Reviewer Materials – Research Section
Research Infrastructure Improvement (RII) Program Track – 1
Vermont EPSCoR

Tentative Title: Adaptation to Climate Change in the Lake Champlain Basin: New Understanding through Complex Systems Modeling

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Research Section Project Overview

Tentative Title: Adaptation to Climate Change in the Lake Champlain Basin: New Understanding through Complex Systems Modeling

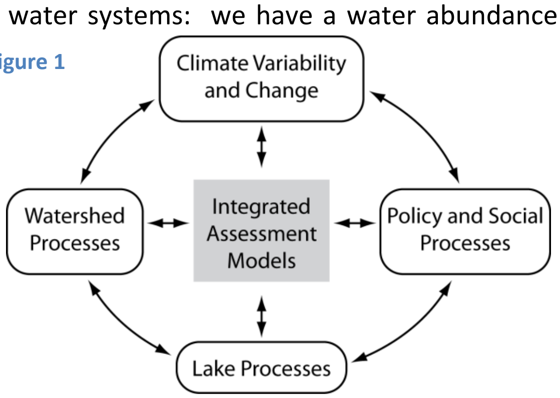
Vermont EPSCoR is preparing a proposal for Research Infrastructure Improvement (RII) Track-1 funding. We seek outside opinions on the first NSF criterion, Intellectual Merit, of our draft proposal. *We need advice on whether our groups will be working on cutting edge science that is of significance to our state, region and nation.* Outcomes from our fundamental research should include policy and societal impacts and a substantial economic impact on the state.

We have chosen the topics of climate change in the Champlain Basin and complex systems modeling for several reasons:

- Our current three year RII grant has supported complex systems modeling of the extant data sets of the Lake Champlain Watersheds; we wish to build upon this research for a longer 5 year RII grant.
- We have substantial expertise in lakes and watersheds at our research university, the University of Vermont, as well as in state agencies, numerous Vermont colleges, and non-governmental groups.
- We have substantial expertise in policy research, including complex systems approaches, in the Gund Institute and the Dept. of Community Development and Area Studies.
- The University of Vermont has recently finished a process to identify spires of excellence for investment; Complex Systems Modeling is one of those spires.
- Our State Science and Technology Plan emphasizes complex systems expertise and environmental resources.
- The state legislature and our Governor have emphasized policy changes to adapt to climate change in the last legislative session.
- Since 88% of Vermont's land is in the "working landscape" of forests and agriculture, the impact of climate change will include a large effect on the state economy that depends upon the green image of agriculture and Lake Champlain and also upon the maple industry and skiing.
- The National Science Foundation is emphasizing climate change research across directorates.

We believe that in Vermont we have a few distinctions in research on climate change impacts on water systems: we have a water abundance and must deal with excess water during severe weather events that degrade receiving waters; we propose to apply our complex systems modeling on a small geographic scale; our policy studies that inform management can have tangible outcomes in a small state that is already proactive in environmental stewardship.

Figure 1



We propose to establish four groups (Figure 1) that will work to test hypotheses and answer science questions. The groups have worked together to create four Idea Papers that describe their proposed research. ***We ask you to critique these Idea Papers for Intellectual Merit.***

In the development of this document, the group developed this set of bullets as context for the reviewers.

- Group 1 Climate Variability and Change: Future climate change has the potential to produce dramatic changes on northern ecosystems, through variations in the state, frequency, and timing of hydrometeorological variables and the amplification of temperature impacts on plant physiology and various aspects of the hydrologic cycle.
- Group 2 Watershed Processes: Landuse will interact with and may amplify the changes associated with projected climate shifts.
- Group 3 Lake Processes: Lakes receive much of the water and sediments from the watershed – changes in rainfall amounts/intensity, temperature, and ice cover will be significantly affected by climate change, and the social/economic policies that can affect landscape use will also impact sediment and nutrient delivery to lakes.
- Group 4 Policy and social Processes: Different policy Actors possess different decision criteria in setting and implementing public policy affecting watershed governance and processes

The groups will interact and also work together on an Integrated Assessment Model that will tie together natural science and socioeconomic changes, providing a way to predict how spatially-explicit modeling of ecosystem services (including supporting, regulating, provisioning, and cultural services) can

- Plan for the provision of **multiple ecosystem services** at desired level, defined by decision makers in terms of critical thresholds, optimal provision, or indifference thresholds, and mapped by precise modeling of actual ecosystem service flows to specifically identified beneficiaries.
- Help address **conflicts for natural resources among multiple, competing beneficiaries**, such as urban, forest, and agricultural land use in lake basins.
- Use a rigorous scientific approach to tackle **unaddressed scaling tradeoffs** in time and space, where the same policies can determine short-term benefits that must be balanced with long-term risks.

New resources will be provided to the groups, but are not detailed in these Idea Papers. Recruitments of new faculty into these four groups will also be part of our infrastructure building for the state.

Faculty Research Team Participants

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Research interests include the design and analysis of experiments and surveys. Current and past research involves quality control, design and analysis of spatial experiments, fitting dose-response curves, and multiple comparisons. Students should have a strong mathematics, statistics, and computer background.

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TBA – new hire (climate modeler)
TBA – RSENR new hire/new Rubenstein director

More group members will be added from non-governmental organizations (Vermont Nature Conservancy), State Agency of Natural Resources, Saint Michael's College, Johnson State College, Norwich University among others.

Group 1: Quantifying the Temporal and Spatial Characteristics of Climate Variability and Climate Change

Lesley-Ann Dupigny-Giroux, Alan K. Betts, Shelly A. Rayback, Andrea Lini, Chris Danforth, John Aleong, new hire (climate modeler)

INTRODUCTION

The climate of Vermont has been described as changeable, with inherent variations over time and space. Climate variability refers to the natural fluctuations that occur in hydroclimatological variables such as precipitation and temperature patterns, storm tracks, and frequency at a number of time scales (annual, decadal, centennial, and even millennial). Such naturally occurring variations make it difficult to distinguish long-term trends in the climate record. Our knowledge about the climate around us is ever improving, although actual observations of climatic parameters in Vermont remain somewhat limited. Today, in the face of natural climate shifts and enhanced greenhouse gas effects, understanding the role played by climate variability becomes critical. Changes in climate regimes could have adverse impacts on tourism, forestry, and water resources in Vermont. In particular, there is growing concern about the ability of farmers to adapt to increasing climate variability. Economically-important species such as sugar maples *Acer saccharum* Marsh. are vulnerable to both cool season vagaries as well as summer extremes such as drought. When considering the nature of extreme atmospheric events, evolving patterns of population growth, land use practices and economic development around the state add a final layer of complexity that must be considered when investigating climate variability (Dupigny-Giroux, 2002).

The consensus view of climate change science is that the Earth's climate is changing largely due to anthropogenically-driven alterations to the chemistry of the atmosphere. However, the longwave radiative forcing from the increase of atmospheric carbon dioxide and other anthropogenic greenhouse gases is relatively small compared to the non-linear response of the climate system, which is amplified by water cycle feedbacks. The water vapor greenhouse is a large positive feedback, operating in all seasons, as atmospheric water vapor is coupled to surface evaporation which generally increases with temperature, where water is available. At all latitudes where mean temperatures are below freezing for an extended cold season, snow-ice-albedo feedback amplifies the winter and spring temperature response though its impact on the surface shortwave budget (Betts, 2009). On the planetary scale, this is driving the coupling of diminishing sea ice and the recent Arctic temperature amplification (Screen and Simmonds, 2010); while on a local scale it is accelerating the decrease in the frozen period for Vermont lakes (Betts, 2010 submitted). Both of these climate feedbacks (water vapor and snow-albedo) are fully coupled to the hydrological cycle, and so they depend on the modes of variability of both local and global weather patterns.

Without question, understanding the geography of global climate change is critical to finding solutions to current and impending climate-related global challenges. The need to quantify past and future climatic change is particularly important for regions of the world with higher population densities such as the northeastern United States. In the last few decades, the anthropogenic forcing has become large enough for model attribution (IPCC, 2007), and at the same time, temperature trends and hydrologic trends (such as the advance in the spring runoff peak) are visible for New England. Increasing global temperatures in the 21st century are predicted to alter the hydrological cycle and precipitation patterns (Allen and Ingram, 2002; Trenberth et al., 2003; Trenberth and Shea, 2005), but there is substantial uncertainty in the hydrological response of the earth system. All these changes are hypothesized to adversely affect human health and livelihoods, and the natural ecosystems on which they depend (Trenberth and Shea, 2005; Jansen et al., 2007; Treydte et al., 2006). Faced with these potential changes, we believe that geography matters. Regional climate reconstructions are needed from the places where people live, such as the Champlain Basin of Vermont, to make models that predict future climate relevant and more accessible to the public; and to accurately inform ecological, hydrological, agricultural, economic and social decision-making processes for our state.

A number of recent reports and groups have explored the nature of Vermont's changing climate and that of New England as a whole. These include the Vermont Climate Collaborative, a statewide, multi-agency effort with the aim of addressing mitigative and adaptative strategies to climate change in sectors such as agriculture, forestry, waste, energy, transportation and land use. Its ultimate goal is to "reduce greenhouse gas emissions and to build the green economy." The Collaborative's focus is on the identification of resources, strategies and education/dissemination of findings and less on understanding the atmospheric drivers behind how Vermont's climate is changing and the feedbacks between and across the physical landscape such as vegetation dynamics, water processes and nutrient flow."Climate Change in the Champlain Basin" (Stager and Thill, 2010) a recent report by The Nature Conservancy uses temperature and precipitation data from the US Historical Climatology Network (USHCN) and an online-based downscaling tool called Climate Wizard to create natural resources guidelines for managers. Their analyses focus on the annual and seasonal timesteps for the 1976-2005 period. Finally, Spierre and Wake (2010) explore trends in precipitation across the northeastern US using instrumental data from 1948 to present.

Climate is now clearly non-stationary on the nominal 30-yr timescale that was used traditionally (Milly, 2008). We need to understand not only trends, but the change in the frequency of extremes, in both temperature and precipitation. Our instrumental records are of limited length, interannual variability is large, and the severity and intensity of extreme events, such as droughts and floods in the longer term, are poorly represented. So the approach we propose is a broad integrated one.

SCIENCE THEMES

The Climate Variability and Change group will explore **four main scientific themes.** These are woven together by the relationship between Vermont's local climate to regional, hemispheric and global forcing functions; the temporal and spatial scales that influence the heterogeneous land-atmosphere-water interactions across the state and; the very different rates of change observed in various parts of the land-atmosphere-water system and their implications for management and policy decisions. Thus, the Climate variability and change group will provide both climate data and analyses for the other groups (Watershed, Lake, Working Landscape, Policy and Societal Impacts) to build upon. The four science themes are:

i. the integration of instrumental, historical documentary and paleoclimate records to quantify the nature and rate of past climate fluctuations and changes at varying temporal scales
ii. using these past climate fluctuations to drive local to regional scale models (statistical, stochastic, neural networks and others) of possible future atmospheric conditions
iii. identifying the role of hemispheric and/or global teleconnections such as the North Atlantic Oscillation (NAO), Tropical/Northern Hemisphere (T/NH) and Pacific North American (PNA) oscillation as drivers of the observed climate fluctuations
iv. quantifying the statistical changes in atmospheric variables, especially those of importance in producing shifts in the hydrology, ecology and phenology of systems around the state

(*i*) *The need for overlapping, long term climate records*

Objective: To create a multi-proxy record of past climate changes and variations using paleoclimate data, documentary evidence (e.g. diaries and journals), and instrumental records, as an analog for understanding and preparing for future changes

Historical climate records & content analysis

In the United States, daily instrumental records at most stations begin in 1948 and continue to the present. This 62-year record is relatively short in climate circles, containing only five overlapping 30-year time periods used by climatologists to compute statistical averages or "normals". These 30-year time frames could also be anomalous from a short-term perspective, but contribute to overall climate variations when viewed over longer (e.g. century scale) time periods. While there are a few stations (e.g. Burlington and St. Johnsbury) across Vermont whose records extend back to the 1890s, these tend to the exception rather than the norm. Several station records begin earlier in the 1800s, but these tend to have data gaps, which are not conducive to many time series and other statistical techniques which require complete, uninterrupted time series.

In order to extend the instrumental record longer than 62 years and still make use of incomplete observations, climatologists employ historical climatology methods. Historical climatology refers to the use of documentary evidence (e.g. "personal and professional diaries and journals; ship logs (both those during voyages or while docked in port); trade journals and ledgers; plantation records; newspaper articles, editorials and advertisements" (Dupigny-Giroux and Mock, 2009)) to extract numerical observations where available, and perform content analysis on descriptive records as a "…way of exploring the inherent shifts in storm tracks" and "changing frequencies of hydrometeorological variables" (Dupigny-Giroux and Mock, 2009). Historical climatology methods are painstaking, require corroboration with other data sources (e.g. ice-out dates) and knowledge of the conditions under which observations were made, in order to increase the accuracy with which results are reported. Dupigny-Giroux (2009) has used these techniques to quantify phenoclimatic fluctuations and the influence of backward seasons on frost, sugar maple production and drought across Vermont and New Hampshire extending back to the 1700s. It is against this longer-term perspective that frequency and severity of extremes such as the 1960s drought and recent changes in precipitation amounts and intensities can be judged.

Hypothesis testing for historical climate analyses

1) Characteristics of climate variables and their related extreme events change over time and space and can be best quantified from a short timestep (hourly or daily) time series that is as long as possible

Dendroclimatology and Stable Isotope Analysis

To extend the climate record beyond the past 200-300 years, climatologists turn to paleoclimatology and dendroclimatology. Over the past three decades, dendroclimatology has played an important role in this effort, and most of the significant large-scale reconstructions of climate of the last millennium are underpinned by tree ring proxies. Whist these reconstructions have filled a vital research gap, they have yet to capture the absolute amplitude of climate variation over the last 1000 years due in part to the statistical limitations of tree ring growth proxies. Questions remain concerning changes to aspects of climate other than temperature, as well as the broader behavior of regional climate systems during periods of temperature anomalies.

Of the various climate proxies available, tree-ring chronologies are the most powerful, high-resolution natural archives. Tree ring records are invaluable for their annual resolution, precise dating, spatial coverage, and climate sensitivity. Unlike the use of ice and lake sediment cores, dendroclimatologists can use tree ring records to define the annual confidence limits of climate variability based on multiple, individual overlapping samples. With these advantages, tree-rings have been used exclusively or in combination with other high resolution proxies to reconstruct past climate variables at regional (Overpeck et al., 1997; Kaufman et al., 2009) and hemispheric-scales (e.g., Jones et al., 1998; Briffa et al., 2000; 2001; Esper et al., 2002; Mann et al., 1999; 2000; 2007) and over multi-century to millennial time periods.

Of the many climate change questions to answer, dendroclimatology strives to determine, with quantifiable precision, whether the magnitude and rate of recent climate change exceed the natural variability of climate over the recent past. Today, dendrochronologists are faced with questions regarding changes to aspects of climate other than temperature, as well as the broader behavior of regional climate systems during periods of temperature anomalies. Thus, there remains a need for: 1) reliable regional reconstructions based on 2) annually resolved proxies that retain both robust low and high frequency climate information, and 3) offer estimates of past climate variables other than warm season temperature.

Our goal is to address these needs through the development of the first, statistically-robust, long-term (400-600 years) climate reconstructions for sites in Vermont based upon multi-parameter dendroclimatological techniques with a particular focus on stable isotope analysis of tree rings. Stable isotope dendroclimatic proxies demonstrate four significant strengths: 1) the influence of climate on isotope fractionation in trees is well understood (Farquhar et al., 1982); 2) the link to climate is less complex than for ring width; 3) they provide a range of climate variables in addition to warm season temperature (e.g. McCarroll et al., 2003; Gagen et al., 2007) and, 4) the perturbing effect of tree age appears to have less influence on stable isotopes than it has on other tree ring parameters, so that low-frequency climate information can be retained with greater certainty (Treydte et al., 2006; Gagen et al., 2007). In addition, stable isotope dendroclimatic time series have been shown to overcome challenges such as heavy detrending and site complacency. The stable isotope chronologies developed will be used in a multi-parameter approach in conjunction with tree ring width and density measurements to derive robust climate reconstructions, with realistic uncertainty estimates, for a variety of climate variables. The variables to be reconstructed may include temperature, sunshine hours and cloudiness based on *^{13}C time series, and temperature, relative humidity, the *^{18}O of precipitation or the occurrence of drought (based on the Standardized Precipitation Index) and cyclones based on *^{18}O time series.

Hypothesis Testing for Reconstructing Climate for Vermont

A set of hypotheses will be tested with the purpose of advancing the use of long term *^{13}C and *^{18}O proxies in climate reconstruction for sites in New England, including

1) tree ring *^{18}O values from high-elevation, mesic sites will demonstrate the strongest relationship with climate variables and *^{18}O source water values.

2) the primary signal recorded in tree ring *^{18}O values will be derived from source water and thus, is linked to an atmospheric signal.

3) the *^{18}O time series-based reconstruction will yield climate information related to the *^{18}O of source water and temperature.

4) the *^{13}C time series-based reconstruction will yield climate information related primarily to total sunshine hours and secondarily to temperature.

(ii) Using complex numerical modeling to parameterize the atmosphere and develop predictions of climate scenarios for Vermont at varying timesteps

With the long-term climate series created in Theme 1, Singular Value Decomposition (SVD) will be used for data compression and identification of the temporal and spatial nuances in the variables. In order to extract the spatial patterns, the climate data will be detrended prior to SVD analysis.

In order to predict future climate scenarios, a seasonally evolving, state-independent estimate of the NCEP (National Center for Environmental Prediction) GFS model bias will be generated using varying time-steps (daily, weekly, monthly) over a selected decadal training period. Averaged over monthly periods and different parts of the state, the difference between forecasts and verifying analyses is an estimate of the the systematic model bias. Subtracting the systematic bias from the time series of forecasts and errors, and normalizing each time series by its standard deviation, we then calculate the N N multivariate error and forecast cross-correlation matrix C. After performing a covariance localization, the cross-correlation matrix C is then decomposed into SVD modes (C=USV#) to identify pairs of spatial patterns that explain as much of possible of the mean-squared temporal covariance between the normalized anomalous forecast error and forecast state time series pairs.

(iii) Role of teleconnections in forcing local climate fluctuations

The atmosphere-ocean coupling displays several modes of variability such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). ENSO correlations during warm events in the North American northeast tend to be weak, although near/above normal winter temperatures are expected. The lack of consistent response in the precipitation signal is complicated by other forcings like the NAO. The latter is best defined in winter and displays variability on a number of time scales from interannual to quasi-biennial (2-3 years), quasi-decadal (6-10) and interdecadal (24, 70) (Hurrell, 1996; Hurrell and van Loon, 1997). Previous studies have shown that New England lies between zones of positive and negative correlation with extreme phases of the NAO (Hurrell, 2000; pers. comm.). One of the avenues that will be explored in this study is whether the monthly and seasonal precipitation variability in Vermont a function of changes in storm tracks and frontal characteristics. This will build on existing studies (Dupigny-Giroux, 1999; Hurtt and Hale, 2001) documenting the influence of the NAO on winter precipitation in the northeast. One of the inherent difficulties in distinguishing the exact nature of the NAO's influence on the North American northeast, lies in the dipole used to capture the centres of mass. Another challenge in decoding the influence of the NAO is the overlapping signal with other modes of variability such as the Pacific North American (PNA) pattern. Both teleconnections exhibit dipole structures that straddle the climatological mean jet stream exit region (Bongioannini Cerlini et al., 1999). Opposing phases of these two oscillations have been found to be conducive to certain storm types and/or track because of the planetary waves produced.

(iv) Statistical analysis of the atmospheric variables

Objective: To quantify the statistical variability of hydrometeorological data such as temperature, precipitation, frost, wind and humidity

While many analyses use the computed average or mean of a given climate variable, this value is "not entirely reliable as an estimate of the climate system's true long-term mean state" and the "mean state is not a typical state" (von Storch and Zwiers, 1999). More appropriate would be the use of Empirical Orthogonal Functions, quantifying the stationarity of the variable's time series and applying time series analysis to determine frequency changes over time (von Storch and Zwiers, 1999). In addition, given the need by other groups (e.g. Watershed and Lake groups) to understand changes in the intensity and amount of precipitation inputs, it is the tails of the distribution rather than the mean value that is of most importance. Similarly, phenoclimatic changes would be needed by the Working Landscape group. A recent study by Rigby and Porporato (2008) outlined a stochastic coupled temperature-phenology model that showed that it is the variance of daily temperature (and not the daily mean) that is the most important factor in influencing frost risk and damage on budbreak and development in the spring. For Vermont, work by Betts (2010, submitted) has shown the importance of quantifying the rate of change of daily temperature minima which are fluctuating slowly vis-à-vis other important related variables such as the first and last freeze dates (28 F (-2 C)) in the winter.

The above data are identified over space and time. The statistical spatial model which incorporates the spatial variation is also dynamic on account of the temporal nature of the data. The optimal estimation and prediction of the unobserved from the observed in the spatial statistical model with its accompanying variances are the main forms of statistical inferences.
Since at every scale variability is well known, the major processes of the research have strong spatial, temporal and exogenous variability which may be uncontrollably. Hierarchical modeling, with simple conditional models, results in a joint complex system with possible global analyses. (Cressie,1991, 2011, Aleong ,2010, Embrechts, P. Klüppelberg, C. and Mikosch, T., 2003, and Santer et al ,2009).

RESOURCES NEEDED

In order to address the aforementioned objectives, a number of human and capital resources are needed. These include a climate modeler hired to complement the techniques employed by Chris Danforth (Math-CEMS) and John Aleong (Statistics/PSS); a postdoctoral fellow to bridge the denchronologocial and stable isotope techniques used by Andrea Lini and Shelly Rayback; a second postdoctoral fellow to bridge the paleoclimate and documentary climate analyses of Lesley-Ann Dupigny-Giroux and Shelly Rayback; an on-line stable isotope ratio mass spectrometer for rapid data processing needed to provide timely results to the other groups; undergraduate research assistants would support data collection and analysis; atmospheric moisture, soil water and plant water analysis; the creation of a geospatial platform in which both historical hydroclimatological data and geophysical data can be shared in a common environment (i.e. projection, datum etc.) and; the creation of an operational Internet-based geomatic platform for climate observation, spatial analysis and the integration/visualization of climate data from varying sources.

References:

Aleong, J (2010). The Generalized Linear Mixed Model with Spatial-Temporal Data. Joint Statistical Meetings, American Statistical Association, Vancouver, BC, Canada, 20August 2010.1Joi0 2010 Joint Statistical Meetings in Vancouver, British Columbia Joint Statistical Meetings in Vancouver, British Columbia

Cressie, Noel A.C,.(1991). Statistics for Spatial Data, Wiley, New York, 1991 (900 pp.). Revised edition. Wiley, New York, 1993,(900 pp.).

Cressie, Noel A.C and Wikle, Christopher K. (2011). Statistics for Spatio-Temporal Data, Wiley, Hoboken, 2011 (in press).

Embrechts, P. Klüppelberg, C. and Mikosch, T.(2003) Modelling Extremal Events for Insurance and Finance Springer-Verlag, 648 pages, corr. 4th printing, 1st ed. 1997.

Santer, B.D.et al. (2009). Incorporating model quality information in climate change detection and attribution studies, PNAS September 1, 2009 vol. 106 no. 35 14778-14783.

Group 2: Characterizing Landscape and Watershed Response Under Variable Climate Regimes

Arne Bomblies, Paul Bierman, Mandar Dewoolkar, Greg Druschel, Maeve McBride, Leslie Morrissey, Deb Neher, Donna Parrish, Donna Rizzo, Don Ross, Mary Watzin, Beverley Wemple, Declan McCabe, Robert Genter

INTRODUCTION

The Lake Champlain basin has an environmental history that reflects the role of a variable and changing climate (Stager and Thrill, 2010). The basin's more recent environmental history reflects the imprint of human settlement and landuse in the basin (VCCAP 2009). Today, the region is entering a new era in which humans interacting with a changing climate brings new uncertainties about ecosystem function and the health of the lake.

The ecology and watershed processes group will utilize an integrated assessment modeling approach to address the complex coupling of hydrology, ecology, and social systems in an effort to understand the impact of climate on the quantity and quality of surface waters and the resultant transport of nutrients, sediment, and pollutants to receiving waters.

The Vermont economy depends on agriculture, forestry and the tourism draw of our natural landscape. Each features strongly in the economy-driven human impact on the Vermont landscape (e.g. in the form of land clearing, disturbance by livestock and vehicles, addition of nutrients from fertilizers, the diversion of streamflow for snowmaking). While agricultural and forested systems themselves are are vulnerable to changes in precipitation, an altered landscape forms the basis for watershed response to climate change and variability that can adversely affect runoff into receiving waters by transporting large amounts of sediment or nutrients. A good example of such landscape-influenced impacts of climate variability was documented in the Chesapeake Bay. In the mid-Atlantic, the record drought of 2002 was followed by a wet year in 2003, leading to a large pulse of contaminants that were stored in the watershed but not flushed until 2003 rainfall yielded high runoff. The resulting contaminant pulse caused severe hypoxia in the bay (Kaushal et al., 2010). Similar connections between climate, landuse and land cover change and climate variability and change have been studied and are anticipated for Vermont as well (Stager and Thill, 2010). Human impacts on the landscape can clearly intensify environmental problems that have societal impacts in the form of ecosystem services. *We propose to establish the relationship between climate variability, human involvement in the landscape, and the magnitude and duration of runoff carrying sediment and nutrient fluxes.*

The presence of two interdependent primary drivers of watershed behavior—climate change and landuse management—creates dynamic linkages and nonlinearities in the climate/landscape/ecohydrology/lake system that can result in emergent behavior and the possibility of multiple stable states. Regime shifts from one stable state to another are possible with changes in the forcing variables. Examples of such regime shifts include—but are not limited to—changes in phenology and species composition, shifts in the proportion of winter precipitation falling as snow, shifting of stream morphology and flow regime, and establishment of hypoxic zones in the lake. The potential social and economic impacts of such regime shifts to the state of Vermont would be quite significant. Examples of such regime shifts specifically impacting Vermont include:

- Climate-induced changes in temperature and precipitation could alter stress-sensitive deciduous tree species and impact Vermont's tourism appeal in the fall foliage season. These climate-induced stresses also make the forest more vulnerable to pest and pathogen outbreaks, threatening the health of the forest ecosystem.

- A change in the extent of sugar maple forests could impact Vermont's maple syrup industry. Shorter, warmer winters are expected to reduce the length of Vermont's maple sugaring season and impact the state's important maple syrup industry. These changes in spring sap flow could have important, though unexplored, hydrologic consequences for the fluxes of water in the soil, vegetation, atmosphere continuum.
- Human policy-driven alterations to the watershed in the form of agricultural practice, biofuels production (including timber harvesting), and urbanization can amplify watershed runoff response to precipitation events. Denuded and cultivated landscapes will yield higher runoff, more landslides, and combined with increases in extreme precipitation events from climate change, these changes will impact stream flow regimes and can lead to changes in river channel position from associated sediment transport. A regime shift from one type of stream morphology and flow regime to another may result, impacting infrastructure and ecological services. Moreover, an increased sediment loading into the lake could shade the littoral zone, altering lake ecology by inhibiting sunlight.
- The same changes in flow regime resulting from climate change and landuse change can impact contaminant and nutrient transport in the watershed. The watershed linkage with the lake ecosystem can yield a regime shift in Lake Champlain from natural conditions to eutrophic or hypoxic conditions if nutrient transport into the lake is exacerbated. Human landscape use in the watershed and associated soil and nutrient management are the drivers of this regime shift.
- Vegetation patchiness can change in the watershed based on human policy and climate drivers, with several internal feedbacks. A regime shift from non-patchy to patchy vegetation or vice versa can affect productivity and erosion, with grazing, land clearing, fires and droughts as possible drivers.
- A shift from genetic diversity to homogeneity of plant genetics across the landscape can result as gene pools narrow and larger tracts of contiguous lands are cropped. Genetic homogeneity increases vulnerability to disease and pest outbreaks. Regional planning and coordination would increase the robustness, stability and resilience of the working landscape.

BACKGROUND AND SCIENCE THEMES

Environmental, water-related problems are innately complex and best solved when the skills of many disciplines are applied in unison. The work we propose here builds on Vermont's Integrated Research on Water in the Environment (iRWE) developed through previous EPSCoR funding initiatives (http://www.uvm.edu/~irwe/). This working group includes a diverse group of faculty and student researchers in several graduate degree-granting programs at the University of Vermont including Engineering, Natural Resources, and Geology. Our efforts have also included collaboration with state and private undergraduate colleges in Vermont through the successful STREAMS project and other research activities. This group constitutes a critical mass of scientists and engineers who work across many disciplines to address socially relevant environmental problems related to water.

Our group's previous research has involved an array of empirical and modeling approaches to assess the effects of landuse change and climate variability on ecology and watershed processes. Rich historical records derived through sedimentological analyses provide decadal to millennial scale reconstructions of landscape erosion and limnological response for Vermont (Brown et al., 2000; Noren et al., 2002; Brown et al., 2002; Jennings et al., 2003; Ferber et al., 2004; Ambers and Wemple, 2008). Empirical studies have explored the role of forest species composition on watershed nutrient cycling and nutrient export (Ross et al., 2009), the source of sediments to Lake Champlain from riverbanks (Borg et al., 2008; Borg et al., under review), the influence of decadal-scale climate variability, water temperatures, and landscape connectivity on fish abundance (Butryn et al., 2009; Sullivan et al., 2009), the consequences of alpine development on water quantity and quality (Wemple et al., 2007), and the influence of deforestation, urbanization and reforestation on channel morphology (McBride et al., 2008; McBride et al., 2009; Pelletier et al., 2007). Novel modeling have used complex systems approach to simulate long-term streamflow (Besaw et al., 2007; Besaw et al., 2009), climate variability and human health (Bomblies et al., 2008), and the effectiveness of watershed classification on stream channel morphology (and aquatic habitat (Cianfrani et al., 2006; Clark et al., 2007; Sullivan et al., 2007; Besaw et al., 2008).

Vermont researchers have a valuable suite of long-term datasets upon which to base future studies of the effects of a changing climate and human landuse on the watershed. The Vermont Agency of Natural Resources has a database of over 3000 stream reaches that have been assessed for geomorphic condition and aquatic habitat (http://www.anr.state.vt.us/dec//waterq/rivers.htm). The Vermont Monitoring Cooperative maintains long-term data on soil and forest health (http://sal.snr.uvm.edu/vmc/). The University of Vermont's Rubenstein maintains records of lake conditions including lake temperatures and nutrient status (http://www.uvm.edu/envnr/rubenstein/). These datasets and others, used for many of the publications cited above, will be used in this project as calibration and validation datasets for our integrated assessment modeling efforts.

Research Questions

Our research questions address five key science themes. These questions involve investigations of the physical and biological behavior of the watershed system and feedbacks between of human actor behavior and policy decisions on watershed processes in the face of variable climate and landuse practices. The questions enumerated below represent the focal point of the ecology and watershed processes group, but the activities of our group cannot be separated from the efforts of the Policy and Societal Impacts (PSIG) group. Our questions include:

1. What are the implications of changes in plant species phenology or composition and hydrometeorological regimes on sediment and nutrient production on the landscape and delivery to waterways (rivers and the lake)?
2. How do land cover and landuse change interact with climate variability to alter the regimes of runoff, sediment, and nutrient production and their delivery to waterways?
3. What feedbacks drive and result from altered water and pollutant delivery to surface waters and the associated internal loading and nutrient cycling within the aquatic environment?
4. What potential alternate stable states can exist in the watershed and the lake, with changes in climate drivers, actor behavior, and policy decisions?
5. If there are alternate stable states, what is the resilience of these states? What is the shape of the dependence of a state variable on the driver? Is it hysteresis, threshold, or is a regime shift in the state simply irreversible?

Proposed Methodology

Classical watershed modeling has assumed static boundary conditions with humans external to the hydrologic system, whereas in the proposed study, humans are internal to the hydrologic system of the Lake Champlain basin and landuse is therefore considered dynamic. For example, changing agricultural policy or demographic pressures yielding increased urbanization (residential/commercial construction) can greatly impact landscapes and watershed behavior. In turn, watershed environmental health and discharge into the lake can feed back to policy driving landuse decisions such as restricting the use of fertilizers, clearing of land, or other legislation governing landuse in an effort to minimize environmental deterioration. We will use the variable climate regimes derived by the Climate Variability and Change group to drive model simulations of expected forcings in the Lake Champlain Basin. We will simulate human involvement in the basin, both as agents of change and as beneficiaries of ecosystem services. In the integrated assessment framework, human social and policy decisions constitute a dynamic driver of ecosystem behavior—in addition to climate forcing—with a two way coupling. Detrimental environmental effects from unanticipated watershed responses will influence policy regulating landuse within the watershed, and it is possible that such human/ecosystem dynamics can result in ecologically and agriculturally devastating regime shifts in the same way that climate change may be responsible for such shifts.

Our overarching goal is to develop integrated assessment models to predict how hydrology and the resulting transport of nutrients, sediment and pollutants in surface waters are likely to be altered by climate variability and management decisions regarding landuse. We envision linked climate, hydrology, ecological systems and human decision models that can update each other's state during simulation to represent all of the relevant two-way couplings. In this way, the true complexity and the dynamics of the coupled human-climate-watershed system can be studied in a virtual field environment. This model can be parameterized and validated with past conditions and provide a reference base to monitor future trends. This may involve gathering data on past sediment transport from lake sediment samples and reconstructing flow regimes prior to large-scale human impacts in the Vermont landscape beginning in the 1700s. However, as we live in a rapidly changing world with non-stationary climate conditions, looking to the past may not be an adequate guide to future climate, because present and future climate changes are well beyond the realm of what has occurred in the past. As a result, we need innovative quantitative analysis and integrated assessment modeling spanning a heterogeneous mixture of spatial and temporal scales to support environmental decision-making involving the co-evolution of complex landscapes and their natural ecosystems while climate changes.

CONCLUSIONS

These analyses proposed here will allow us to evaluate the sensitivities and elasticity of the watershed system that should inform the policy framework for managing terrestrial, river and lake systems. The economic impacts of watershed processes under change scenarios are potentially severe, and can be explored using an integrated assessment approach as proposed here. Evaluation of the resilience of ecosystem/landscape regimes will be an important broader impact of the proposed research. Our research will:

- Evaluate the possibility of several stable states in the environment and resilience of these stable states to perturbations
- Examine different scales & patchiness of landscape management approaches on provision of ecosystem services
- Use mechanistic models to better understand the basic physics of water-sediment-vegetation interactions including feedbacks and uncertainty
- Support empirical field studies aimed at characterizing sediment and nutrient production
- Assess the impacts of projected changes in runoff (due to increased storm frequency and intensity) on the loss of top soil and integrity of aquatic ecosystems
- Advance the value and performance of integrated assessment models for evaluating the impacts and risks posed by climate change and landuse policy decisions
- Evaluate the impact of weather and water variability on ecosystem and local food security (crops, forest, fish, etc.) and its role in health and sustaining the economy

Quantify the impacts of nonstationarity in climate and increases in interannual and intra-annual variability in climate variables such as diurnal temperature range and rainfall

REFERENCES

Ambers, R. K. R., and B. C. Wemple, 2008. Reservoir Sedimentation Dynamics: Interplay and Implications of Human and Geologic Processes. *Northeastern Geology and Environmental Science*, 30(1):49-60.

Besaw, L.E. and D.M. Rizzo. 2007. "Spatial Prediction and Stochastic Conditional Simulation using Artificial Neural Networks", *Water Resources Research* 43, W11409, DOI: 10.1029/2006WR005509.

Besaw, LE., D.M. Rizzo, M. Kline, K.L. Underwood, J.J. Doris, L.A. Morrissey and K. Pelletier, 2009. "Stream Classification using Hierarchical Artificial Neural Networks: A fluvial Hazard Management Tool", *Journal of Hydrology*, doi:10.1016/j.jhydrol.2009.04.007.

Besaw, L. , K. Pelletier, D. M. Rizzo, L. A. Morrissey and M. Kline. 2008. "Advances in watershed management and fluvial hazard mitigation using artificial neural networks and remote sensing", Presented at the *ASCE 2008 World Water & Environmental Resources Congress, Environmental and Water Resources Institute*, Honolulu, HI, May 2008.

Besaw, L. E., Rizzo, D. M., Bierman, P. R., and Hackett, W. R., 2010. Advances in ungauged streamflow prediction using artificial neural networks. Journal of Hydrology. v. 386, p. 27-37, doi:10.1016/j.jhydrol.2010.02.037

Bomblies, A., J.-B Duchemin, E. A. B. Eltahir. 2008. Hydrology of malaria: Model development and application to a Sahelian village. Water Resources Research, VOL. 44, W12445, 26 PP., 2008 doi:10.1029/2008WR006917

Borg, J. L., Bierman, P. L., Dewoolkar, M. M., Rizzo, D. M., and Rood, D. under review. "Meteoric ^{10}Be adhered to suspended sediment: transport dynamics in a large New England watershed." Submitted to Journal of Geophysical Research - Earth Surfaces.

Borg, J. L., Dewoolkar, M. M., and Bierman, P. L. (2008), "Evaluation of streambank stability", Conference for Lake Champlain: Our Lake, Our Future, January, Burlington, VT.

Brown, S.L., Bierman, P.R., Lini, A., and Southon, J., 2000, A 10,000 year record of extreme hydrologic events: Geology, v. 28, p. 335-338.

Brown, S., Bierman, P., Lini, A., Davis, P.T., and Southon, J., 2002, Reconstructing lake and drainage basin history using terrestrial sediment layers: analysis of cores from a post-glacial lake in New England, USA: Journal of Paleolimnology, v. 28, p. 219-236.

Butryn, R.S., D.L. Parrish, D.M. Rizzo, and B.C. Wemple. 2009. Predicting brook trout distribution with thermal stress events. 139th Annual Meeting of the American Fisheries Society, Nashville, TN, 31 August- 3 September 2009.

Cianfrani, C., W.C. Hession and D.M. Rizzo, 2006. Watershed Imperviousness Impacts on Stream Channel Condition in Southeastern Pennsylvania", Journal of the American Water Resources Association, 42 (4), 941-956.

Clark, J.S., D.M. Rizzo, M.C. Watzin, W.C. Hession. 2007. "Geomorphic Condition of Fish Habitat in Streams: An Analysis Using Hydraulic Modeling and Geostatistics", *River Research and Applications* 24(7), 885-899, DOI: 10.1002/rra.1085.

Ferber, L.R., Levine, S.N., Lini, A., and Livingston, G.P., 2004, Do cyanobacteria dominate in eutrophic lakes because they fix atmospheric nitrogen? Freshwater Biology, v. 49, p. 690-708.

Jennings, K., Bierman, P., and Southon, J., 2003, Timing and style of deposition on humid-temperate fans, Vermont, United States: Geological Society of America Bulletin, v. 115, p. 182-199.

Kaushal, S.S., Pace, M.L., Groffman,, P.M., Band, L.E., Belt, K.T., Mayer, P.M., and Welty, C. (2010) Land use and climate variability amplify contaminant pulses. *EOS, Transactions, American Geophysical Union* 91(25):221-222.

McBride, M., D.M. Rizzo, and W.C. Hession. 2008. "Riparian Reforestation and Channel Change: A Case Study of Two Small Tributaries to Sleepers River, Northeastern Vermont, USA", *Geomorphology* 102 (3-4) 445-459, doi: 10.1016/j.geomorph.2008.05.008.

McBride, M., C.W. Hession and D.M. Rizzo. 2009. "Riparian Reforestation and Channel Change: How long does it take?", *Geomorphology* doi:10.1016/j.geomorph.2009.11.014.

Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., and Southon, J., 2002, Millennial-scale storminess variability in the northeastern United States during the Holocene epoch: Nature, v. 419, p. 821-824.

Pelletier, K., L. A. Morrissey, D. M. Rizzo, L. Besaw, M. Kline, and B. Cahoon. 2007. "High Resolution Remote Sensing to Characterize Geomorphic Stability of Stream Reaches", *Northeast ARC Users Conference*, Burlington, VT.

Ross, D. S., B. C. Wemple, A E. Jamison, G. Fredriksen, J. B. Shanley, G. B. Lawrence, S. W. Bailey, J. L. Campbell. 2009. A Cross-Site Comparison of Factors Influencing Soil Nitrification Rates in Northeastern USA Forested Watersheds. *Ecosystems*, 12(1): 158-178.

Stager, J.C. and Thill, M. (2010) Climate Change in the Champlain Basin *The Nature Conservancy* Montpelier, Vermont

Sullivan, S.M.P. and M.C. Watzin. 2009. Stream-floodplain connectivity and fish assemblage diversity in the Champlain Valley, Vermont, USA. Journal of Fish Biology 74: 1394-1418.

Sullivan, S.M.P., M.C. Watzin, and W.S. Keeton. 2007. A riverscape perspective on habitat associations among riverine bird assemblages. Landscape Ecology 22: 1169-1186.

Wemple, B. C., J. Shanley, J. Denner, D. Ross, and K. Mills. 2007. Hydrology and water quality in two mountain basins of the northeastern US: assessing baseline conditions and effects of ski area development. *Hydrological Processes,* DOI: 10.1002/hyp.6700.

VCCAP (2009). Vermont Clean and Clear Action Plan. 2009 Annual Report, Vermont Agency of Natural Resources and Vermont Agency of Agriculture, Food and Markets: 95 pp.

Group 3: Effects of Climate Change on Northern Lakes

Greg Druschel, Paul Bierman, Jane Hill, Suzanne Levine, Andrea Lini, Pat Manley, Tom Manley, Ellen Marsden, Leslie Morrissey, Donna Parrish, Donna Rizzo, Eric Smeltzer, Mary Watzin, RSENR new hire/new Rubenstein Lake Laboratory director

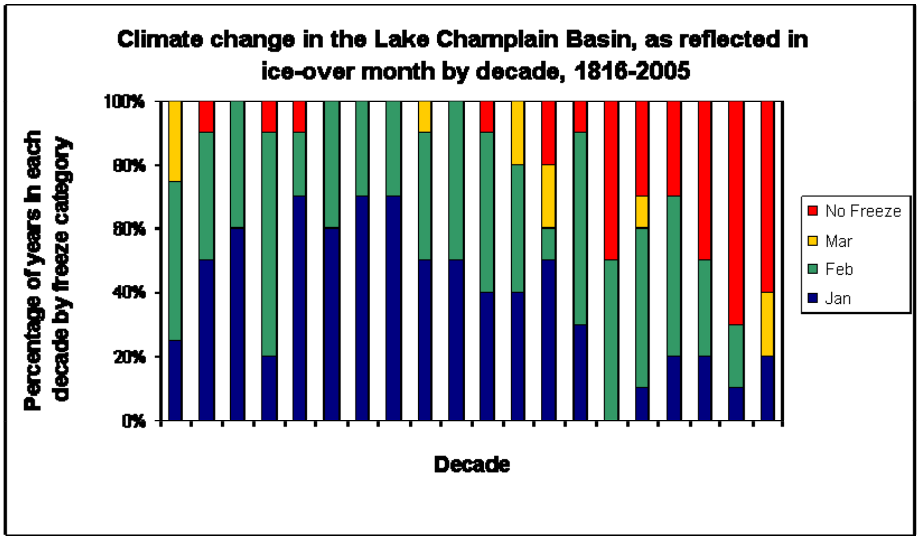

Figure 1 – Ice-over timing of Lake Champlain

The water quality and ecology of northern lakes are significantly affected by water temperature, wind, precipitation amounts, duration and timing of ice cover, and the relative amounts of runoff occurring as snowmelt versus rainfall, all processes expected to be dramatically impacted by climate shifts in coming decades. Lake Champlain and the many smaller lakes in Vermont represent a viable model system for investigating some of the detailed processes that would be expected to shift as climate warming continues. Documented changes in ice cover and ice-out (Hodgkins et al., 2002; Figure 1) indicate Lake Champlain is delicately balanced, as are many northern watersheds, with further warming expected to bring new challenges to the communities that utilize and depend on these water bodies.

While climate change predictions for the Lake Champlain basin are difficult to quantify precisely, it is largely agreed that significant changes in precipitation (amount, timing, and event intensity) and associated sediment transport, ice cover duration and thickness, and temperature of both the atmosphere and water bodies will be experienced (Hayhoe et al., 2007; Stager and Thill, 2010). With increases in temperature and atmospheric moisture-content, precipitation may be expected to increase, with an increasing fraction of winter precipitation falling as rain (Hayhoe et al., 2007). Additionally, models predict that the severity of thunderstorms and the frequency of severe rainstorm events will increase (Hayhoe et al., 2007). Sediment transport as a result of these changes will certainly be affected, with changes as a result of meltwater: rainfall ratios and storm event severity being important drivers predicted to influence sediment and nutrient transport across the watershed and into receiving waters (Mortsch and Quinn, 1996). Lake ice cover effects associated with rapid warming include later freeze over dates, lower freeze-over frequency, lower ice-cover duration, and more rapid water warming and thermal stratification in the spring due to reduced albedo (Jensen et al., 2007; Hodgkins et al., 2002; Austin and Colman, 2008). For northern lakes, the dynamics of sediment redox chemistry and nutrient mobility are affected by changes in the duration and thickness of ice cover in winter (Golosov et al. 2007, Weyhenmayer et al. 2008, Lepperanta and Wang 2008). Decreased ice cover, leading to lessened water column hypoxia and increased temperatures over winter, may significantly impact nutrient availability and cyanobaceria ecology, and may also lead to significant changes in survival of overwintering species ((Aldrich et al. 2001; Golosov et al. 2007; Jackson et al. 2007; Eckert et al. 2003). Temperature changes associated with changing atmospheric temperatures and changes in ice-cover, and changes in the expected severity of storms will affect lake thermal stratification, affecting the timing of epilimnion and hypolimnion mixing. Lake Champlain thermal structure is additionally affected by a very large internal seiche (Hunkins et al., 1998; Manley et al., 1999), which likely has significant effects on nutrient transport as well as biota across much of the trophic structure.

Climate change effects on thermal regimes, water quality, and ecology in northern lakes requires better understanding of the role sediment transport dynamics, ice cover, and thermal structure have on nutrient availability and habitat. Expected changes in nutrient delivery to lakes and the cycling of nutrients between the water column and underlying sediments may have dramatic impacts on phytoplankton and microbial ecology, including the likelihood of cyanobacterial dominance in summer. The seasonality of life history events often is synchronized in predator and prey, so prey cycles sped up by increased temperature can cause predators to starve. A major concern is that already troublesome invasive species, favored by generalist resource requirements, will outcompete native populations as their surroundings change. Alteration of thermal regimes will alter the amount and location of habitats available to fish, affect fish movements and interspecific interactions, and impact their foraging and growth potential (e.g., Brandt et al. 1980, 1993). Increased depth of the summer thermocline will reduce the habitat available to coldwater fishes, squeezing them between stressful temperatures above the thermocline and low oxygen zones near the benthos (Ficke et al. 2005). Changes in fish population abundance and distribution alter stability of aquatic communities, leading to changes in trophic structure and increased potential that exotic species may become established.

Hypotheses:

The Lake Processes group of Vermont's RII proposal will address the following hypotheses focused on how climate change affects (through changing sediment delivery from the watershed associated with precipitation changes, changing ice cover duration and thickness, changing temperature and thermal stratification) key lake processes.

Nutrient delivery / mobility

Nutrient availability in lakes will be controlled by changes in sediment delivery associated with expected increases in high-intensity snowmelt and rainfall events, changes in landuse associated with socioeconomic and policy trends, and changes in ice cover timing/duration and temperature of lake waters and shallow sediments.

Physical limnology

Climate warming and reduced ice cover will result in more rapid water temperature increases in the spring, higher summer water temperatures, more stable and persistent thermal stratification, increased hypolimnetic hypoxia, larger waves and current speeds leading to more shoreline erosion, and changes in the characteristics of the large internal seiche in Lake Champlain.

Microbiota

- Sediment and nutrient delivery from the watershed, nutrient interaction with shallow sediments, severe storm wind mixing event frequency and intensity, and temperature will control phytoplankton bloom initiation, propagation, cessation and ecology in northern lakes; changes to these drivers is expected to be directly linked to climate change and to changes in landuse in the watershed.

- Ice cover changes in thickness and duration will affect sediment and water column redox chemistry and nutrient mobility, in shallow bays these effects may significantly impact the ecology and dynamics of cyanobacterial blooms throughout the year

Macrobiota

- Changes to the temperature and thermal structure of lakes affect fish distributions and reproductive success which can lead to increased chance of invasion by non-native aquatic species and changes in biodiversity.
- Sediment and nutrient delivery to lake systems, in addition to changes in ice cover, can affect the degree of eutrophication and the benthic oxygen supply, reducing the capacity of the lake to support reproduction of benthic-spawning fishes such as lake whitefish, walleye, and lake trout.

Science themes:

Lake processes

Watersheds are the first step in considering how climate change will affect the landscape, but lakes are the ultimate receivers of water and sediment coming off of the landscape – and include the sedimentary record of how past changes have affected the interdependent physical, chemical, and biological parameters of a system. Additionally, Lake systems harbor their own set of habitats that will be impacted by climate change – temperature, sediment delivery, and especially critical in northern ecosystems, ice cover timing/duration may impact water quality and biota considerably.

Research goals:

Nutrient delivery/mobility

- Support empirical field studies/ mesocosm experiments aimed at characterizing sediment and nutrient input to Vermont lakes from external (watershed) and internal (lake sediment) sources based on sediment and nutrient fingerprinting (e.g. trace element and isotopic analysis, organic phosphorus speciation, qPCR, organic carbon fingerprinting).
- Investigate how ice cover thickness and duration impact sediment and water column anoxia through changes in oxygen supply, phytoplankton activity, sediment redox processes, and thermal structure
- Investigate the positive feedback derived from hypoxia-induced flux of nutrients from lake-bottom sediments through *in situ* field observations and mesocosm studies.

Limnology / seiche

- Support the placement of several instrumented moorings at key locations in Lake Champlain to investigate the dynamics of the internal seiche and how it affects nutrient transport and biotic habitat
- Develop models to interrogate both existing physical, chemical, and biological data gathered and new data that needs to be gathered from instrumented moorings if we are to understand changes in thermal stratification and internal seiche respondant to climate change

Microbiota

- Support field studies and experiments investigating how nutrient speciation and source controls cyanobacterial ecology
- Support field and mesocosm experiments to investigate feedback loops between cyanobacterial blooms and shallow sediment-bound nutrients that create significant differences in bloom propagation and duration in lakes

- Investigate how ice cover thickness and duration impacts cyanobacterial ecology through changes in nutrient speciation and release from shallow sediments, overwintering of specific species, and temperature changes.
- Investigate how changes in temperature, sediment delivery/suspension, and nutrient availability affect the microbial base of benthic and pelagic food webs

Macrobiota

- Support field studies investigating how top-down and bottom-up food web changes will impact trophic transfer and lake biodiversity
- Support field studies on how lake temperature controls fish recruitment through timing of female ripening, spawning, egg development, hatch, and availability of plankton at first feeding stage and how thermal changes impact the distribution of fish populations
- Support studies on the links between internal seiche dynamics and biotic processes.
- Support studies investigating how changing hypoxia associated with ice cover may affect the over-wintering survival and reproduction of benthic-spawning fishes such as lake whitefish, walleye, alewife, and lake trout.
- Investigate the impact of changing temperature, sediment, and nutrient delivery on the biodiversity and integrity of aquatic ecosystems.

Tools

- Complex systems models require large, integrated datasets; analysis of current datasets show much of these data to be too inconsistent in method, with gaps in spatial or temporal data to utilize effectively; new data is needed to fully capture links between many physical, chemical, and biological parameters.
- Processes linking sediments, water, and biology are often complex, nonlinear, and nonparametric; we seek to specifically pair complex modeling experts with scientists engaged in field and laboratory experiments to jointly plan data gathering and experimental design as a start-to-finish paring to maximize effective data gathering and modeling efforts at unraveling complicated natural system interactions.
- Paleoenvironmental core samples record how many physical, chemical, and biological parameters are linked as climate changes, we seek to support acquisition and analysis of cores in Lake Champlain and key small lakes to investigate paleoclimate changes in the region to better inform predictive (conceptual and computational) models
- *In situ* sensor arrays deployed in Lake Champlain are needed to gather the physical, chemical, and biological data needed to investigate the role of the internal seiche on nutrient transport and biotic habitats; novel mooring deployments of multiple sensors represent opportunities to couple existing sensor technologies with new sensor development
- Remote sensing imagery acquired over multiple time intervals and combined with *in situ* water column measurements will provide “snapshots” of important lake processes such as cyanobacterial blooms, sediment, and currents over both time and space, we seek to support acquisition of remote sensing data, coordinated with surface and mooring measurements, to inform predictive conceptual and computational models

Integration plan:

Lakes receive much of the water and sediments from the watershed – changes in rainfall amounts/intensity, temperature, and ice cover will be significantly affected by climate change, and the social/economic policies that can affect landscape use will also impact sediment and nutrient delivery to lakes. As a system of interrelated processes, the watershed/landscape and society’s use of these will have a significant impact of lake processes, all of which will be affected by climate shifts.

Working groups in Watershed and Landscape processes will inform lake processes in terms of expected changes in sediment transport dynamics and nutrient speciation and delivery that will be affected by expected changes in climate. The Policy and Economic Impact group will inform lakes about the social and economic changes that will in turn affect sediment and nutrient delivery while the Lakes group will inform them on the expected changes in water quality and habitat resulting. As lakes will be one of the primary repositories of climate change records, the lake studies group will also work with the climate variability group to provide insight on paleoclimate records.

Infrastructure Needs: In order to accomplish the above goals, Vermont scientists and engineers will need:

Water and Sediment chemistry lab: We request funding to support the creation of an integrated lab where water and sediment analyses from lakes and their watersheds can be analyzed under controlled, repeatable, and consistent methods. This lab and technical support is essential to support the range of field and experimental work necessary to determine how climate changes affects lake processes as well as watershed/landscape processes and for integrating research activities with proposed outreach and educational plans. The lab will include a range of equipment for sediment and water characterization, including analysis for nutrients, metals, and critical chemical components in these systems. Analytical equipment to be housed in the lab is listed in Table 1 and represents a focused gathering of existing equipment (much of it obtained with prior NSF and NSF-EPSCoR support) and requested upgrades and key equipment acquisitions combined with committed technician support.

Lake instrumentation: We request funding to support up to 5 instrumented mooring arrays with flow, temperature, particle size, redox (voltammetric and ORP), pH, phosphorus, chlorophyll-a probes. These are the only way to investigate the dynamics of thermal stratification in Lake Champlain, including interrogation of the large internal seiche and it's role on chemical and biotic processes. These instruments will be deployed using the R/V Melosira, an existing research vessel at UVM.

New faculty lines as the University invests in the new spires.

Instrument	Water/sediment parameters	Requested equipment / upgrade
Ion Chromatograph (IC), Cond, UV-Vis, electrochem detectors	Major ions, nitrogen speciation, organic acids in water	existing
High Pressure Liquid Chromatography (HPLC)	Organic acids, pigments, toxin analysis	requested
Gas Chromatograph (GC)	Volatile organics, inorganic and organic gases (e.g. methane, hydrogen sulfide)	requested
Inductively-coupled Plasma Optical Emission Spectrometer (ICP-OES)	Major and trace elements in waters and sediment extractions	existing
Total C, N analyzer (water)	DIC, DOC, DIN, DN	requested
Latchat	Phosphorus, nitrogen species in solution	existing
UV-Vis spectrometers, lab and	Colorimetric analyses, portable	Request lab unit, one field

portable	ones for use in field	unit
Raman spectrometer-microscope, high resolution micro-Raman	Clay, iron oxide/sulfide mineral and organic contaminant analyses	requested
InfraRed spectrometer, Camera	Mineral and volatile organic carbon identification, camera to characterize organic gas fluxes	requested
Fluorescence spectrometer	Organic carbon identification using 3D excitation-emission-intensity analysis	requested
Laser particle sizer	Quantify particle sizes	existing
Gamma spectrometer	Dating of sediments utilizing 210Pb, 137Cs, 7Be	requested
X-ray Fluorescence spectrometer	Element analysis of sediments	existing

Table 1 – Instrumentation collection for core water and sediment analysis lab (some details on assorted equipment for extractions and sample prep not included)

References:

Aldrich, A.P., van der Berg, C.M.G., Thies, H., and Nickus, U., 2001: The redox speciation of iron in two lakes. Marine and Freshwater Research, 52: 885-890.

Austin, J. and S. Colman. 2008. A century of temperature variability in Lake Superior. Limnol. Oceanogr. 53(6):2724-2730.

Eckert, W., Didenko, J., Uri, E., and Eldar, D., 2003: Spatial and temporal variability of particulate phosphorous fractions in seston and sediments of Lake Kinneret under changing loading scenario. Hydrobiologia, 494: 223-229.

Golosev, S., Maher, O.A., Schipunova, E., Terzhevik, A., Zdorovennova, G., and Kirillin, G., 2007: Physical background of the development of oxygen depletion in ice-covered lakes. Oecologia, 151(2): 331-340.

Hayhoe, K., Wake, C.P., Huntington, T.G., Luo, L.F., Schwartz, M.D., Sheffield, J., Wood, E., Anderson, B., Bradbury, J., DeGaetano, A., Troy, T.J., and Wolfe, D., 2007: Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics, 28(4): 381-407.

Hodgkins GA, James IC, Huntington TG (2002) Historical changes in lake ice-out dates as indicators of climate change in New England, 1850–2000. Int J Climatol 22:1819–1827

Hunkins, K., T.O. Manley, P. Manley, and J. Saylor. Numerical studies of the 4-day oscillation in Lake Champlain. Journal of Geophysical Research 103(C9):18,425-18,436 (1998).

Jackson, L.J., Lauridsen, T.L., Sondergaard, M., and Jeppesen, E., 2007: A comparison of shallow Danish and Canadian lakes and implications of climate change. Freshwater Biology, 52: 1782-1792.

Jensen, J.P., E. Jeppesen, K. Olrik and P. Kristensen. 1994. Impact of nutrients and physical factors on the shift from cyanobacterial to chlorophyte dominance in shallow Danish lakes. Canadian Journal of Fisheries and Aquatic Sciences 51: 1692-1699.

Manley, T.O., K. Hunkins, J. Saylor, G. Miller and P. Manley. Aspects of summertime and wintertime hydrodynamics of Lake Champlain. Water Resources Monograph No. 14, American Geophysical Union, pp. 67-115 (1999).

Mortsch, L.D. and Quinn, F.H., 1996: Climate change scenarios for Great Lakes basin ecosystem studies. Limnology and Oceanography, 41(5): 903-911.

Group 4: Policy and Societal Impacts Group (PSIG)

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The Policy and Societal Impacts Group will focus on modeling the policy and governance dynamics that are informed by the integration of alternate policy scenarios associated with climate change processes, watershed processes and landscape phenology that is being investigated by other working groups and factored into a central integrated model (ARIES). Grounded in the theory of Sustainability Sciences, Policy Sciences, and Complexity Sciences, the policy and governance dynamic models will aim at understanding the effects of different policy and governance scenarios on the sustainability of the Lake Champlain watershed system under uncertain yet inevitably changing climatic conditions, societal impacts and changing governance structures (Stager and Thill, 2010). The "adaptive capacity", "resilience" and "vulnerability" of the watershed system under alternate socio-ecological scenarios will be investigated through innovative bottom-up Agent-Based Models (ABMs), Discrete Event Analysis (DEA), Complex System Dynamic Models (CSDs) and other simulation tools.

Changes in land and ecosystems and their implications for multi-scalar environmental change and sustainability are a major research challenge for the human environmental sciences (Folke et al., 2002; Folke et al., 2005; Turner et al., 2007; MEA, 2005; Huitema, et al., 2009). Sustainability science focuses on understanding the complex dynamics that arise from interactions between human and environmental systems (Clark, 2007), which can facilitate social learning through adaptation of governance and policy mechanisms in diverse socio-ecological systems (Ostrom et al. 2007). This working group will address two core theoretical questions that Kates and Clark (2001) posed for sustainability science:

1. How can the dynamic interactions between nature and society – including lags and inertia – be better incorporated into emerging models and conceptualizations that integrate the Earth system, social development, and sustainability?
2. What systems of incentive structures – including markets, rules, norms, and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?

This project focuses on studying the watershed governance network as a complex adaptive system. "Governance is the structure and processes by which people in societies make decisions and share power" that includes "the process of resolving trade-offs and of providing a vision and direction for sustainability, "as well as the implementation and monitoring of this vision" (Folke et al., 2005, p.444). Governance networks are the social systems that encompass multi-scale interactions, emergent behavior, pattern formation, and self-organization, and they are often inherently stochastic or operate in unpredictable ways (Folke et al., 2005; Huitema, et al., 2009; Newig and Frisch, 2009; Koliba, Meek and Zia, 2010). They possess nonlinear couplings, lags, inertia and foresight/situational awareness and feedbacks across multiple processes and scales. They have often emerged through a series of incremental policy actions that are undertaken simultaneously at the local, regional, state, provisional, national levels and international levels.

There is an extensive body of literature regarding the composition and success of regional environmental governance networks to achieve watershed policy objectives. A variety of network administrative organizational structures have arisen to design and implement these policies, including watershed councils, watershed partnerships, watershed committees and watershed management conferences (NRC 1999, Leach and Pelkey 2001, 2002; Koontz et al., 2004; Imperial 2005; Genskow and Bron, 2006; Scholz and Wang, 2005). The environmental governance networks described in the literature often comprise a wide array of local, regional, state and national policy actors, are oriented toward collaborative planning and problem solving, and they try to base their decisions on bio-physical science and social and economic factors (Genshow and Born, 2006, p.57; also see Clark et al., 2005).

The effectiveness of particular regional watershed governance networks to enhance the health, resiliency, and adaptive capacity of regional socio-ecological systems varies greatly (Koontz et al., 2004; Imperial, 2005). The variability in the network design, the existence of political dynamics, and the calibration of hydrological models to the prevailing economic and political realities have all been cited as challenges to drawing definitive conclusions regarding the effectiveness of these regional responses (Bonnell and Koontz, 2007; Imperial, 2009; Newig and Fritsch, 2009).

Ultimately, an integrated modeling system of coupled human and natural systems is essential to provide a scientific foundation for sustainable agriculture, forestry, urban growth and environmental policy development, vulnerability reduction, and resilience enhancement of watershed systems and their management. This project will draw on extensive case study data from one watershed to develop a calibrated simulation model of the social dynamics shaping regional policy decisions and implementation strategies. The governance of complex adaptive systems for sustainability goals requires new tools for policy analysis and evaluation (Bankes, 2002; Norton, 2005). Conventional methods of quantitative and qualitative policy analysis alone are not sufficient to adequately address system uncertainty inherent in managing complex adaptive systems (Bankes, 2002). To model these dynamics we will apply complex systems dynamics (CSD), discrete-event analysis (DEA), and agent-based modeling (ABM) simulation techniques to understand the emergent patterns of *formation*, *operation* and *performance* of social structures of multiple policy actors taking part in the watershed governance networks of the Lake Champlain basin. Existing integrated land use, climate change, transportation, and economic development models have been designed to forecast the scenarios of outputs and outcomes that arise as a result of certain policy decisions. These models, however, generally represent the human and cross-institutional governance systems as “black boxes” that shape the design and implementation of policy tools. In practice, these black boxes are populated by inter-organizational networks of agents from the public, private, and nonprofit sectors, who span geographic scale, and implement complex decision heuristics. *To date, there have been few attempts to develop integrated models analyzing the complex structures and operational dynamics of inter-organizational networks that emerge to govern the regional-scale environmental planning regimes across traditional administrative boundaries*. The aim of our research is to develop an integrated model of regional environmental governance networks using CSD, DEA, and ABMs, generating a clear and compelling set of “governance informatics” in the process. Governance informatics are, essentially, pieces of information regarding the process dynamics of a network’s underlying governance structures and functions. Governance informatics have a vast potential to facilitate adaptive policy responses, generate social learning, foresight and situational awareness among different decision makers in the system, improve understanding of lags and inertia, and above all, move beyond the notion of one-size-fit-all governance panaceas.

Hypotheses

A series of hypothesis that are grounded in the extensive theoretical frameworks that have been devised to study the complex dynamics of environmental governance networks will be tested. The assumptions of four models will draw upon: the Advocacy Coalition Framework (Sabatier and Jenkins-Smith, 1993), the Institutional Analysis and Development (IAD) framework (Ostrom, 1990, 2005), the Policy Streams model (Kingdon, 1984), and the Governance Network Analysis (GNA) framework (Rhodes, 1997; Sorensen and Torfing, 2008; Koliba, Meek and Zia, 2010). Each of these frameworks contributes a unique set of considerations that are useful in developing complex adaptive systems models of environmental governance networks. Each framework will be used to structure a set of hypothesis from which to test both the efficacy of the overall model, as well as the specific assumptions that have been advanced through these policy models and frameworks. These assumptions will be drawn on to model the adaptability and resilience of Lake Champlain watershed socio-ecological system in the face of uncertain climatic change. These hypothesis will be posited along a time series continuum that captures the historical evolution of the system over a 35 year time period beginning in 1988 with the initiation of the Lake Champlain Basin Program and extending to the year 2023 through which various "business as usual" and catastrophic events (such as extreme flooding events; collapse of the ski or maple syrup industry; anticipated population shifts) scenarios may be extrapolated. Differences in the socio-ecological systems dynamics (both in terms of the natural and social components) will be used to draw comparisons between time periods.

The first hypothesis will be drawn from assumptions guiding the Advocacy Coalition Framework (ACF) that focuses on the role that the belief systems of specific advocacy coalitions play in shaping public policy (Sabatier and Jenkins-Smith, 1993; Leach and Pelkey, 2001; Weible, Sabatier and Lubell, 2004). In the context of watershed governance these belief systems are often framed through certain economic considerations (such as economic development, farming, tourism), environmental stewardship considerations (such as broad environmental advocacy, or specific issue advocacy), or evidence drawn from scientific data. The relative strength of a given advocacy coalition at any one point in time will be ascertained through the triangulation of the kinds of methodological approaches mentioned above.

H1: The dominance of a shared-belief network of advocacy coalitions (e.g. farmers and economic developers) over other advocacy coalitions in the policy system (e.g. environmentalists, scientists) in time period (T-1) will result in the emergence of policy tools/actions in time period (T) that align with the policy goals ascribed to by the dominant coalition network

The second hypothesis will draw on the Institutional Analysis and Development (IAD) framework, through which the "action arenas" involving specific combinations of policy actors bargaining over different kinds of collective action rules are analyzed. The IAD framework has been used to assess the efficacy of diverse institutional designs, such as decentralized, locally based collective action rules versus centralized, or top down institutional mechanisms for governing environmental commons (Ostrom 1990, 2005). As such, strong emphasis is placed on analyzing the relationship between the collaborative capacity of the network and the network's effectiveness in achieving pro-environment outcomes.

H2: Decisions made by a consensus (or majority rule; or oligarchy) of policy actors through the deliberative processes of the LCBP steering committee in time period (T-1) will result in policy actions in time period (T) that yield highly successful (or moderately successful; or ineffective) outcomes for the sustainability of region's watershed.

The third hypothesis will draw on the Policy Streams framework, which emphasizes the existence of problem, policy tool selection, and political alignment streams that, when coupled, open up policy windows for enabling change in policies (Kingdon, 1984). The manifestation of each stream will be identified through the preponderance of critical events (such as catastrophic events, the issuing of public reports, news accounts of the scope of the environmental problem, or the focus of debate during an election cycle), the creation and/or implementation of specific policy tools (laws, regulations, grant programs, public information campaigns, etc.) or suites of policy tools, and the existence of higher degrees of political activity undertaken across a range of actors in the dynamic policy systems.

H3: Occurrence of critical events in the socio-ecological system will trigger policy change when political and policy (solution) streams are aligned. Conversely, when political and policy (solution) streams are not aligned, occurrence of critical events alone will not trigger policy change that ensures a sustainable trajectory of the socio-ecological system.

The fourth hypothesis is drawn from the Governance Network Analysis framework, which emphasizes the type of policy actors and the nature of the ties between policy actors that exist to carry out one or more policy function (Koliba, Meek and Zia, 2010). In this study, particular attention is paid to the flow of resources(financial, political, social, knowledge and human capital) across ties and the extent to which these resource flows are governed through certain combinations of network accountability (construed in terms of democratic anchorage, reliance on market forces, and the preponderance of vertical, horizontal and professional accountabilities).

H4: As the density of financial, human, knowledge and social capital resources that flow through the regional governance network increases over time, the more likely it is that sustainable policy action will be undertaken.

Different conceptual notions of vulnerability and resilience have been explored in disciplines as diverse as human geography, political ecology, human ecology, disaster management, emergency management, climatic change, and human dimensions of global change. Related theories have been reviewed over the years by Dow (1992), Ribot et al. (1996), Cutter (1996, 2003), Pelling (2003), Bankoff et al. (2004), Ionescu et al. (2005), Kasperson et al. (2005), Eakin and Luers (2006), Fussel and Klein (2006), Fussel (2007), Adger (2006), and Janssen et al . (2006). From this diversity of approaches, we conceptualize vulnerability and resilience as inversely related properties of a coupled natural and human system, as elaborated by Turner et al., (2003a, b) in the context of a social-ecological system. Here, vulnerability is defined as the degree to which human and environmental systems are likely to experience harm due to aperturbation or stress (e.g. Kasperson et al., 2003; Turner et al., 2003a, b). Vulnerability has become a central focus of the global change and sustainability science research communities (IHDP, 2001; IPCC, 2001, 2007; Kates et al., 2001; Kasperson, 2001). Human vulnerability involves the “degree to which someone’s life and livelihood is put at risk” by a hazard, and thereby reflects a lack of “capacity to anticipate, cope with, resist, and recover from” the hazard (Blaikie et al 1994, p.9). Resilience, then, “determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change of state variable, driving variables, and parameters, and still persist (Holling, 1973, p. 17). Ecological resilience, defined as the ability of a set of mutually reinforcing structures and processes to persist in the presence of disturbance and stresses (Holling, 1973; Gunderson, 2000), is particularly prominent within the discourse of the global change vulnerability community (Carpenter et al., 2001; Folke et al., 2002; Kasperson et al., 2003). This system level framework for vulnerability (and resilience, by implication) has been applied in a range of empirical assessments (Luers et al. 2003, Luers 2005, O’Brien et al. 2004, Schroter et al., 2005; Ionescu et al., 2005). Derived from the synthesis of this research, we will test the following hypothesis:

H5: Societal impacts of global climate change in Lake Champlain watershed basin, mediated without any proactive governance approaches, enhance the vulnerability and reduce the resilience of socio-ecological systems. Conversely, proactive governance approaches will reduce *the vulnerability and enhance the resilience of the socio-ecological systems.*

Luers et al. (2003, p.255) suggest that "although vulnerability research has produced an insightful and extensive literature in the social and global-change sciences, the application of the concept in policy-driven assessments has been limited by a lack of robust metrics to model and measure vulnerability within and across systems." The primary objective of vulnerability assessments typically appears to be to identify people or places that are most susceptible to harm and to identify vulnerability-reducing actions (Stephen and Downing, 2001; Downing et al., 2001). Luers et al. (2003) proposed a new system level approach to quantify vulnerability for policy analytical purposes that integrates four essential concepts: the state of the system relative to a threshold of damage, sensitivity, exposure, and *adaptive capacity*. We plan to extend the application of this conceptual notion from a uni-dimensional (i.e. farmer vulnerability) to a multi-dimensional measure (mathematically expressed as a vulnerability vector). In addition to assessing the vulnerability of farmers in a coupled natural and human system from endogenous and exogenous stressors, we will also measure other system level vulnerabilities, e.g. vulnerability of ecosystems from changes in water quality and water quantity engendered by agricultural and settlement (urban) practices of human societies. We will alsoanalyze the interactions of various system level vulnerabilities under multiple policy scenarios, decision heuristics and endogenous and exogenous stressors such as climatic change and land use patterns. In particular, we will test the following additional hypotheses:

H6: Under business-as-usual policy scenarios, societal actors in LCWB have limited adaptive capacity, and display inertia and lags in responding to climate change signals. In contrast, under sustainable policy development scenarios, societal actors in LCWB have enhanced adaptive capacity, and overcome inertial and lagged response to climate change signals.

H7: Current incentive structures in LCWB are not effective in reducing the vulnerability of different societal actors (e.g. farmers, tourist industry and other actors cited in Nature Conservancy Report (Stager and Thill, 2010). Furthermore, alternative incentive structures, such as proactive risk insurance mechanisms or information campaigns in the LCWB, could be more effective in reducing the vulnerability of different societal actors.

H8: Different societal actors perceive uncertain climate change forecast information through the lenses of their ideologies, values and previous experiences that results in under- or over-estimation of the risk posed by climatic change. Furthermore, improvements in the communication of uncertain climate forecast information could improve the adaptive capacity and reduce the vulnerability of societal actors in the lake Champlain socio-ecological system.

References

Adger, W. N. (2006). "Vulnerability." Global Environmental Change 16:268-281.

Bankoff, G., G. Frerks and D. Hilhorst eds. (2004). Mapping Vulnerability: Disasters, Development and People. London: Earthscan

Blaikie, P., T. Cannon, I. Davis, and B. Wisner. (1994). At Risk: Natural Hazards, People's Vulnerability, and Disasters. London: Routledge.

Bankes, S. (2002). Tools and techniques for developing policies for complex and uncertain systems. *PNAS*. 99(3). 7263-7266.

Bonnell, J.E. and Koontz, T.M. (2007). “Stumbling forward: The organizational challenges of building and sustaining collaborative watershed management.” Society and Natural Resources. 20: 153-167.
Carpenter, S. and B. Walker, Anderies, J.M., Abel, N. (2001). "From metaphor to measurement: resilience of what to what? ." Ecosystems 4:765-781.
Clark, B.T., Burkhardt, N., and King, N.D. (2005). Watershed management and organizational dynamics: Nationwide findings and regional variation. Environmental Management. 36(2): 297-310.
Clark, W. C. (2007). Sustainability Science: A room of its own. *Proceedings of the National Academy of Sciences (PNAS)* 104(6): 1737-1738.
Cutter, S.L. (1996). "Vulnerability to environmental hazards." Progress in Human Geography 20:529-539.
Dow, K. 1992. "Exploring differences in our common future(s): the meaning of vulnerability to global environmental change." Geoforum 23:417-436.
Downing, T.E. and R. Butterfield, Cohen, S., Huq, S., Moss, R., Rahman, A., Sokona, Y., Stephen, L. (2001). Climate Change Vulnerability: Linking Impacts and Adaptation. Oxford: University of Oxford.
Eakin, H. and A.L. Luers. (2006). "Assessing the vulnerability of social-environmental systems." Annual Review of Environment and Resources 31:365–394.
Folke, C., S. Carpenter, Elmqvist, T., Gunderson, L., Holling, C. and B. Walker, Bengtsson, J., Berkes, F., Colding, J., Danell, K., (2002). "Resilience and sustainable development: building adaptive capacity in a world of transformations." Scientific Background Paper Prepared for the Environmental Advisory Council to the Swedish Government. ICSU Series for Sustainable Development, No. 3. Available online: http://www.resalliance.org/reports/resilience and sustainable development.pdf.
Folke, C., Hahn, T. Olsson, P. and Norberg, J. (2005). Adaptive governance of social-ecological systems. Annual Review of Environmental Resources. 30:441-73.
Fussel, H.-M. and R.J.T. Klein. (2006). "Climate change vulnerability assessments: an evolution of conceptual thinking." Climatic Change 75:301-329.
Fussel, H.-M. (2007). "Vulnerability: A generally applicable conceptual framework for climate change research." Global Environmental Change 17:155-167.
Genskow, K.D. and Born, S.M. (2006). “Organizational dynamics of watershed partnerships: A key to integrated water resource management.” Journal of Contemporary Water Research & Education. 135: 56-64.
Gunderson, L. (2000). "Ecological resilience—in theory and application." Annual Review of Ecology and Systematics c31:425–439.
Huitema, D., Mostert, E., Egas, W., Moellenkamp, S. Pahl-Wostl, C. and Yalcin, R. (2009). Adaptive water governance: Assessing the institutional prescriptions of adaptive (co-) management from a governance perspective and defining a research agenda. Ecology and Society. 14(1): 26
Holling, C.S. (1973). "Resilience and stability of ecological systems." Annual Review of Ecology and Systematics 4:1-23.
IHDP, (International Human Dimensions Program) Update. (2001). Special issue on vulnerability,
Available on line at http://www.ihdp.org 2:1-16.
Ionescu, C., R.J.T. Klein, J. Hinkel, K.S.K. Kumar and R. Klein. (2005). "Towards a Formal Framework of Vulnerability to Climate Change." NeWater Working Paper 2, Potsdam Institute for Climate

Impact Research, Potsdam.
IPCC (2008). Climate Change 2007: Synthesis Report, An Assessment of the Intergovernmental Panel on Climate Change, 73pp.
IPCC, (Intergovernmental Panel on Climate Change). (2001). Impacts, adaptation, and vulnerability climate change 2001: Third Assessment Report of the IPCC. Cambridge, UK.: Cambridge University Press.
Janssen, M.A., M.L. Schoon, W. Ke and K. Borner. 2006. "Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change." Global Environmental Change 16:240-252.
Imperial, M. T. (2005). Using collaboration as a governance strategy. *Administration & Society, 37*(3), 281-320.
Imperial, M.T. (2009). Paradoxes, possibilities, and the obstacles to integrated water resource management: Lessons from the institutional rational choice literature. Paper presented at the International Symposium on society and Resource Management (ISSRM). July, 2009. Vienna, Austria.
Kasperson, R.E., K. Dow, Archer, E., Caceres, D., Downing, T., T. Elmqvist, Eriksen, S., Folke, C., Han, G., Iyengar, K., Vogel, C. and K. Wilson, Ziervogel, G. (2005). "Vulnerable people and places." In Ecosystems and Human Wellbeing: Current State and Trends, eds. R. Hassan, R. Scholes and N. Ash. Washington, DC: Island Press.
Kasperson, J.X. and R.E. Kasperson, Turner II, B.L., Schiller, A., Hsieh, W.-H. (2003). "Vulnerability to global environmental change." In The Human Dimensions of Global Environmental Change, eds. A. Diekmann and T. Dietz, Jaeger, C., Rosa, E.S. Cambridge: MIT.
Kates, R. W., and Clark W.C. (2001). Sustainability Science. *Science* 292(5517): 641-642.
Kingdon, J. (1984). *Agendas, Alternatives, and Public Policies*. New York: Harper Collins.
Koliba, C., Meek, J. and Zia, A. (2010). Governance networks in public administration and public policy. New York: Taylor and Francis.
Koontz, T., Steelman, T., Carmin, J., Korfmarcher, K., Moseley, C., & Thomas., C. (2004). *Collaborative Environmental Management: What Roles for Government?* . Washington, DC: Resources for the Future.
Leach, W.D. and N.W. Pelkey. (2001). "Making Watershed Partnerships Work: A Review of the Empirical Literature." Journal of Water Resources Planning and Management 127(6).
Leach, W.D., N.W. Pelkey and P.A. Sabatier. (2002). "Stakeholder Partnerships as Collaborative Policymaking: Evaluation Criteria Applied to Watershed Management in California and Washington." Journal of Policy Analysis and Management 21(4).
Luers, A.L. (2005). "The surface of vulnerability: An analytical framework for examining environmental change." Global Environmental Change 15:214-223.
Luers, A.L., D. B. Lobell, S. S. Leonard and C. L. Addams.(2003). "A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico." Global Environmental Change 13:255-267. O'Brien, K.L., R. Leichenko, Kelkarc, U., Venemad, H., Aandahl, G. and H. Tompkins, Javed, A., Bhadwal, S., Barg, S., Nygaard, L., West, J. 2004. "Mapping vulnerability to multiple stressors: climate change and globalization in India." Global Environmental Change 14:303-313.
Millennium Ecosystem Assessment (MEA) (2005). Available online http://www.millenniumassessment.org/en/index.aspx
National Research Council. (1999). New Strategies for America's Watersheds. Washington, D.C.: National Academy Press.
Newig, J. and Fritsch, O. (2009). Environmental governance: Participatory, multi-level- and effective? Environmental Policy and governance. 19: 197-214.

Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. New York: Cambridge University Press.
Ostrom, E. (2005). *Understanding institutional diversity*. Princeton, NJ: Princeton University Press.
Ostrom, E., Marco A. J. and John M. A. (2007) Going beyond panaceas. *Proceedings of the National Academy of Sciences (PNAS)* 104: 15176-15178.
Pelling, M. (2003). The Vulnerability of Cities: Natural Disasters and Social Resilience. London: Earthscan.
Ribot, J.C., A.R. Magalhaes and S.S. Panagides eds. (1996). Climate Variability, Climate Change and Social Vulnerability in the Semi-arid Tropics. Cambridge: Cambridge University Press.
Rhodes, R. (1997). *Understanding governance: Policy networks, governance, reflexivity and accountability*. Buckingham: Open University Press.
Sabatier, P. A., and Jenkins-Smith, H.C. (1993). *The advocacy coalition framework: An assessment*. Boulder, CO: Westview Press.
Scholz, J.T. and Wang, C. (2006). Cooptation or transformation? Local policy networks and federal regulatory enforcement. American Journal of Political Science. 50(1): 81-97.
Schroter, D., W. Cramer, Leemans, R., Prentice, I.C., Araujo, M.B., N.W. Arnell, Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., A.C. de la VegaLeinert, Erhard, M., Ewert, F., Glendining, M., J.I. House, Kankaanpaa, S., Klein, R.J.T., Lavorel, S., Lindner, M., M.J. Metzger, Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., S. Sabate, Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T. and K. Thonicke, Thuiller, W., Tuck, G., Zaehle, S., Zierl, B. (2005). "Ecosystem service supply and vulnerability to global change in Europe." Science 310:1333-1337.
Sorensen, E., & Torfing, J. (Eds.). (2008). *Theories of Democratic Network Governance*. New York: Palgrave Macmillan.
Stager, C. and Thill, M. (2010). *Climate change in the Champlain Basin: What natural resource managers can expect and do.* Saranac Lake, NY: The Nature Conservancy.
Stephen, L. and T.E. Downing. (2001). "Getting the scale right: a comparison of analytical methods for vulnerability assessment and household-level targeting." Disasters 25:113-135.
Turner, B. L., E. F. Lambin (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences (PNAS)* 104(52): 20666-20671
Turner II., B.L., R.E. Kasperson, Matson, P.A., McCarthy, J.J., Corell, Christensen R.W., L., Eckley, N., Kasperson, J.X., Luers, A. and M.L. Martello, Polsky, C., Pulsipher, A., Schiller, A. 2003a. "A framework for vulnerability analysis in sustainability science." Proceedings of the National Academy of Sciences 100:8074–8079.
Turner II., B.L., P.A. Matson, McCarthy, J.J., Corell, R.W., Christensen, Eckley L., N., Hovelsrud-Broda, G.K., Kasperson, J.X., Kasperson, Luers R.E., A., Martello, M.L., Mathiesen, S., Naylor, R., Polsky, C. and A. Pulsipher, Schiller, A., Selin, H., Tyler, N. (2003b). "Illustrating the coupled human-environment system for vulnerability analysis: three case studies." Proceedings of the National Academy of Sciences 100:8080-8085.
Weible, C., Sabatier, P.A., and Lubell, M. (2004). "A comparison of a collaborative and top-down approach to the use of science in policy: Establishing marine protected areas of California." *The Policy Studies Journal.* 32(2): 187-207.