigning management** activities focuses on the idea that rather than restoring habitats to historic conditions, or managing for historic range of variability, the management and restoration goals would be adjusted to current and anticipated future conditions (Millar et al. 2007, Magness et al. 2011).

4.2 The Adaptation Strategy Workshop

In December 2012, the Vermont ANR convened a workshop to provide a forum and initiate the process of developing adaptation strategies around key climate change factors. Participants included a mix of climate change and natural resource experts as well as policy makers and managers. A major goal of the workshop was to brainstorm on ways in which the ANR can move forward with developing adaptation strategies around key climate change factors. Four workgroups focused on strategies to address ecological impacts on the habitat groups: Ponds and lakes; rivers; wetlands; and upland forests. The strategies were in direct response to the vulnerability assessments developed during the July vulnerability workshop.

As with the July workshop, participants were divided into the habitat groups based on their area of expertise. Worksheets were provided to focus on specific scenarios and to elicit parallel information from each breakout group (Appendices 4A-D). In the first breakout session, relatively simplistic likely/probable scenarios of future climate and ecological conditions were described (in keeping with Cross et al. 2012 and AWFA 2009). Next, expected ecological effects and sensitivity/mediating factors associated with these scenarios were summarized based on results from the vulnerability assessments, and the groups were asked for additional insights. Then, participants brainstormed adaptation strategies, framed by the following question: What actions or strategies could increase the beneficial impact of mediating factors, reduce vulnerability to exposures/effects, and create greater resilience for the habitat type? While doing this, the groups kept the following categories in mind and attempted to ensure that each category had at least some representation:

- Monitoring and assessment
- Technical assistance related to climate and adaptation issues
- Regulation
- Education and outreach/engagement
- Conservation/land stewardship and land use planning

Initially, the workshop organizers thought the groups would be brainstorming separate sets of strategies for each scenario, and in some cases for specific habitats (e.g., precipitation-dependent peatlands). However, it soon become apparent that many of the strategies applied to multiple scenarios and multiple habitats, so the brainstormed strategies were ultimately compiled into one list and participants noted which strategies applied only to specific scenarios or habitats. The cross-cutting nature of some strategies may be an advantage when implementation is considered, in that wide applicability may be preferable to limited applicability. In some sessions, the groups also identified key research needs and data gaps needed to support some of the strategies.

In the second breakout session, each group selected at least one strategy and then one specific on-the-ground action or step or investment needed to implement the strategy. After the groups noted whether actions were existing or new, they discussed which program or entity should be involved and which broad habitat groups (rivers, lakes, wetlands, upland forest) the action applied to. Then they rated the action-item based on the following considerations (see 'Top Picks' worksheet template in Appendix 4E):

- Effectiveness at mitigating (e.g., scientific basis for recommending this action)
- Operational feasibility (e.g., Amount of $, resources required to implement)
- Degree of current implementation
- Level of alignment with current policies, procedures, BMPs
- Social/political acceptability and feasibility
- Potential for securing funding

In the final session, a participant from each group gave a 5-minute summary of their top picks for adaptation strategies and described the implementation of an on-the-ground management action. To conclude, the following questions were discussed:

- Where do strategies repeat and overlap? Which have the greatest synergy among habitat types?
- What was missing from our discussions?
- Of the topics discussed, which are outside the purview of the ANR?
- Was the process that was followed at this workshop valuable? How well did it work? What would you change?
- If the ANR moves forward with this, who is interested in participating in that process?

Results from the brainstorm sessions are included in Appendices 4F-I and are discussed in more detail in Section 4.3.

4.3 Next steps

Much of Vermont's success in dealing with future climate change effects will depend upon its ability to respond, recover and adapt. Preparedness and advance planning will be essential. This section of the report provides guidance and recommendations to ANR for planning and regulatory initiatives aimed at addressing the effects of climate change. The steps that are recommended here represent a compilation of focus areas and needs identified by sector leads, participants at the December 11 adaptation strategies workshop, publications and reports completed by outside agencies, and data gaps that were apparent to Tetra Tech in compiling this report.

Potential next steps are organized into 3 sections:

- Establish guiding principles, process and products (Section 4.3.1).
- Continue the work initiated at the vulnerability assessment and adaptation strategies workshops (Section 4.3.2).
- Follow up on the initiatives/focus areas that were identified as important cross-sector themes at the adaptation strategies workshop (Section 4.3.3).

If the state moves forward with any of these, it will need to put systems and an organizational framework in place to achieve them. Chances for success will be improved if these efforts (1) span sectors; (2) if scientists and managers are engaged in collaborative dialogue; and (3) if the state involves a wide array of stakeholders in the process, including local experts, state, federal and private organizations other state agencies (e.g., VTrans and ACCD), interested public audiences, and natural resource-based industries whose interests will be affected by climate change (e.g., agriculture, forestry, hunting, fishing, wildlife viewing, skiing/snowmobiling, tourism and other recreational user groups).

4.3.1 Establish Guiding Principles, Process and Products

Moving ahead, it would be helpful if the state developed a cohesive plan with higher level guiding principles to address climate change-related issues, such that the various groups working on these issues would understand how their efforts fit into a bigger picture. Steps that would help take the state in that direction include:

- Adopting guiding principles and tools for managing in light of uncertainty, including a formal endorsement or acknowledgement of the spectrum of management actions (resistance, resilience, enabling transformation, and realigning management).
- Developing a formal process for integrating climate change and management actions into Agency planning processes.
- Defining end products and objectives.

4.3.1.1 Management approach in light of uncertainty

As discussed in Section 4.1.2, goals, objectives, or priorities of managers may change in response to current or future climate change. Agencies will need to develop and implement strategies based on incomplete or uncertain information and adjust these strategies as needed based on monitoring or new information. Given the pace and magnitude of climate change, a more flexible form of management will be increasingly important (AWFA 2009). In light of these changes, the ANR should consider evaluating whether its current principles, strategies and planning approaches adequately address these challenges.

If the ANR decides to integrate adaptation planning into its existing efforts, it can look to numerous recent publications for guidance (for example, U.S. EPA 2009, Halofsky et al. 2011, Peterson et al. 2011, Weeks et al. 2011, Poiani et al. 2011). Staudinger et al. (2012) distills information from these publications into five general principles, which can be readily incorporated into most conservation and management planning processes:

- Link actions to climate impacts.
- Embrace forward-looking goals.
- Consider broader landscape context.
- Select strategies robust to an uncertain future.
- Employ agile and informed management.

The ANR can also look to a number of existing tools for making management decisions in the context of incomplete information, uncertainty, risk and change (Staudinger et al. 2012). These tools, which are described in more detail in Appendix 4J, include:

- Adaptive management (e.g., Conroy et al. 2011).
- Scenario-based planning (e.g., Peterson et al. 2003).
- Structured decision-making (e.g., Ohlson et al. 2005).
- Risk management (e.g., Willows and Connell 2003).

4.3.1.2 Process for integrating climate change into planning and implementation

This report provides a very initial look at what the ANR is currently doing to conserve natural resources, species and habitats through the lens of climate change. Further planning will require that the ANR look in far greater depth at new approaches and tools, as well as its budgets, staffing, and guidance to determine what additional actions it should be taking in light of a changing climate (AFWA 2012).

If the ANR decides to adopt a formal process for integrating adaptation planning into its existing planning efforts, it can repeat the procedures presented in this report in greater depth and with greater specificity relative to programs, budgets, staffing, and regulation. The process includes identifying the resources to be protected, defining vulnerabilities, and formulating feasible adaptation strategies and actions. These steps were outlined in preceding chapters. The final step is implementing the strategies and actions, with monitoring and assessment of each of the steps to confirm their efficacy.

In addition to the process used in developing this report, the ANR can look to several publications for guidance. Appendix 4K contains several examples of step-by-step processes that have been adopted by other entities, including those put forth by the Climate-Smart Conservation workgroup convened by the National Wildlife Federation (Stein et al. written communication 2012, in Staudinger et al. 2012), the Association of Fish and Wildlife Agencies, U.S. EPA and the Center for Climate Strategies (CCS). As discussed in Section 1, because this project has an ecological focus and involves the ANR's Forestry, Fisheries, Wildlife and Water Resources sectors, the management plans that have greatest relevance to this project are the Vermont Surface Water Management Strategy (SWMS), the Vermont Forest Resources Plan (FRP) and the Vermont Wildlife Action Plan. Table 27 lists the long-term goals/desired future conditions currently included in these plans. These goals should be reassessed in light of climate-related impacts and vulnerabilities to ensure they are forward-looking and climate-informed.

The appropriate timeframe for integrating climate change into existing planning efforts will vary among projects. Table 28 describes timeframes for integration including ‘no regrets’ (within 5 years), anticipated (5-15 years) and ‘wait and watch’ (15-30 year), which have been commonly applied by other entities (Comer et al. 2012). A planning horizon of about 30 years is often considered reasonable for climate sensitive projects because there is much more certainty about the impacts of climate over the next 20-30 years versus beyond (Staudinger et al. 2012).

Table 27. Goals in Vermont planning documents with relevance to this project.

Planning Document	Year Published/ Updates Due	Long-Term Goals/Desired Future Conditions
Vermont Forest Resources Plan (FRP) - State Assessment and Resource Strategies (Plan) (Vermont Forest, Parks, & Recreation2010)	2010/2015	• Conserve **biological diversity** across all landscapes. • Maintain and enhance **forest ecosystem health and productivity.** • Maintain and enhance forest contribution to **ecosystem services.** • Maintain and enhance an **ethic of respect for the land, sustainable use and exemplary management.** • Vermont has a **legal, institutional and economic framework** in place for forest conservation and sustainability.
Wildlife Action Plan (Kart et al. 2005)	2005/2015	• Conserve, enhance, and restore Vermont's natural communities, habitats, and species and the ecological processes that sustain them. • Provide a diversity of fish- and wildlife-based activities and opportunities that allow the safe and ethical viewing, regulated harvesting, and utilization of fish, plant and wildlife resources consistent with the North American model of fish and wildlife conservation. • Maintain safe fish and wildlife based activities and limit harmful human encounters with fish and wildlife species and provide general public safety service incidental to primary fish and wildlife enforcement duties.
Surface Water Management Strategy (VT DEC 2013)	updated as necessary	• Protect, maintain, enhance and restore the biological, chemical and physical integrity of all surface waters. • Support the public use and enjoyment of water resources. • Protect the public health and safety.

Table 28. Situations in which 'no regrets,' 'anticipated' and 'wait and watch' actions have been commonly applied by other entities (Comer et al. 2012).

Actions	Timeframe	Situations in which commonly applied
No regrets	Within the next 5 years	When the climate change factors relate to the stressors that are best known and are currently being addressed within managed areas; considered relatively robust to uncertainty in how climate change will play out in a given location.
Anticipated	Over the coming 5-15 years	Where indirect effects stressors are less well known, and/or interactions with climate change are less clear; additional information will be required to move forward, but participants could foresee their implementation.
Wait and watch	Anticipate over a 15-30 year timeframe	Limited amount of current knowledge; research questions are specified, investment will be required over upcoming decades in order to determine appropriate management actions.

4.3.1.3 End products

This report represents a first step in helping the ANR develop climate change adaptation strategies. If Vermont decides to pursue this further, it should decide what end products it is working towards. One possibility could be a comprehensive adaptation plan. These plans are typically a multi-sector effort involving water resources, agriculture, forestry, terrestrial and aquatic ecosystems, , growth and land use, energy development, and public health (AFWA 2009, Choudhury 2012). As of March 2011, sixteen states (AK, CA, CT, FL, IL, MA, MD, ME, NC, NH, NY, OR, PA, VA, WA, and WI) either had an integrated state-level adaptation plan for biodiversity conservation or were in the process of completing their State adaptation plan (Choudhury 2012). Seven of those states (CT, FL, MA, ME, OR, PA, and WA) had a legislative mandate to create a sector-wide state adaptation plan. Those that were not prompted by legislative mandates were mostly guided by an executive order from the state's governor (AFWA 2009, Choudhury 2012).

Whatever the end product, climate change is such an active area of research that the ANR should plan to update any climate sensitive reports – notably those related to habitat, invasive species, and variability in temperature and rainfall- periodically. In particular, the ANR should plan to review and integrate results from the U.S. Global Change Research Program's National Climate Assessment (NCA) reports, which are updated at least every 4 years and act as status reports about climate change science and impacts on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity. The next National Climate Assessment (NCA) is scheduled to be completed in 2013.

4.3.2 Continue Work Initiated at the Workshops

While progress was made on vulnerability assessments and adaptation strategies during this project, results presented in this report should be regarded as a first step, not a final product, and warrant closer review by experts. If the ANR decides to continue the work that was initiated during the vulnerability assessment and adaptation strategies workshops, the four major habitat groups (forests, rivers, lakes/ponds and wetlands) should continue to meet so that they can build on this work. The groups should have adequate representation from each sector (as appropriate) and outside experts should also be included. Lists of potential participants can be found in Appendix 4L. The ANR could also seek assistance from outside groups like the University of Vermont (UVM) Research on Adaptation to Climate Change (RACC) team.

This section contains recommendations on follow-up tasks that would help the ANR move forward with climate change vulnerability assessments and development of adaptation strategies. Prior to engaging in these efforts, it would be helpful if the ANRcould provide participants with a clear understanding of what the information produced by these groups would be used for. Also, systems and an organizational framework would need to be put into place to allow for communication and sharing of information across the various work groups.

4.3.2.1 Vulnerability assessments

As discussed in Section 3, a methodology for assessing vulnerability was developed, and vulnerability assessments were completed for a number of habitats and species. However, more work needs to be done. The vulnerability ratings warrant closer review by the ANR experts, and some habitats and species of interest have yet to be assessed. If the ANR decides to continue with the vulnerability assessment work that was initiated during this project, it should consider reconvening the four major habitat groups (forests, rivers, lakes/ponds and wetlands) that met during the vulnerability assessment workshop. Each group could take the following general steps (to start):

1. Review and add to the results in Section 3. If revising any results (e.g., assigning new ratings), each group should carefully document how it arrives at the revision since the group's thinking may change over time and because different people might draw different conclusions from similar lines of evidence.
2. Rate non-climatic stressors, per the methodology used in the report on the Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change (Manomet & NWF 2012a).
3. Identify and prioritize research needs.
4. Conduct periodic literature searches to stay abreast of the latest information and tools that are becoming available (starter lists can be found in Appendices 3G (forests), 3J (wetlands), 3N (rivers) and 3Q (lakes)).
5. Track initiatives being carried out at the national, regional, state, local levels that pertain to each habitat group.

In addition to these general steps, a starter list of more specific tasks for each habitat group can be found in Table 29. Additional resources that could potentially be used for habitat-level vulnerability assessments in Vermont include NatureServe's Habitat Climate Change

Vulnerability Index (HCCVI) (Comer et al. 2012), and the landscape change models/conservation decision-support tools currently being developed by the University of Massachusetts and partners (McGarigal et al. 2011).

Table 29. Starter list of more specific tasks for each major habitat group.

Habitat group	**Tasks**
Forests	1. Finish the modeling/expert elicitation exercise on tree species that is currently being conducted by Vermont Forest, Parks, & Recreation. 2. If forest formation-level assessments are deemed useful, review the assessment on spruce-fir forests that was completed at the vulnerability assessment workshop and complete similar worksheets for northern hardwood and oak-pine forest formations (or natural community types within those formations, as appropriate). 3. Assess additional forests types, such as urban forests. 4. Conduct periodic literature searches; add new citations to Appendix 3G (consider making this into an annotated bibliography). 5. Watch for final results from the following outside efforts: a. The regional-level NEAFWA report on the Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change (Manomet & NWF 2012a). b. The state-level habitat vulnerability assessments from New York and New Hampshire.
Rivers	1. Review and finalize the classification scheme developed during the vulnerability assessment workshop (Appendix 3D). a. Reconcile differences with the classification scheme used by Fish & Wildlife (Appendix 3K) (e.g., should additional classes, such as cold water/low elevation/mussel streams in the Lake Champlain Valley be broken out). 2. Review and finalize the table on expected effects of key climate factors on physical processes that shape stream ecosystems (Table 22). 3. Conduct periodic literature searches; add new citations to Appendix 3L (consider making this into an annotated bibliography). 4. Watch for final results from the following outside efforts: a. The regional-level NEAFWA report on climate change and cold water fish habitat in the Northeast (Manomet & NWF 2012b). b. The regional-level watershed-scale climate change vulnerability assessment being conducted by U.S. EPA Office of Research and Development (contact: Britta Bierwagen: Bierwagen.Britta@epa.gov).

Table 29. Continued …

Lakes	1. Review and finalize the classification scheme developed during the vulnerability assessment workshop (stratified and unstratified). a. Reconcile differences with the classification scheme used by Fish & Wildlife (Appendix 3O) (dystrophic, mesotrophic, oligotrophic). 2. Revisit the discussion on whether littoral habitat and eutrophic lakes should be assessed separately. 3. Conduct periodic literature searches; add new citations to Appendix 3N (consider making this into an annotated bibliography).
Wetlands	1. Review and finalize the vulnerability assessment worksheets. a. Ensure that the Water Resource-Wetlands group has a chance to review worksheets that were completed after the workshop. 2. Conduct periodic literature searches; add new citations to Appendix 3I (consider making this into an annotated bibliography) 3. Watch for final results from the following outside efforts: a. The regional-level NEAFWA report on the Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change (Manomet & NWF 2012a). b. The state-level habitat vulnerability assessments from New York and New Hampshire.

In addition to reconvening the forests, rivers, lakes and wetlands habitat groups, the ANR could seek assistance from the Vermont Weather Climate Research group being run by Lesley-Ann L. Dupigny-Giroux (VT_WX_CLIMATE_RESEARCH@list.uvm.edu) and the UVM Research on Adaptation to Climate Change (RACC) team on the following tasks: .

1. Review Section 2 of this report.
2. Review the climatic data inventory in Appendix 2A.
3. Update projection data as appropriate after the 2013 NCA report is finalized.
4. Ask each major habitat group to provide a climatic data 'wish list.'
5. Disseminate desired information and tools to each group (as able).
6. Identify and prioritize research needs.
7. Conduct periodic literature searches to stay abreast of the latest information and tools that are becoming available.

The ANR could use the results of continuing vulnerability assessments that are being assembled for the 2015 Wildlife Action Plan updates. Tasks could include:

1. Review the species worksheets that have been completed to date (Appendix 3B).
2. Conduct assessments on additional species.
3. Disseminate species-level information to the appropriate habitat groups.

4. Discuss anticipated future changes, such as:
   a. What are the implications of a species, such as the Bicknell's Thrush, being listed for climate change?
   b. The ANR should start a dialogue on the use of translocations or "assisted migrations" management for climate-sensitive species with poor mobility (e.g. Eastern Pearlshell mussel).
   c. What will be the role of non-native and invasive species in climate-altered ecosystems? Will managers adopt goals focused on sustaining ecosystem processes and services rather than compositional patterns, which emphasize native species?
5. Identify and prioritize research needs.
6. Conduct periodic literature searches to stay abreast of the latest information and tools that are becoming available.

Additional resources that could potentially be used for species-level vulnerability assessments in Vermont are listed in Table 30.

Table 30. Additional resources that could potentially be used for species-level vulnerability assessments in Vermont.

Resource	Description
NatureServe's Climate Change Vulnerability Index (CCVI) (NatureServe 2011)	Uses a scoring system that integrates a species' predicted exposure to climate change within an assessment area and three sets of factors associated with climate change sensitivity, each supported by published studies: 1) indirect exposure to climate change, 2) species-specific factors (including dispersal ability, temperature and precipitation sensitivity, physical habitat specificity, interspecific interactions, and genetic factors), and 3) documented response to climate change. Results can vary depending on climatic projection, life history and distribution data that are used. Thus, we recommend that the input data come from critically-reviewed, primary sources (examples of such sources can be found in Appendix 4N).
Whitman et al. 2012	Vulnerability of Wildlife and Plant Species of Special Concern in Maine - contains expert elicitation results for 442 species.
Schlesinger et al. 2011	Calculated the relative vulnerability of 119 of New York's Species of Greatest Conservation Need (SGCN) using NatureServe's CCVI.
Matthews et al. 2007	A Climate Change Atlas for 147 Bird Species of the Eastern United States.
Vermont Forests, Parks & Recreation, in progress	Expert elicitation on vulnerability and adaptation of 30 tree species.

4.3.2.2 Continued development of adaptation strategies

As discussed in Section 4.2, the four major habitat groups (forests, rivers, lakes/ponds and wetlands) that met during the adaptation strategies workshop brainstormed lists of adaptation strategies that would strengthen the resilience of habitats and species to changing climate scenarios (such as increased temperature and more frequent large precipitation events). Results from these brainstorm sessions can be found in Appendices 4F-I.

If the ANR decides to move forward with the adaption strategies work that was initiated through this project, it could reconvene these groups and ask them to review and add to the lists in Appendix 4F-I. The groups could follow a methodology similar to that which was used at the workshop. The groups could identify which strategies are most likely to be effective across a range of climatic scenarios versus those that may only be effective under a particular scenario (AWFA 2009). This does not require precise modeling; rather, it can be done using simplistic climatic scenarios like those that were used at the workshop.

Another tool that the groups could use are the conceptual diagrams that were developed for the vulnerability assessments; these can be used to identify steps in the causal pathways where management actions can be applied (Appendices 3I (wetlands), 3M (rivers) and 3P (lakes)). Also, more and more outside resources are becoming available. Some examples are listed in Table 31. It is important that each group conducts periodic literature searches to stay abreast of the latest information and tools.

Table 31. Examples of publications that provide helpful information on developing adaptation strategies (this is by no means all-inclusive; many more resources exist).

Resource	Description
Glick et al. 2011b	A review of climate change adaptation literature (www.nwf.org/~/media/PDFs/Global-Warming/Reports/Moving-the-Conservation-Goalposts-2011.ashx).
Mawdsley et al. 2009	A Review of Climate-Change Adaptation Strategies for Wildlife Management and Biodiversity Conservation.
Dawson et al. 2011	Journal article that discusses possible adaptation responses in terms of intensity of intervention.
NCADAC 2013 (draft)	The National Climate Assessment will be finalized in 2013; it contains more information on adaptation strategies than the previous document.
Staudinger et al. 2012	Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment.
Lawler et al. 2010	Journal article on resource management in a changing and uncertain climate.

Table 31. Continued …

Association of Fish and Wildlife Agencies 2009	Voluntary guidance for States to incorporate climate change into State Wildlife Action Plans and other management plans.
USFWS and NOAA 2012	National fish, wildlife, and plants climate adaptation strategy (http://www.wildlifeadaptationstrategy.gov/).
Thompson, E.H. 2002	Vermont's Natural Heritage: Conserving Biodiversity in the Green Mountain State.
State adaptation reports	Examples are listed in Appendix 1A (e.g., Massachusetts, New York, Connecticut, Wisconsin).
Swanston and Janowiak, 2012	Forest adaptation resources: climate change tools and approaches for land managers. US Forest Service Gen. Tech. Rep NRS-87.

Many of the strategies that were discussed at the workshop and that are described in the literature are broad-level. While these are helpful for identifying ranges of management options, a 'one size fits all' generalized approach does not work when it comes to implementation, as there are too many site-specific factors to consider. The broad level strategies must be translated into actionable site- and target-specific recommendations (Heller and Zavaleta 2009). If the ANR wants to develop a more formal framework for translating these principles and strategies into place- and target specific actions, possible frameworks include the Adaptation for Conservation Targets (ACT) framework described in Cross et al. 2012 and the framework used by Comer et al. 2012 to develop lists of 'no regrets', 'anticipated' and 'wait and watch' actions.

In addition to reconvening the major habitat groups, the ANR could conduct a comprehensive inventory of existing on-the-ground management actions that includes the following information:

- List of management actions and specific responsibilities for each.
- Resources (e.g. money, staff time) being devoted to each action from agency and other sources.
- Some measure of effectiveness at mitigating (e.g. scientific basis for recommending this action).
- Degree of current implementation (e.g. geographic reach, timeframes, regularity).
- Level of alignment with current policies, procedures, and best management practices.
- Social/political acceptability and feasibility.
- Potential for securing supplemental funding.
- Expected timeframe for implementation.
- Assessment of whether the action can be used to address climate change.

These lists could be organized by the management categories listed in

Table 32, which are used in the Vermont Surface Water Management Strategy.

Table 32. Management categories used in the Vermont Surface Water Management Strategy.

Management Category	Description
Monitoring & Assessment	Activities to document locations of climate change impacts and identify areas to protect or remediate.
Technical Support	Programs to assist individuals and organizations with the development of projects to address climate change.
Rules and Regulations	That address climate change, including permitting programs.
Education and Outreach	Activities that confer understanding to the general public on the importance of the stressor.
Funding	Programs that provide cost-share assistance or complete funding for projects.

4.3.3 Follow up on focus areas identified at the adaptation strategies workshop

At the adaptation strategies workshop, the following initiatives/focus areas were identified as important cross-sector themes that would strengthen the resilience of habitats and species to changing climate scenarios:

- Promoting resilience by reducing other stressors
- Conserving refugia
- Monitoring and assessment
- Data infrastructure
- Landscape-level planning
- Groundwater
- Sustainable flows
- Ecosystem services

If the ANR and its partners decide to pursue any of these focus areas, this section discusses steps that could be taken to further these initiatives. These focus areas have not been prioritized.

4.3.3. 1 Promote resilience and resistance by reducing other stressors

Ecosystems already are showing impacts from a range of anthropogenic stressors including land use change, pollution and non-native invasive species. Complex interactions can occur among these stressors, and teasing out climate change effects from these other stressors can be challenging. Overall, it is anticipated that climate change will magnify the effect of many of these existing stressors on ecosystems and species (Staudinger et al. 2012). On top of this, as evidenced during Irene, the way in which humans respond to climatic events can become new stressors themselves and may exacerbate existing threats.

In light of this, strategies aimed at reducing stressors will take on added importance and urgency. Reducing others stressors was a significant topic of discussion at the adaptation strategies workshop and is also a common theme in the literature. This is generally regarded as one of the most valuable and least risky strategies available for climate change adaptation, because many of these strategies are likely to be beneficial regardless of future climate conditions, and oftentimes there is a large existing body of knowledge about their impacts and solutions (thus the term 'no regrets' strategy) (Comer et al. 2012).

If the ANR decides to pursue this focus area, it should consider performing the following tasks:

- Conduct an inventory of the ANR actions and planning efforts aimed at reducing existing stressors, as described in Section 4.3.2.2
- Assess these actions in light of climate-related impacts and vulnerabilities (do these actions adequately protect the environment and human populations from the additional stresses of climate change?)

In addition to these general needs, at the workshop, some specific themes emerged as having added importance. These included:

- **Reducing impacts from nonpoint source pollution** (e.g., sediments, phosphorus, and nitrogen). These pollutants are expected to be exacerbated due to increases in storm intensity and heavy precipitation events. Resulting changes in natural stream morphology and related hydrographs could also negatively impact aquatic ecosystems (U.S. EPA 2012a). During the adaptation strategies workshop, participants discussed Act 138, known as the Rivers and Lakes Bill (S.202), which was signed into law by Governor Shumlin in 2012. Act 138 should be evaluated in light of climate change (does it provide adequate protection of Vermont's water resources in light of changing climatic conditions?). Also, because much of its focus is on human infrastructure, it should be evaluated in light of ecological considerations as well. During our informal assessment of Act 138 at the workshop, many of its features were believed to be beneficial under future climate scenarios, including:

    - Restore beneficial functions of wetlands, floodplains, river corridors, riparian and shoreland areas.
    - Reducing floodplain and river corridor encroachment.
    - Reducing stormwater runoff.
    - Lakeshore protection.
    - Protecting riparian buffers

- **Improving flood resiliency**. A recent report by the Lake Champlain Basin Program outlines 15 policy recommendations that would help protect life and property along tributary corridors. Examples include identifying Fluvial Erosion Hazard (FEH) areas, conducting flood hazard mapping, establishing lakeshore protection areas, and developing Risk Management Plans for critical water infrastructure sites and hazardous waste sites (LCBP 2013).

- **Managing streams for equilibrium condition.** With the increased likelihood of heavy precipitation events, protection of river processes and floodplain function take on added importance. Provisions in Act 138 as well as guidance from the Vermont River Management Program (RMP) on river corridor protection and restoration projects and river corridor easements (Kline 2010a, Kline 2010b, VT DEC 2013b) can help provide such protections.

- **Decreasing Runoff and Increasing Stormwater Infiltration**. This would improve flood resiliency in light of projected increases in storm intensity and heavy precipitation events. Actions could include:
  - Wetland and floodplain restoration.
  - Green Infrastructure/Low Impact Development.

- **Providing better technical assistance, guidance materials and alignment of programs and funds at the town and community level**. At the workshops, it was noted by many participants that municipal elected officials and appointed boards are often unaware of the authority that they do have under Vermont law to manage and protect shorelines, wetlands, and riparian areas through zoning, planning, and conservation actions. A greater mutual understanding of state and municipal authorities and options for improved resource protection was seen as highly beneficial. Among the areas for action discussed were strategies for:
  - Providing technical assistance and guidance materials to towns and communities that will help them better understand climate change impacts and will empower them to act
  - Aligning state level programs and funds (including Municipal Planning Grants and other non-ANR resources) to make it easier for towns to address issues associated with climate change, or to enable watershed groups or other NGOs to assist towns with climate change adaptation specifically in mind

- **Reducing impacts from invasive species, insect and disease pests.** These are likely to become more pervasive due to warming temperatures, an increase in the frequency of extreme events and increasing carbon dioxide concentrations (Driscoll et al. 2011). Managers will have to reevaluate the role of non-native and invasive species in climate-altered ecosystems and make decisions on whether to adopt goals on sustaining ecosystem processes and services rather than compositional patterns.

- **Targeting areas with high chances of recoverability**. Since there are limited resources for implementation of climate change adaptation strategies, it will be important for the ANR to get the “best bang for its buck.” Examples of existing methodologies that can be used to help target areas for restoration include:
  - Tactical Basin Planning (one component of which is identification of healthy or recoverable watersheds).
  - Identification of critical source areas (e.g., Missisquoi Bay Basin Project: Identification of Critical Source Areas of Phosphorus Pollution (http://www.lcbp.org/ijc.htm) (LCBP 2010)).

    - When fully implemented, the Act 138 "Rivers Bill" will allow the ANR to regulate floodplain developments through a General Permit, which would create an opportunity to spend limited state resources on those floodplain activities which have the greatest potential to impact floodplain functions.
  - **Sizing infrastructure (e.g., culverts) to accommodate sediment transport and connectivity**. This takes on added importance in light of projected increases in storm intensity and heavy precipitation events, as it improves the resiliency of the road network and allows for the passage of aquatic organisms (Milone & MacBroom 2009).

- **Taking measures to protect against maladaptive human responses**. Much of Vermont's success in dealing with extreme climatic events will center on how it responds, recovers and adapts. Sometimes addressing one stressor may exacerbate another. It is important to anticipate these situations and take steps to ensure that the response and recovery does not worsen potential impacts from future events. Examples of future scenarios that could be discussed include:
  - If extended summer low flow periods occur as projected, this could result in increased water demand (e.g., for irrigation). Does Vermont have systems in place to handle this potential increase?
  - If total annual precipitation increases and more heavy precipitation events occur, it is possible that more drainage systems (e.g., tile drains that remove excess water from the soil) will be put into place. If this happens, what impacts will this have on hydrology and water quality in receiving waters?

There are a number of existing resources that may be helpful to the ANR in its efforts to reduce existing stressors in light of climate change. Some examples are listed in Table 33.

Table 33. Resources that may be helpful to the ANR in its efforts to reduce existing stressors in light of climate change.

Resource	Description
NCADAC 2013 (draft)	The National Climate Assessment will be finalized in 2013; it contains information on interactions between climate change and existing stressors.
Staudinger et al. 2012	Chapter 5 is about Impacts of Climate Change on Already Stressed Biodiversity, Ecosystems, and Ecosystem Services (http://assessment.globalchange.gov).
U.S. GCRP 2009	Educational materials can be found in its report titled 'Climate literacy - the essential principles of climate sciences - a guide for individuals and communities' (http://www.globalchange.gov/resources/educators/climate-literacy).
Lake Champlain	Lake Champlain TMDL work that takes climate change into account is currently being performed by Tetra Tech; also watch for nutrient modeling work being done by the UVM RACC team.
VT DEC and VTrans (2013)	The Vermont River Management Program (RMP)/VTrans standard operating procedures for managing streams, the RMP's rule on culvert sizing, and the 2013 road and bridge standards that contain stormwater management practices to improve resilience of road network

Table 33. Continued …

Riparian buffers (VANR 2005)	The ANR's Riparian Buffers and Corridors Technical Papers (http://www.anr.state.vt.us/site/html/buff/buffer-tech-final.pdf).
River restoration (Palmer et al. 2005)	This journal article contains insights on how to define success in river restoration: Palmer et al. 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology 42: 208–217.
Wetland Reserve program (USDA NRCS 2013)	Farm Bill programs, such as the Wetland Reserve program, can provide compensation to landowners to protect areas that provide important habitat for wetland birds (http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/easements/wetlands/).
Greenseams (Milwaukee Metropolitan Sewerage District 2013)	Greenseams: Flood Management in Milwaukee is a pioneering flood management plan that utilizes green infrastructuregreen infrastructure technology and has assisted with the acquisition of over 2,100 acres of flood prone, hydric (water absorbing) soils within the Milwaukee metropolitan area (http://www.conservationfund.org/project/greenseams_program).
Recovery Potential Screening Tool (U.S. EPA 2012b)	EPA's Recovery Potential Screening Tool assists restoration programs in deciding where to invest their efforts for greater likelihood of success (http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/recovery/index.cfm).
Healthy Watersheds Initiative (U.S. EPA 2012c)	Identifying and Protecting Healthy Watersheds Concepts, Assessments, and Management Approaches. This technical document was developed to help implement the Healthy Watersheds Initiative (HWI) (http://water.epa.gov/polwaste/nps/watershed/hw_techdocument.cfm).
Wilbanks and Fernandez 2012	Climate Change and Infrastructure, Urban Systems, and Vulnerabilities – Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment (http://www.esd.ornl.gov/eess/Infrastructure.pdfhttp://www.esd.ornl.gov/eess/Infrastructure.pdf).

4.3.3.2 Conserving refugia

Participants at the adaptation strategies workshop expressed a strong interest in taking measures to protect refugia. The term 'refugia' was not formally defined, but it was loosely interpreted to mean a place on the landscape where organisms could survive periods of unfavorable climatic conditions. Workshop participants seemed particularly interested in protecting and monitoring cold water species, but were also interested in tracking trends in cool and warm water taxa.

If the ANR and its partners decide to pursue this focus area, they should consider performing the following tasks:

1. Develop a methodology (with a sound scientific basis) for defining and identifying refugia within each major habitat group.
2. Identify indicators to track.
3. Identify refugia.
4. Prioritize.
5. Protect.
6. Monitor (are hypotheses holding true? are organisms responding as expected?).
7. Adapt as need be.

There are a number of existing resources that could potentially be used to help identify refugia. Some of these are listed in Table 34.

Table 34. Potential mechanisms for identifying refugia that were discussed at the adaptation strategies workshop and via follow-up exchanges.

Resource	Description
Ashcroft 2010	Provides guidance on how to define the term "refugia" and contains a list of potential methodological issues that can arise when identifying refugia.
BioFinder (VANR 2013) (aquatic and terrestrial)	BioFinder is a map and database identifying Vermont's lands and waters supporting high priority ecosystems, natural communities, habitats, and species. The most comprehensive assessment of its kind in Vermont, BioFinder was developed to further stewardship and conservation efforts (http://biofinder.vermont.gov/).
VT DEC (streams)	Utilize information gathered for Tactical Basin Planning: • Water Quality and Biological Assessments • Stream Geomorphic Assessments • Assessment and Listing Process • Identification of Healthy or Recoverable Watersheds Consider the following additional information: • Connectivity (Martin and Apse 2011) • Invasive species (http://imapinvasives.org/vtimi/map/)
U.S. EPA (2013a, unpublished) (streams)	Utilize GIS layers that are being created for the regional, watershed-scale vulnerability assessment. Examine distributions of stream macroinvertebrate thermal indicator taxa (Appendix 3L).
NEAFWA 2011 (forests and wetlands)	Utilize the GIS layers from the Northeastern Terrestrial Habitat Mapping Project; this is a standardized terrestrial wildlife habitat classification system for the Northeast
Olivero and Anderson 2008 (streams)	Utilize the GIS layer from the Northeast Aquatic Habitat Classification; this includes a thermal classification scheme.
Anderson et al. 2012 (terrestrial)	Utilize information gathered for the report "Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region."

At the workshop, some potential mechanisms by which the ANR could protect refugia were discussed. Examples include:

- **Education and outreach**
    - Disseminating information to the appropriate partners (in this case, planning and conservation commissions, land trusts, NGOs, etc.).
    - Holding a workshop for the VT League of Cities & Towns.
- **Alignment of resources**
    - Allowing more funds from the Vermont Housing and Conservation Board to be used for protection of surface waters and associated natural resources.
    - Create a conservation fund dedicated to lakeshore properties and wetlands (either existing land trusts could utilize this fund or new lake and wetland trusts could be formed).
    - Create incentives through the current use program.
    - Create incentives, involving all state programs, to promote greater water quality and flood resilience.
    - Evaluate all grant programs to determine whether they are incentivized to accomplish the desired result
- **Regulatory**
    - Designate aquatic refugia as Outstanding Resource Waters.
    - Enact provisions of Act 138 that restore beneficial functions of wetlands, floodplains, river corridors, riparian and shoreland areas.

4.3.3.3 Monitoring and assessment

Monitoring data will take on added importance, and different forms, in light of climate change. These data are needed to inform adaptive management and help managers make decisions in increasingly complex and uncertain situations (AFWA 2009). While there is a need for improved species and habitat monitoring across entire ranges and regions, it is unlikely that states will have sufficient resources and expertise to address these needs adequately on their own.

Participants at the adaptation strategies workshop emphasized repeatedly the importance of improving and adjusting monitoring efforts and of enlisting help from outside organizations such as citizen scientist organizations, universities and NGOs. If the ANR and its partners decide to pursue this focus area, it would be helpful to start with the following steps:

1. Conduct an inventory of existing citizen, university, government and NGO monitoring efforts, including budgets, geographic coverage, information gathered, and staffing.
2. Evaluate whether these data and methods are sufficient in light of climate-related exposures, impacts and vulnerabilities.
3. Explore additional monitoring possibilities, including the potential for volunteer or crowd-sourced data and for creating a collaborative data clearinghouse.
4. Identify and prioritize needs.
5. Conduct periodic literature searches to stay abreast of the latest information and monitoring tools that are becoming available.

6. Track initiatives being carried out at the national, regional, state and local levels that pertain to each habitat group.
7. Identify and pursue funding opportunities.

If the ANR and its partners conduct an inventory, they could start by reviewing the monitoring information that Tetra Tech compiled for this project (see Appendix 2A for climatic data, Appendix 4N for long-term monitoring data and Appendix 4O for data gaps). The following types of questions should be addressed:

- What indicators/parameters are being collected?
- Who is collecting these data?
- Where are the data being housed?
- What are the objectives of the monitoring program that these data are being collected for?
- Is the monitoring program likely to continue achieving its objectives in light of climate change?
- What else can we ask people to collect (e.g. should we ask citizens collecting lake ice out data to start collecting ice-in data as well?)
- Are there existing monitoring frameworks that can be utilized if we ask people to collect new information?

It is also important that the ANR and its partners give careful consideration to the indicators that are being collected and tracked over time. As noted throughout the workshops, non-traditional indicators such as ice-in and leaf-out dates are important in climate change monitoring. Effective indicators have the following characteristics (per Janeto et al. 2012):

- They represent a basic understanding of how a system (or some component of the system) works.
- They are quantitatively meaningful, can be tracked over time, and are able to be tied-back either to measurements or models.
- Their derivation is well-documented and transparent, and the data on which they depend are well understood with respect to their quality and heritage.
- They are able to represent uncertainties in underlying measurements and knowledge.
- They are easily interpreted and useful for decision-making.

In addition to these general needs, at the workshop and in Tetra Tech's data gap analysis, some specific themes emerged as having added importance. These included:

- **Climate change response/adaptation monitoring**. In this project initial steps were taken towards assessing vulnerabilities of habitats and species to climate change. These assessments are based largely on modeling and expert elicitation. It will be important for the ANR to collect observational data to track whether climatic changes are occurring as projected, whether species and habitats are responding as expected and which mediating factors (e.g. orientation, shading) provide the greatest buffering capacity against warming temperatures and changing precipitation patterns.

The State currently monitors forest health indicators annually from aerial survey and ground plot information on species distribution, growth, regeneration, mortality, soil conditions, spring and fall phenology, pests, and forest disturbances. As a partner in the Vermont Monitoring Cooperative, the State also monitors forest conditions at high elevations where other weather and environmental monitoring is co-located, such as on Mount Mansfield and in the Lye Brook Wilderness. Given the diverse nature of each forest stand, and the individual land use histories, stand level monitoring by forest professionals would greatly enhance understanding of forest changes and the effectiveness of adaptation strategies.

- Sentinel monitoring networks. Currently there is a lack of adequate time-series data to support analysis of trends and variability in ecologic conditions. To help fill this data gap, in recent years, various groups within the ANR have established long-term monitoring sites in minimally disturbed rivers, lakes and wetlands. Monitoring at these sites is currently being conducted by the Monitoring, Assessment & Planning Program, the Wetlands Program, and Lakes and Ponds. Each network should be re-evaluated in light of climate change (Is the current site selection adequate? Are ranges of elevational and latitudinal gradients being captured? Should more parameters be collected?). Some immediate needs for these networks, broken down by habitat group, include:

  - Rivers
    - Find funding to purchase water temperature sensors and pressure transducers for sites that lack gages
    - Seek assistance with installation of the pressure transducers
    - Develop thermal indicator metrics for stream macroinvertebrate taxa (Appendix 3K) and track trends in these metrics over time
    - Work with municipalities, regional commissions, and others to ensure that long-term gaging sites are continued

  - Wetlands
    - Find funding to support the hiring of an additional staff member
    - Work to resolve lab issues that arose after Irene

  - Lakes
    - Design an inland lakes monitoring network that has a mix of stratified and unstratified lakes
    - Research which parameters to collect (temperature, wind, cloud cover, ice, dissolved organic carbon (DOC[2]), water clarity, etc.)
    - Find funding for implementation

[2] DOC is the tea-colored material that comes largely from decomposition of terrestrial plants. It plays many important roles in aquatic ecosystems. In recent decades, studies have shown an approximate doubling in the amount of DOC in inland waters (Findlay 2005, Evans et al. 2006). DOC will be an important parameter to track in light of climate change because precipitation-driven increases in DOC concentration not only increase the cost of water treatment for municipal use (Haaland et al. 2010), but also may alter the ability of sunlight to inactivate parasites and pathogens in water, by absorbing ultraviolet radiation (UV) that would otherwise be an effective control (Staudinger et al. 2012).

- Forests
    - Use new tools such as "Biofinder" to re-assess forest monitoring locations.
    - For existing monitoring plots, intensify monitoring of regeneration as an indicator of the future forest.
    - Develop guidelines for and work towards broader implementation of monitoring at the stand level to evaluate changes and the effectiveness of adaptation strategies, including indicators such as:
        - early regeneration success (<6 years post harvesting),
        - level of tree dieback and mortality unassociated with harvesting,
        - frequency of species based on their regional distribution (northern or southern edge of range), and
        - frequency and intensity of disturbance agents (pests, droughts, fire, invasive plants).

- **Develop a statewide, cross-sector, long-term monitoring plan for brook trout**. Brook trout are considered to be highly vulnerable to climate change due to their specific thermal and hydrologic requirements (Appendix 4N). Different groups within and outside of the ANR (e.g. Monitoring, Assessment & Planning Program, Fisheries, Green Mountain National Forest) are currently collecting information on brook trout but there is not a cohesive statewide monitoring plan for tracking long-term trends in the distribution and abundance of this important species.

- **Citizen science** could help fill the void of biodiversity time series data if tools are provided to mobilize citizen scientists to deposit and share data in readily accessible networks (Staudinger et al. 2012). This would be a win-win because the ANR would get much needed data while raising public awareness and appreciation for biodiversity. Efforts should be made to expand and build on existing efforts in Vermont (see Appendix 4N), and to pursue an organized, collaborative approach with organizations statewide.

- **Airborne and satellite remote sensing**. Technological advancements continue to be made. Different types of sensors can now be combined on the same aircraft to provide information on ecosystem composition and function (Asner et al. 2008, Vierling et al. 2011, Swatantran et al. 2012). Eventually, these airborne sensors will be deployed on satellite platforms, which will enable global observations of key elements of biodiversity (some *in situ* data will still need to be collected in order to validate or "ground truth" the aerial imagery) (Staudinger et al. 2012). It is important that the ANR stay abreast of the latest technology and monitoring tools because a number of different types of imagery could potentially be used to help with monitoring efforts in forests, rivers[3], lakes and wetlands.

[3] At the workshop, the rivers group discussed how valuable it would be to obtain additional Light Detection And Ranging (LIDAR) imagery. Efforts are underway to collect statewide LIDAR imagery but they are slow to move forward due to funding limitations. In light of climate change, it would be valuable to collect multi-date imagery, so that sediment budgets could be calculated and tracked over time. Depending on the timing and frequency at which the imagery is taken, sediment estimates could potentially be correlated with specific storm events as well. To learn more, contact the Statewide LiDAR team (David Brotzman - davidb@vcgi.org).

- **Track the spread of invasive species.** Warming, an increase in the frequency of extreme events, and increasing carbon dioxide concentrations are thought to have facilitated the spread of invasive species (Driscoll et al. 2011). Efforts should be made to inventory as much of the State as possible for invasive species, upload the data into iMapInvasives (http://imapinvasives.org/vtimi/map/), forecast and prioritize emerging threats and develop proactive plans for early detection and eradication of the highest priority species. This is an area that could be aided by development of citizen monitoring.

Some resources that might be helpful to the ANR if it decides to pursue this focus area are listed in Table 35.

Table 35. Resources on monitoring and descriptions of regional and national monitoring initiatives.

Resource	Description
AFWA 2012	This document by the Association of Fish and Wildlife Agencies provides excellent guidance on monitoring strategies in light of climate change.
NCA Indicators (Janetos et al. 2012)	This report titled 'National Climate Assessment Indicators: Background, Development, & Examples' provides excellent guidance on the selection of indicators.
US EPA (2013, in progress)	In 2011-2012 with the assistance of Northeastern states and EPA Region 1, EPA's Global Change Impacts and Adaptation Group and Tetra Tech laid the analytical foundation for a pilot reference monitoring network for freshwater medium-high gradient wadeable streams in Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island and New York. Five sites in Vermont have been proposed for this network. For more information, contact Britta Bierwagen (Bierwagen.Britta@epamail.epa.gov). Tetra Tech is currently working with U.S. EPA on a document on Guidelines for Continuous Monitoring of Temperature and Flow in Wadeable Streams.
National Network of Reference Watersheds (NWQMC 2011)	Efforts are underway to establish a collaborative and multipurpose National Network of Reference Watersheds and Monitoring Sites for Freshwater Streams in the United States. National Water Quality Monitoring Council. (2011). These efforts are being coordinated with the GCRP network described above. More information is available at: http://acwi.gov/monitoring/workgroups/wis/National_Reference_Network_for_Streams.pdf
Hydrologic climate-response program (Hodgkins et al. 2009)	A framework has been established for U.S. Geological Survey hydrologic climate-response program in Maine. Efforts are underway to find funding for this network (pubs.usgs.gov/fs/2009/3044/pdf/fs2008-3044_508.pdf).
National initiatives on water supply and water quality issues (U.S. EPA 2012d)	In the National Water Program 2012 Strategy: Response to Climate Change report, EPA describes an initiative aimed at improving access to vetted climate data and hydrological science, modeling and assessment tools.
Euro-limpacs indicators (2013)	The Euro-limpacs consortium has done extensive work on identifying indicators for climate change impacts in Europe (http://www.climate-and-freshwater.info).
VFWD 2000	Evaluation of Wild Brook Trout Populations in Vermont Streams. Project No: F-36-R-3; this report could be used as a starting point for designing a statewide monitoring plan for tracking long-term trends in the distribution and abundance of brook trout.

4.3.3.4 Data infrastructure

Workshop participants would like to see a platform created that allows for sharing, accessing and disseminating information. This theme was also identified in Staudinger et al. 2012 ("improved observation capabilities, more sophisticated data infrastructures and modeling platforms, as well as coordinated, landscape-level monitoring approaches will continue to be essential in improving climate change research; greater coordination among observations, databases, modeling, and emerging policy mechanisms will increase our ability to detect, track, project, and understand climate induced changes in biodiversity").

If the ANR and its partners decide to pursue this focus area, they should consider performing the following tasks:

- Evaluate what is currently being done with monitoring and assessment data -
  - Is the current system adequate?
  - What type of information is currently being collected?
  - Who is collecting the information?
  - Where are those data being housed?
  - What types of new information does the ANR and its partners want to collect?
  - How will these data be used?
  - Who will be using these data?
  - What types of functionality will they want?
- Conceptualize options for storing and sharing information.
- Track data infrastructure initiatives being carried out at the national, regional, state, local levels.
- Identify potential funding opportunities.

4.3.3.5 Landscape-level planning

One of the main impacts of climate change will be to increase the likelihood and magnitude of shifts in the distributions of species, habitats, and ecosystems. Although Vermont's current network of protected lands and waters, and the many public, private and non-profit agencies involved, are important resources for protecting biodiversity and ecosystems, as habitats and species shift their locations, the current network of protected areas, the stewardship and management approaches used, and the process currently used to prioritize conservation parcels may become insufficient or require substantial changes. Many of the climate adaptation strategies that are now being designed focus on enhancing habitat connectivity (e.g., Heller and Zavaleta 2009, Groves et al. 2012, Manomet 2010c); but additional focus on conservation and conservation stewardship for resilience, and prioritizing acquisitions, will need to be incorporated as climate change effects are better understood.

Habitat connectivity and landscape-level planning were common themes at the adaptation strategies workshop as well. Strategies that were commonly cited across habitat groups included:

- Identify and preserve movement corridors, noting where this could also provide greater connectivity for the spread of invasive species.

- Improve habitat connectivity to facilitate movement of displaced organisms (e.g., by improving culvert sizing in road/bridge standards).
- Improve buffering to safeguard core, high-quality habitats or natural systems function.
- Conserve large blocks of habitat where large areas can facilitate adaptation and resilience.

If Vermont decides to pursue this focus area, it should consider forming a work group that:

- Conducts an inventory of the ANR actions and planning efforts aimed at enhancing habitat connectivity.
- Links to other land conservation funds, trusts, and organizations active in Vermont and adjacent states to get a consolidated picture of land conservation efforts and investments.
- Assesses these actions in light of climate-related impacts and vulnerabilities.
- Explores additional possibilities for implementing landscape-level planning.
- Identifies situations in which enhanced connectivity is likely to be undesirable (e.g. concerns have been raised about connected landscapes potentially becoming “pipelines” for invasive species).

There are a number of existing resources that can help aid in these efforts. Some examples are listed in Table 36.

Table 36. Resources for landscape-level planning.

Resource	Description
TNC	The Staying Connected Initiative (SCI). This is a Nature Conservancy-led four-state, 21-partner group of Vermont organizations and agencies that has come together to find ways to secure habitat connectivity.
Anderson et al. 2012 (terrestrial)	Utilize information gathered for the report “Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region.”
National initiatives on habitat corridors (U.S. EPA 2012d)	U.S. Environmental Protection Agency. 2012. National Water Program 2012 Strategy: Response to Climate Change**.** The NWP intends to develop a national framework for a network of remaining healthy watersheds and aquatic ecosystems, including natural infrastructure for habitat corridors, and intends to support state and tribal efforts.
BioFinder (VANR 2013) (aquatic and terrestrial)	BioFinder is a map and database identifying Vermont's lands and waters supporting high priority ecosystems, natural communities, habitats, and species. The most comprehensive assessment of its kind in Vermont, BioFinder was developed to further stewardship and conservation efforts (http://biofinder.vermont.gov/).

Northeast Aquatic Connectivity (Martin and Apse 2011)	Northeast Aquatic Connectivity - An Assessment of Dams on Northeastern Rivers (http://static.rcngrants.org/sites/default/files/final_reports/NEAquaticConnectivity_Report.pdf)
Invasive speciesmapping (TNC 2013)	Continued mapping of invasive species across the state will take on added importance (http://imapinvasives.org/vtimi/map/).
Jackson and Pringle 2010	Journal article that describes situations in intensively developed landscapes in which *reduced* hydrologic connectivity is desirable.
VT DEC (streams)	Make use of the existing Tactical Basin Planning framework.

4.3.3. 6 Groundwater

Groundwater is a very important yet poorly understood resource. Groundwater flow paths are often complex; data and information are limited, difficult to collect and highly technical; and in-depth study and analysis can be expensive (Brown et al. 2007). Despite our knowledge gaps, we do know that groundwater can serve very important ecological functions in aquatic systems. In streams, wetlands and lakes, it can help maintain flows that are vital to organisms, and baseflow or cool water inputs can help mediate responses to warming temperatures (Brown et al. 2007, Tague et al. 2008). Groundwater is also important for humans since it provides much of the Nation's public and domestic water supply and supports agricultural and industrial pursuits (USGS 2009). We are unsure exactly how groundwater will be affected by climate change, but do know that changes in temperature and precipitation patterns can have a substantial influence on recharge, discharge, and water-table fluctuations in many aquifers (USGS 2009), and that groundwater dynamics vary over space and time based on climate, topography, landscape, and geological characteristics.

At the adaptation strategies workshop, participants expressed an interest in trying to move forward with the following items:

1. **Find funding for the "Comprehensive Groundwater Characterization of Targeted Watersheds" modeling exercise**, which would look at water budgets and base flow issues. The models would allow for the testing of various scenarios related to groundwater/surface water interaction on a watershed scale. The Vermont Geological Survey (VGS) has proposed this work through a DEC strategic planning process. If funding is obtained, it will take two years from July 1, 2013 to finish two targeted watersheds.
2. People acknowledged a **general need for developing a better understanding of groundwater resources (extent, source and movement) in Vermont**. Information on base flow availability and/or contributions is needed in order to develop water quantity and water quality management strategies.
3. **Integrating groundwater into the Surface Water Management Strategy**. Interactions between surface and groundwater are difficult to observe and measure (thus, groundwater is often ignored in water-management considerations and policies), but the importance of considering ground water and surface water as a single resource has become increasingly evident (Winter et al. 1998).
4. **Establishing a sentinel groundwater monitoring network**. Currently there is a groundwater level monitoring network funded by the USGS that consists of 13 wells in different geographic areas. With funding cuts, USGS is carrying a minimal network of sand and gravel wells. The network's main purpose is to get a sense of drought conditions in the State. Limitations of the current network include:

    - There are no bedrock wells in the system (groundwater in Vermont is generally contained in either bedrock fractures or glacial deposits of sand and gravel).
    - The network does not monitor for water quality.

Additional data gaps were evident to Tetra Tech as this report was compiled. These include:

- Developing a better understanding of which species depend on groundwater, and how/why they rely on groundwater.
- Developing a better understanding of how alterations in the amount and quality of groundwater affect groundwater-dependent biodiversity.
- A state-wide inventory or mapping of groundwater resources that integrates with or builds off of the geologic map that was recently completed (Ratcliffe et al. 2011) would be useful. This would apply to both water availability and to water quality.
- Learn more about recharge rates.

Some outside resources that could potentially serve as useful models for furthering knowledge of groundwater resources in Vermont are listed in Table 37. This list is not all-encompassing.

Table 37. Outside resources that could potentially serve as useful models for furthering our knowledge of groundwater resources in Vermont.

Resource	Description
Brown et al. 2007	A Methods Guide for Integrating Groundwater Needs of Ecosystems and Species into Conservation Plans in the Pacific Northwest. Limited tools are available for identifying linkages between biodiversity and patterns of groundwater systems. This guide can be used by people with no technical training in groundwater hydrology. It was developed for the Pacific Northwest, so rock permeability would be quite different in Vermont, but otherwise it could be a reasonable analogy.
California's Groundwater Ambient Monitoring & Assessment Program (GAMA) project	CA has a program designed to assess water quality basin by basin, for a host of constituents related to specific issues. It combines water quality, geochemistry, geology, and flow to understand and assess the resource (http://www.waterboards.ca.gov/gama/).
New York State Groundwater Assessment	NY has a program to assess ambient ground water quality in basins across the state. Using a basin approach similar to that used for the surface water program, they sample in each of NY's 8-digit Hydrologic Unit Code (HUC) basins over a 5-year period. This is conducted jointly with USGS. (http://www.dec.ny.gov/docs/water_pdf/305bgrndw10.pdf).
New Hampshire Groundwater Assessment	Statewide aquifer maps like New Hampshire's could be helpful for statewide planning (e.g. Moore et al. 2002 - http://water.usgs.gov/pubs/pp/pp1660/).

In addition to groundwater quality and quantity, Vermont should also evaluate its groundwater regulations in light of climate change to understand potential vulnerabilities for this resource. Climate change could contribute to an increased demand for water withdrawals within the State (e.g. more irrigation due to prolonged summer low flow periods; increased withdrawals for snowmaking due to a decreased snow pack), as well as from outside the State (e.g. water shortages in other States, contamination of drinking water supplies).

4.3.3.7 Sustainable flows

Extended summer low flow periods are projected to occur in Vermont due to changing patterns of precipitation and snowmelt and increased water loss due to evaporation as a result of warmer temperatures. At the adaptation strategies workshop, participants in the rivers and lakes breakout sessions expressed concerns about impacts this will have on water supply, water quality and habitat functions. Ecological impacts were discussed, since flow regime is a primary determinant of the structure and function of aquatic and riparian ecosystems. Workshop participants also talked about impacts on water use and infrastructure, since water needs for agriculture, industry, and energy production, and waste water treatment are likely to increase, and even moderate reductions in low summer flows could put pressure on surface water resources (UCS 2006a). Balancing human and ecological needs is likely to become more challenging in the future.

If the ANR and its partners decide to pursue this focus area, they should consider performing the following tasks:

- Assess Vermont's current flow regulations in light of climate-related impacts and vulnerabilities -
    - Are they forward-looking and climate-informed?
    - Do they adequately protect Vermont's water resources given the changes in hydrology that are projected to occur (in particular the extended summer low flows)?
    - Do they take into account anticipated changes in water demand (e.g. increase in water withdrawals and water storage for irrigation)?
    - Do they adequately account for ecological considerations?
    - Is adequate information available to make informed decisions?
- Evaluate whether the flow statistics that typically constitute design flows for water quality planning (e.g. 7Q10s - the lowest 7-day average flow that occurs (on average) once every 10 years) will still be adequate under future climate scenarios.
- Explore proactive actions that could be taken to ensure that drinking water and wastewater systems (water sector) are sustainable and can fulfill their public health and environmental mission.
- Track national and regional initiatives and potential funding opportunities.

If it is concluded that updates should be made to Vermont's flow regulations, there are a number of resources that Vermont could look to for guidance. Some examples are listed in Table 38. These include Ecological Limits of Hydrologic Alteration (ELOHA), which is a framework for developing regional environmental flow standards. Vermont can also learn from actions taken by other states, such as Maine. In 2007, Maine became the first state in the USA to adopt statewide environmental flow and lake level standards based on principles of natural flow variation necessary to protect aquatic life resources and important hydrological processes (for more details, see Table 38). Descriptions of actions that other states have taken can be found in Appendix 4P.

Table 38. Resources that Vermont could look to for guidance on sustainable flow issues.

Resource	Description
Maine Department of Environmental Protection 2007	Chapter 587: In-stream Flows and Lake and Pond Water Levels. To enact this rule, Maine set up an incentive program with farmers and an Agricultural Water Management Board to coordinate activities. The Board is comprised of members from Maine DEP, Department of Agriculture, federal agencies, and various commodity groups. Funds come from NRCS, which uses the rule as source for accessing EQIP and AMA funds. The state initially passed an irrigation bond as well to provide additional funds (that has now run out). DEP works closely with potato growers, which have the greatest irrigation demands, and public water supply companies. For more information, contact Nick Archer: nick.d.archer@maine.gov.
ELOHA (Poff et al. 2010)	Journal article on the Ecological Limits of Hydrologic Alteration (ELOHA): a new framework for developing regional environmental flow standards.
Massachusetts Sustainable-Yield Estimator (Archfield et al. 2010)	A decision-support tool to assess water availability at ungaged stream locations in Massachusetts (pubs.usgs.gov/sir/2009/5227/).
National initiatives on water supply and water quality issues (U.S. EPA 2012d)	U.S. Environmental Protection Agency. 2012. National Water Program 2012 Strategy: Response to Climate Change (http://water.epa.gov/scitech/climatechange/2012-National-Water-Program-Strategy.cfm)
EPA's Climate Resilience Evaluation and Awareness Tool (CREAT) (2013b)	Software that assists drinking water and wastewater utility owners and operators in assessing their risk to potential climate change impacts(http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm)
Handbook for Water and Wastewater Utilities (U.S. EPA 2012e)	Planning for Sustainability – A Handbook for Water and Wastewater Utilities, Report EPA-832-R-12-001. (http://water.epa.gov/infrastructure/sustain/upload/EPA-s-Planning-for-Sustainability-Handbook.pdf).
Climate Ready Water Utilities Toolbox (U.S. EPA 2011)	Provides access to resources containing climate-related information relevant to the water sector (http://www.epa.gov/safewater/watersecurity/climate/toolbox.html.http://www.epa.gov/safewater/watersecurity/climate/toolbox.html).
Safe Water RI (in progress)	Tetra Tech is evaluating the impacts of climate change on drinking water utilities in Rhode Island. This project will be completed in 2013.
WaterSMART (USBR 2011)	A publication by the U.S. Department of the Interior, Bureau of Reclamation on how to Sustain and Manage America's Resources (http://www. usbr.gov/WaterSMART/)

4.3.3.8 Ecosystem services

Humans benefit from a multitude of resources and processes that are supplied by ecosystems, such as timber and agricultural yields, recreation (e.g. winter sports, angling), nutrient cycling, waste processing and protection from natural hazards. Some refer to these as "ecosystem services." It is easier to place a value built infrastructure than on ecosystem services, since the former have easily recognized economic value. Vehicles like fishing licenses, stormwater permits, wetland mitigation, etc. are attempts to put monetary value on ecosystem services. However, the valuation attempts do not capture all of the services provided by ambient environmental systems, such as a forest stand in a potential development zone. In addition, the valuation is often based on willingness to pay rather than on comprehensive loss of benefit due to management of the ecosystem. Identifying and conveying clear connections between biodiversity loss, reduced ecosystem services, and societal benefits remains a challenge (Staudinger et al. 2012).

At the workshop, participants expressed an interest in doing a better job of identifying and quantifying the goods and services that ecosystems provide, especially since climate change is likely going to result in the loss or disruption of some ecosystem functions. This is an active area of research, and more and more guidance documents and tools are becoming available (for some examples, see Table 39). Not all of these approaches require converting things to a dollar value; measures like reduced risk, jobs and human well-being can also be effectively captured (Reyers et al. 2012).

If the ANR and its partners decide to pursue this focus area, they should consider performing the following tasks:

1. Review resources like the ones listed in Table 39
2. Work on developing language/information on ecosystem services that could potentially be integrated into planning documents and educational materials
3. Conduct periodic literature searches to stay abreast of the latest information and tools
4. Track the international and national initiatives (IPBES and QuEST) that are described in Table 39.

Table 39. Examples of initiatives, guidance documents and tools for assigning values to ecosystem services.

Resource	Description
Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)	Established in 2010, this organization is akin to an Intergovernmental Panel on Climate Change (IPCC) for biodiversity (see Larigauderie and Mooney 2010). IPBES provides an international policy framework for domestic action linking its assessments of climate to those for biodiversity and ecosystem services.
White House report (PCAST 2011)	The White House charged the Federal interagency community to conduct a Quadrennial Ecosystems Services Trends (QuEST) Assessment, which will provide an integrated and comprehensive overview of the condition of the country's ecosystems, with projected trends in ecosystem change. This effort will be closely coordinated with the National Climate Assessments.
Staudinger et al. 2012	Chapter 7 Proposed Actions for the Sustained Assessment of Biodiversity, Ecosystems, and Ecosystem Services.
Griffiths et al. 2012	U.S. Environmental Protection Agency Valuation of Surface Water Quality Improvements. This article addresses three issues that have been particularly challenging in estimating the benefits from water quality improvement: defining standardized measures of water quality improvement, measuring benefits arising from ecological protection and restoration, and measuring nonuse benefits.
U.S. GCRP, National Climate Assessment 2011	Valuation Techniques and Metrics for Climate Change Impacts, Adaptation, and Mitigation Options (http://globalchange.gov/images/NCA/valuation%20workshop%20report_final_12-13-2011.pdf).
Perrings et al. 2011	Journal article on the Biodiversity and Ecosystem Services Science-Policy Interface.
U.S. EPA 2010	Guidelines for Preparing Economic Analyses (http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf).
UCS 2009	Quantifies the cost of inaction in the report titled "Climate Change in the United States – The Prohibitive Costs of Inaction."

4.4 Summary

This report can be used as a reference in future planning steps as the ANR continues to address climate change effects to sensitive natural resources. The framework described within this document and presented during two workshops can become the basis for future climate change processes. The basic structure of the framework includes (1) projections of climate change exposures, (2) evaluation of the vulnerability of habitats and species, and (3) definition of adaptation actions, strategies, and priorities. Each of these steps was initiated during preparation of this report using existing literature and regional studies as well as input from natural resource and climate experts. These initial efforts could not be comprehensive and do not represent a climate change plan. They are merely examples of parts of a process that the ANR can use as a basis in ongoing efforts, either as a unified agency-wide climate change plan or for integrating climate information into existing planning efforts.

From the multiple existing statewide and regional climate change projections, we see that there is general consensus that temperatures are likely to rise, precipitation patterns will change, and extreme weather events will occur more frequently and to greater degrees. While multiple sources agree on the general trends, they do not agree completely on the magnitude of the changes over equal time periods. We can be relatively certain that the trends are evidence of future conditions and we will experience the projected changes, though the time-frame is uncertain. While we see variation in projections across the northeast region, variation of effects in Vermont are associated with latitude and elevation only in theory.

Vulnerability assessments were conducted to identify which species or habitats are likely to be most strongly affected by projected climatic changes and to understand why these resources are likely to be vulnerable. The results presented in this report are based largely on expert elicitation and modeling, and represent a compilation of information from the first workshop, follow-up exchanges, reports from other states, the regional NEAFWA report and published literature. Results should be reviewed closely and developed in greater depth as more information becomes available. The process that was developed for documenting exposures, sensitivities, and mediating factors at the first workshop could be used if additional habitats and species of interest are assessed in the future.

The adaptation actions arrived at during the second workshop represent substantial strategies for implementation in the future. The strategies are in keeping with what is being published in other states. However, the workshop was limited in scope due to time constraints. The identified strategies will need to be developed in greater depth and additional strategies need to be identified to address new approaches and different vulnerabilities. The process by which adaptation actions were derived can be repeated to identify new strategies. The workshop format and worksheets allow exploration of the feasibility of implementation of actions, at least as a first step.

Dire warnings of warming trends continue to dominate the current media with regards to climate change. Extreme weather events such as superstorms Irene and Sandy have been experienced in Vermont and the region. Because these trends and conditions are expected to continue, the ANR should be encouraged that investment in climate change adaptation will pay off with protections of natural resources. Although the projections and vulnerabilities are full of uncertainties, existing climate trends which may compound existing stressors should add emphasis to the urgency in treating the stressors, at least.

5 Literature Cited

Adaptation Subcommittee to the Governor's Steering Committee on Climate Change. (2010). The Impacts of Climate Change on Connecticut Agriculture, Infrastructure, Natural Resources and Public Health. (pp. 195). Available from http://www.ct.gov/deep/lib/deep/climatechange/impactsofclimatechange.pdf

Association of Fish and Wildlife Agencies, Teaming With Wildlife Committee, State Wildlife Action Plan (SWAP) Best Practices Working Group. 2012. Best Practices for State Wildlife Action Plans—Voluntary Guidance to States for Revision and Implementation. Washington (DC): Association of Fish and Wildlife Agencies. 80 pages. Available online: http://www.fishwildlife.org/files/SWAPBestPractices.pdf

AFWA (Association of Fish and Wildlife Agencies). 2009. Voluntary Guidance for States to Incorporate Climate Change into State Wildlife Action Plans and Other Management Plans. Washington, DC: AFWA. Available online: http://www.fishwildlife.org/files/AFWA-Voluntary-Guidance-Incorporating-Climate-Change_SWAP.pdf

Allen, J. D. 1995. Stream ecology: Structure and function of running waters. Chapman & Hall, New York, 388 pp.

Amiro, B. D., B. J. Stocks, M. E. Alexander, M. D. Flannigan, and B. M. Wotton. 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. International Journal of Wildland Fire 10:405–413.

Anderegg , W.R.L, Kane, J.M. and L.D.L. Anderegg. 2012. Consequences of Widespread Tree Mortality Triggered by Drought and Temperature Stress. Nature Climate Change. Advance online publication. Available from: http://wrlanderegg.com/wp-content/uploads/2011/11/Andereggetal2012_NatureClimChange_ConsequencesForestDieOff.pdf

Anderson, M. G., Clark, M. and Sheldon, A. O. 2012. Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region. (pp. 168) The Nature Conservancy Eastern Conservation Science.

Anderson, M. G. and Ferree, C. E. 2010. Conserving the Stage: Climate Change and the Geophysical Underpinnings of Species Diversity. PLoS ONE, 5(7), e11554. Retrieved from http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0011554

Archfield, S. A., Vogel, R. M., Steeves, P. A., Brandt, S. L., Weiskel, P. K. and Garabedian, S. P. (2010). The Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungaged stream locations in Massachusetts. (Scientific Investigations Report 2009–5227). Reston, VA: U.S. Geological Survey. Available from http://pubs.usgs.gov/sir/2009/5227/

Ashcroft, M.B. 2010. Identifying refugia from climate change. Journal of Biogeography 37: 1407–1413. Available online: http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2699.2010.02300.x/pdf

Asner G.P., Hughes R.F., Vitousek P.M., Knapp D.E., Kennedy-Bowdoin T., Boardman J., Martin R.E., Eastwood M., and Green R.O. 2008. Invasive plants transform the three-dimensional structure of rain forests. Proceedings of the National Academy of Sciences 105: 4519-4523.

Betts, A. K. 2011a. Vermont Climate Change Indicators. Weather, Climate and Society 3:106-115.

Betts, A. K. 2011b. Climate Change in Vermont (unpublished report). Available online: http://www.anr.state.vt.us/anr/climatechange/Pubs/VTCCAdaptClimateChangeVTBetts.pdf

Bottrill MC, Joseph LN, Carwardine J, Bode M, Cook C, Game ET, Grantham H, Kark S, Linke S, McDonald-Madden E, Pressey RL, Walker S, Wilson KA, and Possingham HP. 2008. Is conservation triage just smart decision making? Trends in Ecology and Evolution 23: 649-654.

Brooks, A. and Zastrow, J. (2002). The Potential Influence of Climate Change on Offshore Primary Production in Lake Michigan. *J. Great Lakes Res.*, *28*(4), 597–607.

Brown, T. J., B. L. Hall, and A. L. Westerling. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: An applications perspective. Climatic Change 62:365–388.

Brown, J., Wyers, A., Aldous, A. and Bach, L. 2007. Groundwater and Biodiversity Conservation: A Methods Guide for Integrating Groundwater Needs of Ecosystems and Species into Conservation Plans in the Pacific Northwest. (pp. 176) The Nature Conservancy. Available from http://www.waconservation.org/data/collins/GroundwaterMethodsGuideTNC_Jan08.pdf

California Environmental Protection Agency. 2013. GAMA – Groundwater Ambient Monitoring & Assessment Program [web page]. Available from http://www.waterboards.ca.gov/gama/

Choudhury A. (Ed). 2012. AFWA 2011 State Climate Adaptation Summary Report. Washington, DC: Association of Fish and Wildlife Agencies. Available at: http://www.fishwildlife.org/files/AFWA2011StateClimateAdaptationSummaryReport.pdf

Collins, M. J. 2009. Evidence for changing flood risk in New England since the late 20th century. Journal of the American Water Resources Association 45:279–290.

Comer, P. J., B. Young, K. Schulz, G. Kittel, B. Unnasch, D. Braun, G. Hammerson, L. Smart, H. Hamilton, S. Auer, R. Smyth, and J. Hak.. 2012. Climate Change Vulnerability and Adaptation Strategies for Natural Communities: Piloting methods in the Mojave and Sonoran deserts. Report to the U.S. Fish and Wildlife Service. NatureServe, Arlington, VA. Available from https://connect.natureserve.org/publications/hccvi

Conroy MJ, Runge MC, Nichols JD, Stodola KW, Cooper RJ. 2011. Conservation in the face of climate change: the roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty. *Biological Conservation* 144: 1204-1213

ConserveOnline. (2012). ELOHA Toolbox. The Nature Conservancy. Available from http://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/ELOHA/Pages/ecological-limits-hydrolo.aspx

Craig RK. 2010. “Stationarity is dead” – long live transformation: five principles for climate change adaptation law. Harvard Environmental Law Review 34: 9-75.

Cross, M.S., Zavaleta, E.S., Bachelet, D., Brooks, M.L. , Enquist, C.A.F., Fleishman, E., Graumlich, L.J., Groves, C.R., Hannah, L., Hansen, L., Hayward, G., Koopman, M., Lawler, J.J. , Malcolm, J., Nordgren, J., Petersen, B., Rowland, E.L., Scott, D., Shafer, S.L., Shaw, M.R. and G.M. Tabor. 2012. The Adaptation for Conservation Targets (ACT) Framework: A Tool for Incorporating Climate Change into Natural Resource Management. Environmental Management 50(3): 341-351.

Dawson TP, Jackson ST, House JI, Prentice IC, and Mace GM. 2011. Beyond predictions: Biodiversity conservation in a changing climate. *Science* 332:53-58.

DeGaetano, A.T., and R.J. Allen. 2002. Trends in twentieth-century temperature extremes across the United States. Journal of Climate 15:3188–3205.

Donelson JM, Munday PL, McCormick MI, and Pitcher CR. 2011. Rapid transgenerational acclimation of a tropical reef fish to climate change. Nature Climate Change 2: 30-32.

Driscoll DA, Felton A, Gibbons P, Felton AM, Munro NT and Lindenmaye DB. 2011. Priorities in policy and management when existing biodiversity stressors interact with climate change. *Climatic Change 111:* 533-557.

Dudley, R.W., and Hodgkins, G.A. 2005. Trends in timing, magnitude, and duration of summer and fall/winter streamflows for unregulated coastal river basins in Maine during the 20th century: U.S. Geological Survey Scientific Investigations Report 2005–5021, 26 p.

Dudley R.W., and Hodgkins, G.A. 2002. Trends in streamflow, river ice, and snowpack for coastal river basins in Maine during the 20th century: U.S. Geological Survey Water-Resources Investigations Report 02–4245, 26 p.

Elosegi, A., Diez, J. and Mutz, M. 2010. Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. Hydrobiologia 657: 199–215.

Euro-limpacs. 2013. Climate change –a threat to aquatic ecosystems [web page]. Available from http://www.climate-and-freshwater.info/

Evans CD, Chapman PJ, Clark JM, Monteith DT, and Cresser MS. 2006. Alternative explanations for rising dissolved organic carbon export from organic soils. *Global Change Biology* **12**: 2044-2053.

Fazey I, Gamarra JGP, Fischer J, Reed MS, Stringer LC, and Christie M. 2010. Adaptation strategies for reducing vulnerability to future environmental change. *Frontiers in Ecology and Environment* **8**: 414-422.

Findlay SEG. 2005. Increased carbon transport in the Hudson River: unexpected consequence of nitrogen deposition? *Frontiers in Ecology and the Environment* **3**: 133-137

Foden, W., Mace, G., Vié, J.-C., Angulo, A., Butchart, S., DeVantier, L., Dublin, H., Gutsche, A., Stuart, S. and Turak, E. 2008. Species susceptibility to climate change impacts. In: J.-C. Vié, C. Hilton-Taylor and S.N. Stuart (eds). The 2008 Review of The IUCN Red List of Threatened Species. IUCN Gland, Switzerland. Available online: http://cmsdata.iucn.org/downloads/climate_change_and_species.pdf

Galbraith, H. 2012. DRAFT NY Habitat Vulnerability Assessments.

Gawler, S.C., M.G. Anderson, A.P. Olivero, and M. Clark, M. 2008. The Northeast Habitat Classification and Mapping Project (NEHCMP). A report to the Virginia Department of Game and Inland Fisheries on behalf of the Northeast Association of Fish and Wildlife Agencies and the National Fish and Wildlife Foundation. Final Report. NatureServe, Boston. Available from http://rcngrants.org/content/northeastern-terrestrial-wildlife-habitat-classification

Girvetz, E. H., Zganja, C., Raber, G. T., Maurer, E. P., Kareiva, P. and Lawler, J. J. 2009. Applied Climate-Change Analysis: The Climate Wizard Tool. *PLoS ONE*, *4*(12), e8320. Retrieved from
http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0008320

Glick P, Stein BA, and Edelson N. 2011a. Scanning the Conservation Horizon: a Guide to Climate Change Vulnerability Assessment. Washington, DC: National Wildlife Federation. Available at: http://www.nwf.org/vulnerabilityguide

Glick P, Chmura H, and Stein BA. 2011b. Moving the Conservation Goalposts: A Review of Climate Change Adaptation Literature. Washington, DC: National Wildlife Federation. Available at: http://www.nwf.org/~/media/PDFs/Global-Warming/Reports/Moving-the-Conservation-Goalposts-2011.ashx

Goode, J.R., Luce, C.H. and Buffington, J.M. 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology 139-140: 1–15.

Griffiths, C., Klemick, H., Massey, M., Moore, C., Newbold, S., Simpson, D., Walsh, P. and W. Wheeler. 2012. U.S. Environmental Protection Agency Valuation of Surface Water Quality Improvements. Review of Environmental Economics and Policy, 6(1): 130–146.

Groves CR, Game ET, Anderson MG, Cross M, Enquist C, Ferdana Z, Girvetz E, Gondor A, Hall KR, Higgins J, Marshall R, Popper K, Schill S, and Shafer SL. 2012. Incorporating climate change into systematic conservation planning. Biodiversity and Conservation. Available online: https://adapt.nd.edu/resources/274

Haaland S, Hongve D, Laudon H, Riise G, and Vogt RD. 2010. Quantifying the drivers of the increasing colored organic matter in boreal surface waters. Environmental Science & Technology 44: 2975-2980.

Hagerman S, Sowlatabadi H, Satterfield T, and McDaniels T. 2010. Expert views on biodiversity conservation in an era of climate change. *Global Environmental Change* 20: 192-207.

Halofsky JE, Peterson DL, O'Halloran KA, and Hawkins-Hoffman C (Eds). 2011. Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Hansen, J., Sato, M. and R. Ruedy. 2012. Perception of climate change. Proceedings of the National Academy of Sciences 109 **(37)**: E2415-E2423.

Hayhoe, K., C. P. Wake, T. G. Huntington, L. Luo, M. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the U.S. Northeast. Climate Dynamics 28:381-407.

Heathwaite AL. 2010. Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. Freshwater Biology 55: 241–257.

Heller NE and Zavaleta ES. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological Conservation* 142: 14-32.

Hodgkins, G. A. 2010. Historical changes in annual peak flows in Maine and implications for flood-frequency analyses. U.S. Geological Survey Scientific Investigations Report 2010–5094.

Hodgkins, G. A., Lent, R. M., Dudley, R. W. and Schalk, C. W. 2009. Framework for a U.S. Geological Survey hydrologic climate-response program in Maine. (Open-File Report 2009–1115, pp. 29) U.S. Geological Survey. Available from pubs.usgs.gov/fs/2009/3044/pdf/fs2008-3044_508.pdf

Hodgkins, G.A., and Dudley, R.W. 2006a. Changes in late-winter snowpack depth, water equivalent, and density in Maine, 1926–2004: Hydrological Processes, v. 20, p. 741–751.

Hodgkins, G.A., and Dudley, R.W. 2006b. Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002: Geophysical Research Letters, v. 33: L06402, doi 10.1029/2005GL025593.

Hodgkins, G.A., and Dudley, R.W. 2005a. Changes in the magnitude of annual and monthly streamflows in New England, 1902–2002: U. S. Geological Survey Scientific Investigations Report 2005–5135, 37 p.

Hodgkins, G.A., Dudley, R.W., and Huntington, T.G. 2005b. Summer low flows in New England during the 20th century: Journal of the American Water Resources Association, v. 41, p. 403–412.

Hodgkins, G.A., Dudley, R.W., and Huntington, T.G. 2005c. Changes in the number and timing of days of ice-affected flow on northern New England rivers, 1930–2000: Climatic Change, v. 71, p. 319–340.

Hodgkins, G. A., R. W. Dudley, and T. G. Huntington. 2003. Changes in the timing of high river flows in New England over the 20th century. Journal of Hydrology 278:244–252.

Hodgkins, G.A., James, I.C., II, and Huntington, T.G. 2002. Historical changes in lake ice-out dates as indicators of climate change in New England, 1850–2000: International Journal of Climatology, v. 22, p. 1819–1827.

Horizon Systems. 2012. NHDPlus Version 1 (Archive) Data Extensions - NLCD 2001 Catchment Allocation and Accumulation Attributes. Available online: http://www.horizon-systems.com/NHDPlus/NHDPlusV1_download.php#NLCD 2001 Catchment Allocation and Accumulation Attributes

Huntington, T.G., Hodgkins, G.A., Keim, B.D., and Dudley, R.W., 2004, Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000): Journal of Climate, v. 17, p. 2626–2636.

IPCC (Intergovernmental Panel on Climate Change). 2007a. Climate change 2007: working group II: impacts, adaptation and vulnerability. Cambridge, UK and New York, NY Cambridge University Press. Available from http://ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

IPCC (Intergovernmental Panel on Climate Change). 2007b. Climate change 2007: AR4 Synthesis report. Cambridge, UK and New York, NY: Cambridge University Press. Available from http://ipcc.ch/publications_and_data/ar4/syr/en/contents.html

IPCC (Intergovernmental Panel on Climate Change). 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press. Available from http://ipcc.ch/pdf/special-reports/srex/SREX_Full_Report.pdf

Isaak, D.J. and B.E. Rieman. 2013. Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. Global Change Biology 19: 742–751.

Iverson, L., Prasad, A. and Matthews, S. 2008. Modeling Potential Climate Change Impacts on the Trees of the Northeastern United States. *Mitigation and Adaptation Strategies for Global Change*(13), 517-540. Retrieved from http://treesearch.fs.fed.us/pubs/15295

Jackson, CR and CM Pringle. 2010. Ecological benefits of reduced hydrologic connectivity in intensively developed landscapes. BioScience 60:37-46.

Janeto et al. 2012. National Climate Assessment Indicators: Background, Development, & Examples. Available from http://downloads.usgcrp.gov/NCA/Activities/NCA-Indicators-Technical-Input-Report-FINAL--3-1-12.pdf

Karl, T.R., J.M. Melillo, and T.C. Peterson, (eds.). 2009. Global Climate Change Impacts in the United States. Cambridge University Press, 189 pp. Available online: http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

Kart, J., R. Regan, S.R. Darling, C. Alexander, K. Cox, M. Ferguson, S. Parren, K. Royar, B. Popp, editors. 2005. Vermont's Wildlife Action Plan. Vermont Fish & Wildlife Department. Available at: http://www.vtfishandwildlife.com/library.cfm?libbase_=Reports_and_Documents

Keim, B. D., M. R. Fischer, and A. M. Wilson. 2005. Are there spurious precipitation trends in the United States Climate Division database? Geophysical Research Letters 32:L04702.

Kliejunas, J.T. 2011. A risk assessment of climate change and the impact of forest diseases on forest ecosystems in the Western United States and Canada. Gen. Tech. Rep. PSW-GTR-236. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 70 p. Available from http://www.fs.fed.us/psw/publications/documents/psw_gtr236/

Kline, M. 2010a. Vermont ANR River Corridor Planning Guide: to Identify and Develop River Corridor Protection and Restoration Projects, 2nd edition. Waterbury, VT: Vermont Agency of Natural Resources. Available online: http://www.vtwaterquality.org/rivers/docs/rv_rivercorridorguide.pdf

Kline, M. 2010b. A Guide to River Corridor Easements. (pp. 31) Vermont Agency of Natural Resources Department of Environmental Conservation River Management Program. Available online: http://www.vtwaterquality.org/rivers/docs/rv_RiverCorridorEasementGuide.pdf

Kratz, T. K., K. E. Webster, J. L. Riera, D. B. Lewis, and A. I. Pollard. 2006. Making sense of the landscape: geomorphic legacies and the landscape position of lakes. Pages 49-66 in Magnuson, J. J., T. K. Kratz, and B. J. Benson (eds.) Long-Term Dynamics of Lakes in the Landscape: Long-Term Ecological Research on North Temperate Lakes. Oxford University Press, New York. 400pp.

Lake Champlain Basin Program (LCBP). 2010 . Missisquoi Bay Basin Project: Identification of Critical Source Areas of Phosphorus Pollution. Available online: http://northernlakechamplain.files.wordpress.com/2012/04/csa-final-report-stone-enviro-12-15-12.pdf

Lake Champlain Basin Program (LCBP). 2012. State of the Lake and Ecosystems Indicators Report. Available online: http://sol.lcbp.org/.

Lake Champlain Basin Program. 2013. Flood Resilience in the Lake Champlain Basin and Upper Richelieu River. Available online: http://www.lcbp.org/wp-content/uploads/2013/04/FloodReport2013_en.pdf

Langford, T. E. L., Langford, J. and S.J. Hawkins. 2012. Conflicting effects of woody debris on stream fish populations: implications for management. *Freshwater Biology*, *57*(5), 1096-1111. 10.1111/j.1365-2427.2012.02766.x Retrieved from http://dx.doi.org/10.1111/j.1365-2427.2012.02766.x

Larigauderie A, and Mooney HA. 2010. The intergovernmental science-policy platform on biodiversity and ecosystem services: moving a step closer to an IPCC-like mechanism for biodiversity. *Current Opinion in Environmental Sustainability* **2**: 9-14.

Lawler JJ, Tear TH, Pyke C, Shaw MR, Gonzalez P, Kareiva P, Hansen L, Hannah L, Klausmeyer K, Aldous A, Bienz C, and Pearsall S. 2010. Resource management in a changing and uncertain climate. Frontiers in Ecology and the Environment 8: 35-43.

Link JS, Nye JA, and Hare JA. 2010. Guidelines for incorporating fish distribution shifts into a fisheries management context. *Fish and Fisheries* **12**: 461-469.

Loarie S.R., Duffy P.B., Hamilton H.H., Asner G.P., Field C.B. and D.D. Ackerly. 2009. The velocity of climate change. Nature 462: 1052–1055.

Logan, J.A., Régnière, J. and J.A. Powell. 2003. Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and the Environment 1(3): 130-137. Available online: http://www.usu.edu/beetle/documents/Loganet.al.2003.pdf

Magness DR, Morton JM, Huettmann F, Chapin III FS, and McGuire AD. 2011. A climate change adaptation framework to reduce continental-scale vulnerability across conservation reserves. *Ecosphere* 2: article 112.

Magnuson, J. J., D. M. Robertson, B. J. Benson, R. H. Wynne, D. M. Livingstone, T. Arai, R. A. Assel, R. G. Barry, V. Card, E. Kuusisto, N. G. Granin, T. D. Prowse, K. M. Stewart, and V. S. Vuglinski. 2000. Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science 289:1743-1746.

Maine Department of Environmental Protection. 2007. Chapter 587: In-stream Flows and Lake and Pond Water Levels. Available online: http://www.maine.gov/sos/cec/rules/06/096/096c587.doc

Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife. 2010a. Climate Change and Massachusetts Fish and Wildlife: Volume 1 Introduction and Background. Available from: http://www.mass.gov/eea/docs/dfg/dfw/habitat/cwcs/climate-change-intro.pdf

Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife. 2010b. Climate Change and Massachusetts Fish and Wildlife: Volume 2 Habitat and Species Vulnerability. Available from: http://www.mass.gov/eea/docs/dfg/dfw/habitat/cwcs/climate-change-habitat-vulnerability.pdf

Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife. 2010c. Climate Change and Massachusetts Fish and Wildlife: Volume 3 Habitat Management. Available from: http://www.mass.gov/eea/docs/dfg/dfw/habitat/cwcs/climate-change-habitat-management.pdf

Manomet Center for Conservation Sciences and National Wildlife Federation. 2012a. The Vulnerabilities of Fish and Wildlife Habitats in the Northeast to Climate Change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet, MA.

Manomet Center for Conservation Sciences and the National Wildlife Federation. 2012b. Climate change and cold water fish habitat in the Northeast: a vulnerability assessment. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative Manomet, Plymouth, MA.

Martin, E. H. and Apse, C. D. 2011. Northeast Aquatic Connectivity - An Assessment of Dams on Northeastern Rivers. (pp. 102) The Nature Conservancy, Eastern Freshwater Program. Available from http://static.rcngrants.org/sites/default/files/final_reports/NEAquaticConnectivity_Report.pdf

Matthews, S. N., Iverson, L. R., Prasad, A. M. and Peters, M. P. (2007-ongoing). A Climate Change Atlas for 147 Bird Species of the Eastern United States [database]. Delaware, OH: Northern Research Station, USDA Forest Service. Available from http://www.nrs.fs.fed.us/atlas/bird

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. Fine-resolution climate projections enhance regional climate change impact studies. Eos Trans. AGU 88:504.

Mawdsley JR, O'Malley R, and Ojima DS. 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. Conservation Biology 23: 1080-1089.

McGarigal, K., Compton, B., Plunkett, E., Willey, L., Delucca, B., Grand, J., et al. 2011. Assessment of Landscape Change in the North Atlantic Landscape Conservation Cooperative: Decision-Support Tools for Conservation. Available at: http://www.northatlanticlcc.org/resources/pdfs/McGarigal_Sustainable_Landscapes.pdf/at_download/file

Medalie, Laura, and Horn, M.A.2010. Estimated water withdrawals and return flows in Vermont in 2005 and 2020: U.S. Geological Survey Scientific Investigations Report 2010–5053, 53 p. Available online: http://pubs.usgs.gov/sir/2010/5053

Millar C, Stephenson NL, and Stephens SL. 2007. Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications* 17: 2145-2151.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? Science 319:573-574.

Milone & MacBroom. 2008. The Vermont Agency of Natural Resources Reach Habitat Assessment (RHA). (pp. 209) Vermont Agency of Natural Resources Departments of Environmental Conservation and Fish and Wildlife. Available from www.vtwaterquality.org/rivers/docs/rv_RHAProtocolReport.pdf

Milone & MacBroom, I. 2009. The Vermont Culvert Aquatic Organism Passage Screening Tool. (pp. 120). Waterbury, VT: Vermont Agency of Natural Resources Department Fish and Wildlife. Available from http://www.vtfishandwildlife.com/library/Reports_and_Documents/Aquatic%20Organism%20Passage%20at%20Stream%20Crossings/_The%20Vermont%20Culvert%20Aquatic%20Organism%20Passage%20Screening%20Tool.pdf

Milwaukee Metropolitan Sewerage District. 2013. Greenseams [web page]. Accessed on 1 February 2013. Available from http://v3.mmsd.com/greenseams.aspx

Montgomery, D., and J. Buffington. 1997. Channel-reach Morphology in Mountain Drainage Basins. Geological Society of America Bulletin; v. 109; no. 5; pp 596-611.

Monzón J, Moyer-Horner L, and Palamar MB. 2011. Climate change and species range dynamics in protected areas. *BioScience* **61**: 752-761.

Moore, R.B., Schwarz, G.E., Clark, S.F., Walsh, G.J. and J.R. Degnan. 2002. Factors Related to Well Yield in the Fractured-Bedrock Aquifer of New Hampshire . U.S. Geological Survey Professional Paper 1660. Available from http://water.usgs.gov/pubs/pp/pp1660/

Nakicenovic, N., J. Alcamo, G. Davis, B. deVries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T. Y. Jong, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi. 2000. Intergovernmental

Panel on Climate Change Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, UK. Available at:
http://ipcc.ch/pdf/special-reports/emissions_scenarios.pdf

National Climate Assessment and Development Advisory Committee (NCADAC). 2013. National Climate Assessment (draft). Available from http://ncadac.globalchange.gov/

National Water Quality Monitoring Council (NWQMC). 2011. Establishing a Collaborative and Multipurpose National Network of Reference Watersheds and Monitoring Sites for Freshwater Streams in the United States. Available from
http://acwi.gov/monitoring/workgroups/wis/National_Reference_Network_for_Streams.pdf

NatureServe. 2011. The NatureServe Climate Change Vulnerability Index (Version 2.1). Available online: http://www.natureserve.org/prodServices/climatechange/ccvi.jsp

New Hampshire Fish and Game. 2012. DRAFT Climate Change Vulnerability Assessments. Available from http://nhcollaborative.org/media/Adaptation_WG_Final_Report_100512.pdf

New York State. nd. New York State Groundwater Assessment. Accessed 1 February 2013. Available from http://www.dec.ny.gov/docs/water_pdf/305bgrndw10.pdf

Northeast Association of Fish and Wildlife Agencies (NEAFWA). 2011. Northeastern Terrestrial Habitat Classification System (NETHCS), a standardized terrestrial wildlife habitat classification system for the Northeast. Available online:
http://conserveonline.org/workspaces/ecs/documents/ne-terrestrial-habitat-mapping-project

Ohlson DW, McKinnon GA, and Hirsch KG. 2005. A structured decision-making approach to climate change adaptation in the forest sector. *The Forestry Chronicle* 81: 97-103.

Olivero, A. P. and Anderson, M. G. 2008. Northeast Aquatic Habitat Classification. The Nature Conservancy. Available from http://rcngrants.org/content/northeastern-aquatic-habitat-classification-project

Palmer et al. 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology 42: 208–217

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. *Annual Reviews of Ecology, Evolution, and Systematics* 37: 637-669.

President's Council of Advisors on Science and Technology (PCAST). 2011. Sustaining environmental capital: protecting society and the economy. 145 p. Available at:
http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_sustaining_environmental_capital_report.pdf

Pealer, S. and Dunnington, G. 2011. Climate Change and Vermont's Waters. Available from
http://www.anr.state.vt.us/anr/climatechange/Pubs/VTCCAdaptWaterResources.pdf

Perrings C, Duraiappah A, Larigauderie A, and Mooney H. 2011. The Biodiversity and Ecosystem Services Science-Policy Interface. *Science* **331**: 1139-1140.

Peterson DL, Millar CI, Joyce LA, Furniss MJ, Halofsky JE, Neilson RP, and Morelli TL. 2011. Responding to climate change in national forests: a guidebook for developing adaptation options. General Technical Report PNW-GTR-855. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Peterson GD, Cumming GS, and Carpenter SR. 2003. Scenario planning: a tool for conservation in an uncertain world. *Conservation Biology* **17**: 358-366.

Poff, N.L., J.D. Allan, M. B. Bain, J.R. Karr, K.L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. 1997. The natural flow regime: a new paradigm for riverine conservation and restoration. BioScience 47:769-784. Available online: http://rydberg.biology.colostate.edu/poff/PoffPublicationsPDF.htm#1997

Poff N.L., B. Richter, A.H. Arthington, S.E.Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M. Freeman, J. Henriksen, R.B. Jacobson, J. Kennen, D.M. Merritt, J. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme & A. Warner. 2010. The Ecological Limits of Hydrologic Alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology 55:147-170. Available online: http://rydberg.biology.colostate.edu/poff/PoffPublicationsPDF.htm#2010

Poiani KA, Goldman RL, Hobson J, Hoekstra JM, and Nelson KS. 2011. Redesigning biodiversity conservation projects for climate change: examples from the field. *Biological Conservation* 20: 185-201.

Poole, G. C. and C.H. Berman. 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation. *Environmental Management*, *27*(6), 787–802. doi: 10.1007/s002670010188 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11393314

Prasad, A. M., Iverson, L. R., Matthews, S. and Peters, M. 2007-ongoing. A Climate Change Atlas for 134 Forest Tree Species of the Eastern United States [database]. Delaware, OH: Northern Research Station, USDA Forest Service. Available from http://www.nrs.fs.fed.us/atlas/tree

PRISM Group, Oregon State University, 2012. http://www.prismclimate.org

Ratcliffe, N.M., Stanley, R.S., Gale, M.H., Thompson, P.J., and Walsh, G.J., 2011, Bedrock geologic map of Vermont: U.S. Geological Survey Scientific Investigations Map 3184, 3 sheets, scale 1:100,000. Available online: http://pubs.usgs.gov/sim/3184/

Reyers B, Polasky S, Tallis H, Mooney H, and Larigauderie A. 2012. Finding a Common ground for biodiversity and ecosystem services. *BioScience* 62(5): 503-507.

Ricupero, K. 2009. Changing streamflow patterns in the New England region: Implications for ecosystem services, water users and sustainable resources management. Master of Science thesis. Department of Civil and Environmental Engineering, University of Maine, Orono, 212 pages. Available at: http://digitalcommons.library.umaine.edu/etd/758/

Rodenhouse, N. L., Christenson, L. M., Parry, D. and Green, L. E. 2009. Climate change effects on native fauna of Northeastern forests. Canadian Journal of Forestry Research, 39, 249-263. Retrieved from www.esf.edu/efb/parry/pubs/Rodenhouse_etal_2009.pdf

Rosenzweig, C., Solecki, W., DeGaetano, A., Hassol, S. and Grabhorn, P. 2011. Responding to Climate Change in New York State: The ClimAID Integrated Assessment for Effective Climate Change Adaptation. Albany, NY: New York State Energy Research and Development Authority. Available from http://www.nyserda.ny.gov/-/media/Files/Publications/Research/Environmental/EMEP/climaid/responding-to-climate-change-synthesis.ashx

Rosgen, D. and L. Silvey, 1996. Applied River Morphology, Wildland Hydrology, Pagosa Springs, CO.

Ruhl JB. 2010. Climate change adaptation and the structural transformation of environmental law. *Environmental Law* 40: 363-431

Rustad, L., Campbell, J., Dukes, J.S., Huntington, T., Lambert, K.F., Mohan, J., Rodenhouse, N. 2012. Changing Climate, Changing Forests: The Impacts of Climate Change on Forests of the Northeastern United States and Eastern Canada. US Forest Service, Northern Research Station, General Technical Report NRS-99. Available from: http://nrs.fs.fed.us/pubs/41165

Schlesinger, M. D., Corser, J. D., Perkins, K. A. and White, E. L. 2011. Vulnerability of At-risk Species to Climate Change in New York. New York Natural Heritage Program. Available from http://www.natureserve.org/prodServices/climatechange/pdfs/ccvi_report_ny.pdf

Schumm, S. A. 1977. The Fluvial System. Wiley, New York, New York, USA.

Schwartz, M. D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern hemisphere. *Global Change Biology* 12:343–351.

Scott D and Lemieux C. 2005. Climate change and protected area policy and planning in Canada. *The Forestry Chronicle* 81: 696-703.

Smith, M.P., Schiff, R. and J. MacBroom. 2008. Active River Area: A Conservation Framework for Protecting Rivers & Streams.

Stager, J. C. and Thill, M. 2010. Climate change in the Champlain Basin: What natural resource managers can expect and do. The Nature Conservancy. TNC/NEAFWA. 2011. Northeast Terrestrial Habitat Mapping Project. Available from http://www.nature.org/cs/groups/webcontent/@web/@vermont/documents/document/prd_002936.pdf

Staudinger, M.D., Grimm, N.B., Staudt, A., Carter, S.L., Chapin III, F.S., Kareiva, P., Ruckelshaus, M. and B.A. Stein. 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. Cooperative Report to the 2013 National Climate Assessment. 296 p. Available at: http://www.globalchange.gov/what-we-do/assessment

Strayer, DL. 2010. Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshwater Biology 55: 152-174.

Swanston, C. and M. Janowiak. 2012. Forest adaptation resources: climate change tools and approaches for land managers. US Forest Service Gen. Tech. Rep NRS-87. Available online: http://www.nrs.fs.fed.us/pubs/40543

Swatantran A., Dubayah R., Goetz S., Hofton M., Betts M.G., Sun M., Simard M., and Holmes R. 2012. Mapping migratory bird prevalence using remote sensing data fusion. PLoS ONE 7: e28922.

Tague, C., Grant, G., Farrell, M., Choate, J. and Jefferson, A. 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change*, 86, 189–210.

The Nature Conservancy. 2008. A Classification of the Aquatic Communities of Vermont.

The Nature Conservancy. 2013. *i*MapInvasives [web page]. Accessed 1 February 2013. Available from http://imapinvasives.org

Thompson, Elizabeth H. 2002. Vermont's Natural Heritage: Conserving Biodiversity in the Green Mountain State. A Report from the Vermont Biodiversity Project. 48 pp. Available from https://www.uvm.edu/rsenr/sal/vbp/VBP.pdf

Thomspon, E. H. and Sorenson, E. R. 2000. Wetland, Woodland, Wildland – A Guide to the Natural Communities of Vermont. (pp. 454). Hanover, NH: The Nature Conservancy and the Vermont Department of Fish and Wildlife.

Trombulak, S. C. and R. Wolfson. 2004. Twentieth-century climate change in Northeast and New York, USA. Geophysical Research Letters 31.

Union of Concerned Scientists (UCS). 2006a. Climate Change in the U.S. Northeast - A Report of the Northeast Climate Impacts Assessment. Available at: http://www.climatechoices.org/assets/documents/climatechoices/NECIA_climate_report_final.pdf

Union of Concerned Scientists (UCS). 2006b. Vermont – Confronting Climate Change in the U.S. Northeast. Available online: http://www.climatechoices.org/assets/documents/climatechoices/vermont_necia.pdf

Union of Concerned Scientists (UCS). 2009. Climate Change in the United States - The Prohibitive Costs of Inaction. Available from http://www.ucsusa.org/assets/documents/global_warming/climate-costs-of-inaction.pdf

U.S. Bureau of Reclamation (USBR). 2011. WaterSMART: Sustain and Manage America's Resources for Tomorrow. U.S. Department of the Interior, Bureau of Reclamation, March 22, 2011. Available at: http://www.usbr.gov/WaterSMART/

USDA Natural Resources Conservation Service (NRCS). 2013. Wetlands Reserve Program [web page]. Accessed 1 February 2013. Available from http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/easements/wetlands/

U.S. Department of Agriculture, A. R. S. (2012). USDA Plant Hardiness Zone Map. Available from http://planthardiness.ars.usda.gov/PHZMWeb/#

U.S. EPA, National Center for Environmental Economics 2010. Guidelines for Preparing Economic Analyses. Available from: http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf

U.S. EPA, 2011. Climate Ready Water Utilities Toolbox. Available at: http://www.epa.gov/safewater/watersecurity/climate/toolbox.html.

U.S. Environmental Protection Agency (U.S. EPA). 2012a. Implications of climate change for bioassessment programs and approaches to account for effects. Global Change Research Program, National Center for Environmental Assessment, Washington, DC; EPA/600/R-11/036A. Available from the National Technical Information Service, Springfield, VA, and online at http://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=239585

U.S. EPA. 2012b. Recovery Potential Screening - Tools for Comparing Impaired Waters Restorability [web page]. Available from http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/recovery/index.cfm

U.S. EPA. 2012c. Identifying and Protecting Healthy Watersheds Concepts, Assessments, and Management Approaches. EPA 841-B-11-002. Available from http://water.epa.gov/polwaste/nps/watershed/hw_techdocument.cfm

U.S. Environmental Protection Agency. 2012d. National Water Program 2012 Strategy: Response to Climate Change. Available from http://water.epa.gov/scitech/climatechange/2012-National-Water-Program-Strategy.cfm

U.S. EPA. 2012e. Planning for Sustainability – A Handbook for Water and Wastewater Utilities, Report EPA-832-R-12-001. Available from http://water.epa.gov/infrastructure/sustain/upload/EPA-s-Planning-for-Sustainability-Handbook.pdf

U.S. EPA. 2013a (in progress). Watershed-Scale Climate Change Vulnerability Assessment in the Northeast. Global Change Research Program, National Center for Environmental Assessment, Washington, DC; EPA/600/R-11/xxx.

U.S. EPA. 2013b.Climate Resilience Evaluation and Awareness Tool (CREAT) [web page]. Available from http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm

USFWS (U.S. Fish and Wildlife Service) and NOAA (National Oceanic and Atmospheric Administration). 2012. National fish, wildlife, and plants climate adaptation strategy. Washington, DC: USFWS and NOAA. Available from http://www.wildlifeadaptationstrategy.gov/

U.S. Global Change Research Program. 2009. Climate literacy - the essential principles of climate sciences (second version). Available from http://www.globalchange.gov/resources/educators/climate-literacy

U.S. Global Change Research Program, National Climate Assessment. 2011. Valuation Techniques and Metrics for Climate Change Impacts, Adaptation, and Mitigation Options: Methodological Perspectives for the National Climate Assessment. NCA Report Series, Volume 8. Available from http://globalchange.gov/images/NCA/valuation%20workshop%20report_final_12-13-2011.pdf

USGS. 2009. Effects of Climate Variability and Change on Groundwater Resources of the United States. Fact Sheet 2009–3074. Available online: http://pubs.usgs.gov/fs/2009/3074/pdf/FS09-3074.pdf

USGS 2012. WaterQualityWatch -- Continuous Real-Time Water Quality of Surface Water in the United States, Real-Time Water Temperature. Available at: http://waterwatch.usgs.gov/wqwatch/map?state=vt&pcode=00010

van Vliet, M. T. H., Ludwig, F., Zwolsman, J. J. G., Weedon, G. P. and Kabat, P. 2011. Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water Resources Research*, *47*, W02544. Retrieved from www.agu.org/pubs/crossref/2011/2010WR009198.shtml

Vermont Agency of Natural Resources (VANR). 2005. Riparian Buffers and Corridors Technical Papers. Waterbury, VT. Available online: http://www.anr.state.vt.us/site/html/buff/buffer-tech-final.pdf

Vermont Agency of Natural Resources (VANR). 2011. Resilience: A Report on the Health of Vermont's Environment. Available online: www.anr.state.vt.us/anr/envrptsb/ANREnvReport2011.pdf.

Vermont Agency of Natural Resources (VANR). 2013. BioFinder [web page]. Accessed 1 February 2013.Available online: http://biofinder.vermont.gov/

Vermont Department of Environmental Conservation (VT DEC). 2004. Biocriteria for Fish and Macroinvertebrate Assemblages in Vermont Wadeable Streams and Rivers. Available from http://www.anr.state.vt.us/dec/waterq/bass/docs/bs_wadeablestream1b.pdf

Vermont Department of Environmental Conservation (VT DEC). 2013a. Vermont Surface Water Management Strategy [web page]. Accessed 1 February 2013. Available from http://www.vtwaterquality.org/swms.html

Vermont Department of Environmental Conservation (VT DEC). 2013b. River, River Corridor, & Floodplain Management Programs. Biennial Report to the General Assembly Pursuant to Act 110.

Vermont Department of Fish and Wildlife (VFWD). 2000. Evaluation of Wild Brook Trout Populations in Vermont Streams. Project No: F-36-R-3

Vermont Forest, Parks, & Recreation 2010. Vermont Forest Resources Plan and State Assessment & Resource Strategies. Available from http://www.vtfpr.org/htm/for_resourcesplan.cfm

Vermont Department of Fish and Wildlife (VFWD) 2012. Impacts to Stream Habitat and Wild Trout Populations in Vermont Following Tropical Storm Irene. Project No.: F-36-R-14.

Vierling K.T., Baessler C., Brandl R., Vierling L.A., Weiss I., and Mueller J. 2011. Spinning a laser web: predicting spider distributions using LiDAR. Ecological Applications 21: 577-588.

Wake, C. P. and A. Markham. 2005. Indicators of climate change in the Northeast 2005. Clean Air-Cool Planet, Portsmouth, NH.

Walker B, Holling CS, Carpenter SR, and Kinzig A. 2004. Resilience, adaptability and transformability in social–ecological systems. Ecology and Society 9: 5.

Weeks D, Malone P, and Welling L. 2011. Climate change scenario planning: a tool for managing parks into uncertain futures. Park Science 28: 26-33.

West JM, Julius SH, Kareiva P, Enquist C, Lawler JJ, Petersen B, Johnson AE, and Shaw MR. 2009. U.S. natural resources and climate change: concepts and approaches for management adaptation. Environmental Management 44: 1001-1021.

Whitman, A., Vickery, B., deMaynadier, P., Stockwell, S., Walker, S., Cutko, A., et al. 2010. Climate change and biodiversity in Maine: a climate change exposure summary for participants of the Maine climate change species vulnerability assessment. (Report NCI-2010-2, pp. 22). Brunswick, ME: Manomet Center for Conservation Sciences (in collaboration with Maine Beginning with Habitat Climate Change Adaptation Working Group). Available from http://manometmaine.org/documents/NCI-2010-02_climatechange.pdf

Whitman, A., A. Cutko, P. deMaynadier, S. Walker, B. Vickery, S. Stockwell, and R. Houston. 2012. Climate Change and Biodiversity in Maine: Vulnerability of Wildlife and Plant Species of Special Concern in Maine. Manomet Center for Conservation Sciences in collaboration with Maine Beginning with Habitat Climate Change Adaptation Working Group. Report NCI-2012-3. Brunswick, Maine.

Wilbanks, T. and S. Fernandez. 2012. Climate Change and Infrastructure, Urban Systems, and Vulnerabilities – Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. Available online: http://www.esd.ornl.gov/eess/Infrastructure.pdf

Wilcove DS., Rothstein D, Dubow J, Phillips A, and Losos E. 1998. Quantifying threats to imperiled species in the United States. *BioScience* **48**: 607-615.

Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, and N.G. McDowell. IN PRESS. Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Climate Change : 6. Available online: http://www.fs.fed.us/psw/mtnclim/talks/pdf/Williams.pdf

Willows RI, and Connell RK (Eds). 2003. Climate adaptation: risk, uncertainty and decisionmaking. UKCIP Technical Report. Oxford, UK: United Kingdom Climate Impacts Program.

Winter, T.C. et al. 1998. *Groundwater and Surface Water: A Single Resource.* United States Geologic Survey, Circular 1139. Available online: http://water.usgs.gov/pubs/circ/circ1139

Winter, T. C. 2000. The vulnerability of wetlands to climate change: a hydrologic landscape perspective. *Journal of the American Water Resources Association, 36*(2), 305-311.

Wolock, D. M. 2003. Base-flow index grid for the conterminous United States. (U.S. Geological Survey Open-File Report 03–263) U.S. Geological Survey. Available from http://water.usgs.gov/lookup/getspatial?bfi48grd