# THE LAKE CHAMPLAIN BASIN AS A COMPLEX ADAPTIVE SYSTEM: INSIGHTS FROM THE RESEARCH ON ADAPTATION TO CLIMATE CHANGE (“RACC”) PROJECT

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## INTRODUCTION

Like all large, freshwater lake systems situated within a populated region, the Lake Champlain Basin (“LCB”) is a decidedly “social ecological system,” meaning that human activity has altered the ecosystem through human land use decisions, development patterns, infrastructure, and water management practices to the extent that we may no longer consider ecosystems as divorced from human influence and impact.

Likewise, as paleoclimatological studies have shown, the Earth’s climate (heating and cooling cycles, precipitation patterns, and extreme

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weather events) has directly shaped landscapes and ecosystems and often dictated societies' land use and land management decisions.[2] As the climate changes, it has been the case that landscapes, ecosystems, and human actions are intertwined and adapt in response to one another.

By viewing the LCB as a social ecological system that is adapting in response to climate change, watershed planners can better anticipate the region's water quality challenges. Without managing this adaptation, acceleration in the decline of water quality in the LCB is likely. This article draws on the transdisciplinary research project undertaken by a team of Vermont scientists and students to study and model aspects of the LCB as a complex adaptive system comprising climatological, terrestrial, aquatic, and human components (including public and private social behaviors, land use decisions, and policy and governance responses to water quality needs). We will highlight the activities and some of the preliminary results to emerge from the early stages of the National Science Foundation funded Research on Adaptation to Climate Change ("RACC") project. With a goal to inform the "adaptive management" of the LCB's watersheds, we will also discuss implications of the RACC project for addressing critical policy challenges facing the region.

## I. WHY THINK OF THE LAKE CHAMPLAIN BASIN AS A COMPLEX SOCIAL ECOLOGICAL SYSTEM?

Lake Champlain is the largest lake in the northeastern United States after the Great Lakes. It lies between the states of Vermont and New York and the province of Quebec, Canada to the north. It is 170 km long and at its broadest point it is 20 km wide. It has a maximum depth of 122 m, a mean depth of 23 m, and considerable variation in trophic status and morphology across its extent. The LCB, shared by Vermont, New York, and Quebec, has a land to water ratio of almost 19:1, making water quality in the lake intimately tied to activities on the land.

Some shallow embayments of Lake Champlain, like many freshwater ecosystems around the world, have experienced rapid eutrophication; phosphorus control is a major focus of management with concentrations ranging from 10 μg/L (micrograms per liter or parts per billion) in Burlington Bay to 100 μg/L in Missiquoi Bay. Because municipal point-source treatment has been upgraded throughout the basin, almost 90% of the current phosphorus load is nonpoint source. In Section 303(d) of the

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[2] *See generally* BRIAN FAGAN, THE LONG SUMMER: HOW CLIMATE CHANGED CIVILIZATION (2004) (arguing that changes in climate have shaped societies throughout history).

Clean Water Act, the United States Environmental Protection Agency ("EPA") requires all states to identify waters that are "impaired"—that is, which do not meet the state water quality standards.[3] Once identified, states must analyze and set Total Maximum Daily Load ("TMDL") targets for each pollutant to the water body.

As noted elsewhere in this volume, the State of Vermont has worked to develop a comprehensive TMDL plan for the LCB. Over the last fifteen years, multi-million dollar investments have been made to improve water quality in Lake Champlain and eliminate the algal blooms that impact human and animal health and deter tourists. However, despite the best efforts of many agencies and individuals, these water quality goals have not been achieved in most segments of Lake Champlain, as phosphorus concentrations are either increasing or remaining relatively constant, even with significant implementation of and resource allocation toward phosphorus loading reduction schemes across portions of the LCB.[4]

The LCB is a social-ecological system, composed of both biophysical and social components in which human-derived institutional infrastructure (mixed public and private sector governance arrangements), built infrastructure (road, bridges, treatment of storm, drinking, and wastewater), and economic systems (markets) have inserted themselves into the dynamic structures of biophysical systems to "the extent that the latter have, in the true sense of the word, become socio-ecological." [5] Humans have "homogenized parts of their environment in order to bring [biophysical] dynamics under control," as in the cultivation of land for food production, river corridor management practices, timber harvesting, development of impervious surface, and more. According to Oren Young et al., the survival of social ecological-systems becomes increasingly "dependent on the resilience of their social dynamics in contrast to their purely biophysical dynamics."[6] In other words, the future of social ecological systems is deeply impacted by the decisions that humans make. Human actors living on Vermont's landscape have, for many generations, indelibly altered the landscape and, therefore, Lake Champlain itself. The accumulation of centuries of land use has contributed to the current water quality challenges faced within the LCB.

From the 1700s to the early 1800s, almost eighty percent of the land in

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[3] 33 U.S.C. §1313(a) (2012).

[4] LAKE CHAMPLAIN BASIN PROGRAM, 2015 STATE OF THE LAKE AND ECOSYSTEM INDICATORS REPORT 6, 11 (2015), http://sol.lcbp.org/images/State-of-the-Lake_2015.pdf [https://perma.cc/R7WD-WA9G] [hereinafter STATE OF THE LAKE].

[5] Oran R. Young et al., *The Globalization of Socio-Ecological Systems: An Agenda for Scientific Research*. 16 GLOBAL ENVTL. CHANGE 304, 306.

[6] *Id.*

what is now the State of Vermont was cleared for agriculture and pasture, leading to a huge increase in sediment inputs to streams and rivers. These trends have resulted in a legacy of increased sediment that resides today in terraces and deltas throughout Vermont watersheds and associated receiving lake and pond sedimentary deposits. During and after the Great Depression, some Vermonters abandoned their farmland to head west and much of the landscape reverted to early successional forest. Today, the land in the LCB is about sixty-five percent forested, with the remaining land primarily in dairy-related agriculture (cow herds and corn and hay rotation) and growing residential and commercial development.[7]

One of the major consequences of human action upon the landscape is the production of nonpoint source pollution and transport of excessive nutrient (e.g., phosphorus and nitrogen) loadings to receiving waters. As has been discussed extensively in this volume, the consequences of excessive nutrient loading include the potential for eutrophication of freshwater lakes like Lake Champlain. The sources of nutrient loading have been well documented in studies of the region[8] and include stormwater runoff from developed land where impervious surfaces and spread of fertilizers on lawns, institutional and commercial property, and recreational green spaces contribute to phosphorus and nitrogen loading into local receiving water bodies. Streambank erosion, logging activities, roadway runoff, and wastewater treamtment accounts for other sources of nutrient loading. Agricultural land use practices combined with poor nutrient management practices, such as excessive fertilizer application, often contribute to a substantial portion of the nutrient loading in certain regions. The sheer number and variation of nonpoint sources pose serious challenges to those concerned about water quality.

In the parlance of planning and complexity science, nonpoint source water pollution is a "wicked problem" because of the complex interactions of social, ecological, and climatological factors that contribute to the problem. With such a wide range of sources and complicated consequences, the framing of nonpoint source pollution as a problem involving many different social actors contributes to competing views around the definition of the problem (e.g., the sources) and mitigation strategies, giving rise to a range of policy preferences and strategies considered.[9] Competing views on

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[7] AUSTIN TROY ET AL., UPDATING THE LAKE CHAMPLAIN BASIN LAND USE DATA TO IMPROVE PREDICTION OF PHOSPHORUS LOADING 18 (2007), https://www.uvm.edu/giee/pubpdfs/Troy_2007_Lake_Champlain_Basin_Program.pdf [https://perma.cc/U7M4-2AKP].

[8] *See* STATE OF THE LAKE, *supra* note 4, at 8–10 (describing the various sources of nutrient loading into Lake Champlain).

[9] JOHN W. KINGDON, AGENDAS, ALTERNATIVES, AND PUBLIC POLICIES (1984).

both the nature of problems and intended solutions often lead to "trade-off" or zero-sum considerations. These trade-offs are often framed as being between environmental and economic considerations, pitting costs of managing nonpoint pollution by government institutions, private land owners, businesses, and taxpayers against the anticipated environmental and social benefits of alleviating the problem through specific investments of political and financial capital.

The critical question driving the wickedness of nonpoint pollution is "Who is responsible for causing it?" By definition, nonpoint pollution sources are "nonpoint" because the pollution does not flow from a pipe or other similarly specific, non-distributed source. Monitoring and modeling at the appropriate watershed- and basin-wide scales can, in fact, generate fairly effective estimates of the general sources of nonpoint pollution. But attempting to pin-point specific sources leads to high levels of uncertainty that constrain planning horizons, assignment of accountability, and the political willingness to regulate land use decisions. The use of water sensors and advanced isotopic tracing may possibly play a role in narrowing down the exact sources of nonpoint pollution, but this capacity is still likely a ways off.

To add complication, the impacts of nonpoint pollution are likely driven by significant time lags and legacies of sediment that persist across the system.[10] It may take years and even decades for the cumulative impacts of nonpoint pollution to take effect and manifest as algal blooms in the region's bays.

Adding to the challenge of managing nonpoint pollution is anticipating the impact that climate change may have on adding to the intractability of the problems. RACC research is suggesting that increased temperatures and persistent storm events in northeastern U.S.[11] caused by climate change will likely contribute to the exacerbation of algal blooms.[12] The climate of the Lake Champlain Basin has warmed by 2.1°F since 1976; precipitation has increased by 3 inches over 8 decades; ice rarely covers the main lake anymore and the "freeze up" is delayed 2 weeks compared to the late

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[10] *See* Peter D.F. Isles et al., *Dynamic Internal Drivers of a Historically Severe Cyanobacteria Bloom in Lake Champlain Revealed Through Comprehensive Monitoring*, 41 J. OF GREAT LAKES RES. 818, 828 (2015) (concluding that historical loading is a key factor responsible for eutrophic conditions).

[11] Justin Guilbert et al., *Impacts of Projected Climate Change over the Lake Champlain Basin in Vermont*, 53 J. APPLIED METEOROLOGY & CLIMATOLOGY 1861 (2014).

[12] Asim Zia et al., Climate and Land Use Change Induced Transformations Across a River-Lake Continuum: Insights from an Integrated Assessment Model of Lake Champlain's Missisquoi Bay, 2000-2040, 3 (2015) (unpublished manuscript) (submitted to Environmental Research Letters and on file with Vermont Journal of Environmental Law).

1800s; and precipitation is increasingly in the form of rain delivered through extreme weather events.[13] The snow pack in the watershed and ice cover on rivers and lakes has similarly changed.[14] The results of RACC statistical climate downscaling modeling[15] anticipates further warming, rising surface water temperatures, more rain, and severe weather through the rest of the century, even in the event that greenhouse gas emissions are reduced.

A recent Intergovernmental Panel on Climate Change ("IPCC") report highlights the necessity of an integrated adaptive management approach to risk and resilience.[16] The recent National Climate Assessment echoed the grand challenge of resilience to extreme events induced by climate change: "Climate change, combined with other stressors, is overwhelming the capacity of ecosystems to buffer the impacts from extreme events."[17] "Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts."[18]

The impacts of climate change on water quality and the resultant tangible environmental consequences for nonpoint pollution likely hinges on the choices land users and owners make regarding land use management and land cover decisions (e.g., cutting forests to develop crops, implementation of soil management approaches, utilization of cropping techniques, investments in stormwater infrastructure, etc.). Given the large role that human agency brings to land use decision making, perhaps the most critical questions for water planners concern the persistent jurisdictional knots that compound the problem. Persistent questions are asked but rarely resolved, at least to the satisfaction of key stakeholders. These questions include: "Who is responsible for addressing the causes of nonpoint pollution?"; "How do we balance individual and collective property rights?"; "What are the appropriate intergovernmental programmatic and governance designs that can facilitate a transition from a culture of nutrient waste management to sustainability and resilience?"; and

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[13] Guilbert et al., *supra* note 11.

[14] *Id.*

[15] *Id.*

[16] CLIMATE CHANGE 2007: IMPACTS, ADAPTATION AND VULNERABILITY (Martin Parry et al. eds.,2007)

[17] PETER M. G. CHAPTER 8: ECOSYSTEMS, BIODIVERSITY, AND ECOSYSTEM SERVICES 196, 217 (2014), http://nca2014.globalchange.gov/report/sectors/ecosystems [https://perma.cc/9YGJ-N3E2] (click "Download" in the top corner of the page to download a static PDF of the report chapter).

[18] ARIS GEORGAKAKOS ET AL., CLIMATE CHANGE IMPACTS IN THE UNITED STATES: CHAPTER 3: WATER RESOURCES 70 (2014), http://nca2014.globalchange.gov/report/sectors/water [https://perma.cc/MDE6-BJKQ] (click "Download" in the top corner of the page to download a static PDF of the report chapter).

"What are the ideal strategies to incentivize and shape sound water quality-friendly land use, development, infrastructure, and related decisions?"

The conclusion to draw from this description of the causes and consequences of nonpoint pollution within social-ecological systems like the LCB is that we are dealing with a complex and adaptive system. Wicked problems like those stemming from nonpoint pollution require systems-level views of the relationship between the terrestrial, aquatic, climatological, and social aspects of the system.

A recent National Science Foundation ("NSF") solicitation describes a complex system as one in which individual organisms (or agents) can respond and adapt to changes in their environment, self-organize, and spontaneously reorganize in response to changing conditions. Despite the diverse nature of complexity in physical, biological, social, and engineered systems, there are universal principles, process abstractions, and systems-thinking methodologies that unify the study of complex systems.[19] The essential properties of complex systems (e.g., emergence, scaling phenomena and mechanisms, robustness, adaptability, collective dynamics, complex network characteristics, tipping points and phase transitions, alternate stable states, and selection to the edge-of-chaos) may be studied, modeled, and understood using complex adaptive systems approaches.

The rise of computational power allows us to capture and advance our theories and methods for studying and understanding the relationships between surface water flow and land use, societal governance arrangements and the public policies they create and implement. This understanding can then be extended to policy makers and planners through an "adaptive management" approach.

Adaptive management is a systematic process for improving management policies and practices by learning from the outcomes of management strategies implemented using a systems-level focus.[20] The ideal of adaptive management is to use the tools and findings from the natural and social sciences to inform long-term strategic planning and decision making.

RACC was designed to inform the adaptive management of the LCB. In the next section we provide a basic conceptual architecture used by RACC to describe the LCB as a complex adaptive system and consider

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[19] *See generally* JOHN H. MILLER & SCOTT E. PAGE, COMPLEX ADAPTIVE SYSTEMS: AN INTRODUCTION TO COMPUTATIONAL MODELS OF SOCIAL LIFE (2007) (exploring various methods of modeling complex systems).

[20] Claudia Pahl-Wostl, *The Importance of Social Learning in Restoring the Multifunctionality of Rivers and Floodplains*, 11 ECOLOGY & SOC'Y (2006), http://www.ecologyandsociety.org/vol11/iss1/art10/ [https://perma.cc/X6FH-QSL8].

some ways that systems-level perspectives can be generated for policy makers and other stakeholders.

## II. HOW CLIMATE CHANGE, HYDROLOGICAL SYSTEMS, TERRESTRIAL SYSTEMS HUMAN BEHAVIOR, LAND USE PATTERNS, AND POLICY DECISIONS AND TOOLS ARE CONCEIVED IN RACC

In 2012, the Vermont Experimental Program to Stimulate Competitive Research ("VT EPSCoR") applied for and obtained a multi-million dollar grant from NSF to undertake a transdisciplinary research project designed to study, model, and help inform solutions to nonpoint source pollution in the Vermont portion of the LCB, with a deeper focus on the Missisquoi and Winooski watersheds. Through RACC, VT EPSCoR has built critical laboratory facilities[21] and environmental observatory networks for the Lake and its watersheds, created transdisciplinary research teams that integrate complex systems modeling across all research spheres, and drawn investigators together from many Vermont institutions and the private sector. Through RACC, transdisciplinary teams of social and natural scientists from the University of Vermont, Middlebury College, St. Michael's College, and Johnson State College collaborated to address fundamental, hypothesis-driven research questions: How will the interactions of climate change and land use alter hydrological processes and nutrient transport from the landscape, internal processing, and eutrophic state within the lake, and what are the implications for adaptive management strategies?

To provide an overview of the major sub-questions guiding the RACC project, we provide some detail of the major themes and areas of work undertaken to address them. The Question 1 or "Q1" team is organized around studying the *in-lake* processes impacting lake eutrophication. The Question 2 or "Q2" team is organized around studying the *to-lake* process unfolding at the interface between the terrestrial and aquatic systems. The Question 3 or "Q3" team is focused on the *social, policy, and governance* processes in place that impact land use and land management decisions and practices. The models developed by the three question teams are linked together through an integrated assessment model ("IAM"). Members of all three teams participate in the planning, design, and use of the IAM to generate basic and applied science findings. Recognizing that climate change has already impacted the LCB social-ecological system, another

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[21] For example, one such lab is Social Ecological Gaming and Simulation Lab. *SEGS Mission*, SEGS LAB, http://www.uvm.edu/~segs/segs_mission [https://perma.cc/NU39-V4RG] (last visited July 23, 2016).

team of researchers has downscaled climate model output for the LCB. A brief overview of the RACC scope of work and major sub-questions is provided.

### *A. Monitoring and Modeling the Interaction Between In-Lake Processes*

**RACC Question 1**: What is the relative importance of endogenous in-lake processes (e.g. internal loading, ice cover, hydrodynamics) versus exogenous to-lake processes (e.g. land use change, snow/rain timing, storm frequency and intensity, land management) to lake eutrophication and algal blooms?

The *in-lake*, Q1 team focuses on advanced biogeochemical and hydrodynamic monitoring and modeling of Missisquoi Bay and its watershed to address Question 1 and contribute to addressing the overarching RACC research question. The basic premise driving the *in-lake* research is that the historical loading of nutrients (primarily phosphorus from the Missisquoi River) has ultimately driven the Bay to a eutrophic state, allowing harmful algal blooms occur on a regular basis in the summer; yet, it is unclear to what extent the severity of the blooms is driven by watershed or internal lake processes. Furthermore, it is unknown how both internal and external drivers of nutrient loading and associated harmful algal blooms will evolve under changing climate and land use-management scenarios projected/envisioned for the LCB and how this will be manifest in lake water quality and algal bloom dynamics. To accomplish our research aims, we developed a process-based biogeochemical and hydrodynamic model that can be embedded in the larger integrated assessment model that in turn will simulate watershed, land use, and governance dynamics across the basin, allowing us to project the impact of both climate change and adaptive management over time on Missisquoi Bay water quality and algal dynamics.[22] To achieve this aim, the Q1 team developed an advanced

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[22] To be able to answer Question 1 and develop a model that accurately simulates the drivers of water quality and algal blooms, it is essential to have enough data over time and space that spans critical variables or parameters that drive the system. To accomplish this, Q1 researchers deployed sensors and automated water sample collection units in both Missisquoi Bay and its watershed that were coupled with manual sampling campaigns. In the bay, sensors were deployed to study its physics, chemistry, and ecology at relatively high frequency—a measurement is taken every half hour or hour depending on the sensor. Physical sensors measured water movement (velocity and direction), sediment transport, water temperature and level, and wave height and period. These sensors were distributed across the bay so that we could understand how water and sediment move within the bay. Additionally, sensors were used to monitor the weather affecting the bay with measurements such as wind speed, orientation, air temperature, and relative humidity. At one location in the bay, selected by the team because it was representative of the average depth of the bay and was in a region where algal blooms

monitoring observatory to collect high frequency environmental monitoring data in both the watershed and the bay. These data are then used to develop an advanced physical-ecological-biogeochemical process-based model of Missisquoi Bay to quantify, analyze, and understand the drivers of nutrient and bloom dynamics in the current system, which can be embedded in the larger IAM. This model can then be used in conjunction with other model components outlined in additional sections of this article to address our hypotheses related to existing lake drivers of blooms and water quality and also likely impacts of climate change and opportunities for adaptive management that may suppress nutrient loading and bloom activity in the face of climate change.

Missisquoi Bay is an ideal site to study the relationship between internal and external drivers of nutrient loading and algal blooms. The large (1000 $km^2$) watershed is heavily impacted by nonpoint source pollution of phosphorus and nitrate, the excessive loading of which have caused eutrophication in this system. Indeed, analysis of sediment cores collected in this bay confirm that the onset of eutrophication in the bay coincides

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were frequently observed, the team deployed a biogeochemical monitoring platform. Once an hour, a sensor moved vertically through the water column profile on a winch collecting data every half meter. This sensor unit measures pH, dissolved oxygen, chlorophyll, phycocyanin (a pigment associated with cyanobacteria), temperature, conductivity, and turbidity. These sensors are very useful for studying how the system behaves over various timescales (daily to seasonal cycles) and in response to important disturbances such as storms when manually sampling at the required frequency would be difficult due to their sporadic nature and potentially dangerous conditions. In addition to the sensors, three systems that automatically collected water samples from the platform at different depths every eight hours were deployed. Those samples were collected to measure nutrient concentrations in the bay at much higher frequency than we could manually conduct within our financial and personnel resources constraints, but likely critical to understanding and modeling nutrient dynamics in the bay. Once a week, researchers would visit the biogeochemical monitoring station and collect additional samples that were more sensitive with respect to time of collection and subsequent analyses (e.g., soluble reactive phosphorus, dissolved metals, and nitrogen species). Additionally, sediment cores would be collected each week so that we could monitor the chemical composition of the sediment and how it changed over time in response to varying conditions in the water column. In the winter, the hydrodynamic sensors remained under the ice whereas the biogeochemical platform needed to be removed, but sporadic under-ice grab sampling of water and sediment was conducted. This effort was critical because remarkably little is known about under-ice hydrodynamics and biogeochemistry, yet one of the most obvious harbingers of recent global climate change has been a decrease in the occurrence and duration of ice cover across high latitude lakes. Q1's watershed sampling focused on four sites within the Missisquoi River watershed where automated water sampling systems were deployed to quantify nutrient and sediment loading during storm events. Those efforts were supplemented with additional grab sampling to characterize baseflow and spring melt when the automatic systems were not functioning. The deployment of these monitoring networks allowed us to capture variability in internal and external processes across inter-annual, seasonal, episodic, and even sub-daily timescales. These robust and holistic time series data has enabled the research team to make both significant advances in our understanding of the basic processes in the watershed and lake that impact water quality and algal bloom development and also provide the requisite database to develop a robust model to simulate the Missisquoi Bay system and embed in the RACC IAM. The Q1 team has deployed an array of water sensors (provide details) and analyzed the life cycle of the alga; blooms in Missisquoi Bay.

with excessive nutrient loading in the Missisquoi Basin during the second half of twentieth century. Furthermore, the drivers of these nutrient loadings from the river network to the bay have already been detected generally in a trajectory that promotes more severe and continued nutrient loading.[23] For example, more severe storms (such as Tropical Storm Irene in 2011) promote erosion of the landscape and streambanks, which make them disproportionately impactful on suspended sediment and associated phosphorus loading to the lake. If storm frequency and severity continue to increase in the northeast with climate change as projected,[24] so will the concentration of phosphorous in the lake and potentially the occurrence of harmful algal blooms. Climate change and the landscape management decisions to come will likely amplify the intensity of nutrient delivery to the lake.[25]

The internal morphology and biogeochemistry of Missisquoi Bay are also thought to strongly influence the nutrient loading and bloom dynamics. Because the entire bay is relatively shallow and largely isolated from mixing with the main lake, the chemical processes occurring at the interface between the bay's sediments and water interface (the lake bottom) heavily impact water quality. In this case, the sediments of Missisquoi Bay serve as a long-term repository for phosphorus-rich sediment ("legacy P") derived from many years of erosion in the Missisquoi Basin (nonpoint source external loading of phosphorous). A large fraction of that legacy P is bound to the surface of a particular suite of minerals— iron oxyhydroxides—that are particularly sensitive to oxygen conditions in the water column. Because Missisquoi Bay is so shallow (maximum depth five meters), if conditions in the bottom of the Bay become conducive (low in oxygen) to dissolving those iron minerals that bear much of the legacy phosphorus, that phosphorus can be released and become accessible to algae populations that also need to live near the surface of the lake to convert energy via photosynthesis.[26] This is an example of internal loading of phosphorous,

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[23] GUND INST. FOR ECOLOGICAL ECON. & UNIV. OF VT., VERMONT CLIMATE ASSESSMENT: CONSIDERING VERMONT'S FUTURE IN A CHANGING CLIMATE 185 (Gillian L. Galford et al. eds., 2014), http://dev.vtclimate.org/wp-content/uploads/2014/04/VCA2014_FullReport.pdf [https://perma.cc/3ABR-HBYK]; Guilbert et al., *supra* note 11.

[24] Guilbert et al., *supra* note 11.; JOHN WALSH ET AL., CLIMATE CHANGE IMPACTS IN THE UNITED STATES: CHAPTER 2: OUR CHANGING CLIMATE 20 (2014), http://nca2014.globalchange.gov/report/our-changing-climate/introduction [https://perma.cc/M2KS-JVNB] (click "Download" in the top corner of the page to download a static PDF of the report chapter).

[25] Sujay S. Kaushal et al., *Land Use and Climate Variability Amplify Carbon, Nutrient, and Contaminant Pulses: A Review with Management Implications*, 50 J. AM. WATER RESOURCES ASS'N 585, 588 (2014).

[26] Isles et al., *supra* note 10, at 819, 825; Courtney D. Giles et al., *The Mobility of Phosphorus, Iron, and Manganese Through the Sediment–Water Continuum of a Shallow Eutrophic Freshwater Lake Under Stratified and Mixed Water-Column Conditions*, BIOGEOCHEMISTRY, 2015, at

and for this to occur, environmental conditions need to be present that would consume oxygen in the bottom water of Missisquoi Bay. These conditions include a minimal water column (prolonged thermal stratification), microorganisms that consume oxygen living in the sediment and water, and the temperature of the water and sediment.

Of course all of these drivers of internal phosphorous loading may be differentially impacted by climate change. For example, warmer temperatures could promote more stratification of the water column, which would increase internal loading of phosphorous, yet increased stormy conditions could suppress internal phosphorous loading by mixing the water column and keeping the bottom of the bay relatively well-oxygenated and iron minerals from dissolving. As a result, it becomes apparent that both extensive monitoring of internal and external processes and drivers and sophisticated holistic modeling are necessary to understand and quantify the relative importance of environmental dynamics that control water quality and algal blooms in this system and, in turn, project how climate change and management decisions will impact this complex system.

A number of other Q1-specific accomplishments have been derived from both interpretations of our Missisquoi Bay/Basin monitoring effort, and statistical modeling from the Vermont Department of Environmental Conservation ("DEC") long-term water quality monitoring dataset. For example, Isles et al. demonstrate that our first year of monitoring, 2012, was the strongest algal bloom on record for Missisquoi Bay, primarily due to the particularly hot and dry conditions of that summer that promote internal loading of phosphorous to feed the bloom.[27] Giles et al. established a conceptual model of the hydrodynamic, biogeochemical, and ecological drivers of internal phosphorous loading through analysis of both hydrodynamic and biogeochemical data from Missisquoi Bay, demonstrating how hydrodynamic conditions exert strong internal control on water quality and algal bloom development in the bay.[28] Schroth et al. established a framework for understanding the biogeochemical behavior of phosphorus and metals underneath the ice and how this might impact summer water quality and bloom dynamics, again relying on our hydrodynamic and biogeochemical monitoring data.[29] Currently, Q1 researchers are focused on interpretation of the drivers of the dramatic

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16, http://link.springer.com/content/pdf/10.1007/s10533-015-0144-x [https://perma.cc/XYN5-UT4G].

[27] Isles et al., *supra* note 10, at 821–22.

[28] Giles et al., *supra* note 26.

[29] Andrew W. Schroth et al., *Dynamic Coupling of Iron, Manganese, and Phosphorus Behavior in Water and Sediment of Shallow Ice-Covered Eutrophic Lakes*, 49 Envtl. Sci. & Tech.. 9,758 (2015), http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b02057.

inter-annual variability observed in water quality and bloom dynamics over the 2012–2015 monitoring period, as understanding the drivers of inter-annual variability is an essential, yet often overlooked, precursor to projecting impacts of climate change on many systems.

Concurrently, Q1 researchers have also been mining the historical DEC water quality dataset to learn more about the drivers of water quality across the entire lake, essentially scaling up our focus through use of existing big data. Xu et al. used those data to modify an existing EPA protocol for assessing water quality—the trophic state index—so that it relied on more powerful statistical analyses and took into account ecosystem specific variability.[30] Xu et al. used the same dataset and a similar statistical approach for development of ecosystem specific targets for nutrients in different lake segments.[31] Both of these approaches will be particularly useful to Vermont water quality managers and policy makers and elsewhere when monitoring water quality and trying to predict responses to climate/policy/land use change. Isles et al., using the same dataset, detected climate change impacts on nutrient ratios throughout Lake Champlain, and used those data to develop a conceptual model on what is driving long-term changes in nitrogen and phosphorus in the lake, and how different components of climate change impact water quality in deep and shallow segments of Lake Champlain.[32]

Some major findings from the Q1 team include fresh insights into the role that water column stability has on blue-green algae blooms and particularly the roles that winds and turbidity caused by storm mixing play in the process.[33] Additionally, the role that legacy P plays as a driver of shallow bay blue-green algae blooms is being understood.[34]

### *B. Modeling Terrestrial-Aquatic Systems as "To-Lake" Processes*

**RACC Question 2:** Which alternative stable states can emerge in the watershed and lake resulting from non-linear dynamics of climate drivers, lake basin processes, social behavior, and policy decisions?

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[30] Yaoyang Xu et al., *Quantile Regression Improves Models of Lake Eutrophication with Implications for Ecosystem-Specific Management*, 60 FRESHWATER BIOLOGY 1841 (2015).

[31] *See* Yaoyang Xu, Andrew W. Schroth & Donna M. Rizzo, *Developing a 21st Century Framework for Lake-Specific Eutrophication Assessment Using Quantile Regression*, 13 LIMNOLOGY & OCEANOGRAPHY: METHODS 237 (2015) (using long-term water quality data to revise classic equations of tropic state indices).

[32] Isles et al., *supra* note 10.

[33] *See id.* at 827 (describing the effects of storms on algal blooms in Missisquoi Bay).

[34] *See* Courtney D. Giles et al., *Characterization of Organic Phosphorus Form and Bioavailability in Lake Sediments*, 44 J. ENVTL. QUALITY 882 (2015) (studying the effects of nutrients from sediment on eutrophic conditions in Missisquoi Bay).

The Q2 *to-lake* team seeks to understand how changes in precipitation form (rain versus snow), persistence, and intensity as well as other climate variables interact with changing land use in the LCB watersheds to transport sediment-bound phosphorus to the lake. In addition, the Q2 team seeks to understand other physical impacts of climate change such as changes to stream geomorphic condition and other factors driving stream systems to disequilibrium. For the last two decades, there has been increased water flow and nutrient and sediment loading to Lake Champlain.[35] The human behavioral and 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 associated sediment and nutrient transport. Better understanding of the relationship between streambank characteristics and sediment transport is being pursued by members of the Q2 team.[36] Tracer signature and isotopic tracing could support more "precise" policy applications.[37] With this research, it becomes possible to consider how "regime shifts" occur when one type of stream morphology and flow regime may radically switch, impacting infrastructure and ecological services. Moreover, increased sediment loading into the lake could shade the littoral zone, altering lake ecology by inhibiting sunlight. Also, vegetation patchiness can change in the watershed based on human behavioral, 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.[38]

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[35] STATE OF THE LAKE, *supra* note 4, at 6, 10.

[36] L. Borg et al., Streambank Stability Assessment Using in Situ Monitoring and Computer Modeling (under review with Earth Surface Processes and Landforms) (on file with author); S.D. Hamshaw et al., Quantifying Streambank Erosion: A Comparative Study Using an Unmanned Aerial System (UAS) and a Terrestrial Laser Scanner (2016) (in progress) (on file with author).

[37] *See* Kristen Underwood, Spatial Variation in Stream Power: Application of Neural Kriging to Classify Erosional and Depositional Stream Reaches in a Globally-Conditioned Vermont Headwater Catchment (forthcoming 2016) (using tracer signature and isotopic tracing) (visit http://www.uvm.edu/~epscor/pdfFiles/2016_racc_retreat/15_Underwood%20RACC%20retreat%20Feb6.pdf [https://perma.cc/3HKT-A8RG] for a PowerPoint presentation on the forthcoming paper).

[38] *See* Ibrahim N. Mohammed et al., Univ. of Vt., Coupled Dynamic Modeling to Assess Human Impact on Watershed Hydrology, Presentation at 2014 AGU Fall Meeting (Dec.15–19, 2014) (discussing various models used to simulate the impacts of land use decisions and climate change on Lake Champlain).

Much of the Q2 research has been centered on characterizing the nature of climatic changes in Vermont and the impacts on watershed hydrology. This has involved climate model downscaling to a spatial resolution that is consistent with the watershed models and as analysis of historical climate data. Climate data are used to drive watershed models that simulate the physical processes of water flowing over land, into the subsurface, and through the channel network. The models are parameterized by numerous soil, vegetation, and hydraulic field instruments.

The RACC project has performed necessary climate downscaling work to link coarse-resolution climate model output to local-level impacts, such as topographically-influenced precipitation and temperature changes. The resulting dataset is a high-resolution time series of temperature and precipitation that can be used to drive hydrology models. The RACC project has also developed watershed models to simulate the impacts of climate change on the Missisquoi and Winooski River basins, using the downscaled climate time series as inputs. Land usage, which affects land surface hydrology, changes in the model with changing management practice, and the resulting output is stream discharge and sediment and nutrient loading to the lake under various management and climate change scenarios.

The major findings of the climate downscaling elements of RACC include an increased likelihood of higher temperatures, particularly during the winter months, and increases in the duration of precipitation events during the spring melt-off season and shorter, but stronger precipitation events toward the latter summer months.[39] As a result of these changes, last and first frosts dates are likely to continue to occur earlier and later in the season, respectively. Ice cover on Lake Champlain and snow cover over the entire region are also likely to be significantly less as the century proceeds. The implications of these shifts for the nutrient loading challenges will be addressed as the RACC project proceeds.

### *C. Human Decisions and Behavior on Land Use, Land Cover and Land Management*

**RACC Question 3:** In the face of uncertainties about alternate climate change scenarios, how can science-based, adaptive management interventions (e.g. regulation, incentives, treaties) be designed, valued and implemented in the multi-jurisdictional LCB?

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[39] Justin Guilbert et al., *Characterization of Increased Persistence and Intensity of Precipitation in the Northeastern United States*, 42 GEOPHYSICAL RES. LETTERS 1888 (2015).

The Q3 *social, policy, and governance* team is interested in understanding and modeling how human decision making and behaviors impact nonpoint pollution and the roles that public policy and institutional actors play in managing water quality for the LCB. The Q3 team views the LCB through the lens of land use, policy-making, and resource allocation. Human agents are studied and modeled at two levels: at the "ground" level as landowners and land users,[40] and at the institutional level as policy makers, resource allocators, and regulators in intergovernmental relations and governance networks.[41] To model the behaviors and decision making of land owners and users, an interactive land use transition agent based model ("ILUTABM") has been developed.[42]

Figure yy. below depicts current (2011) land cover using NLCD Land Cover Classification categories, and several land cover scenarios (for instance: pro-forest and pro-crop scenarios) extending into 2041 as produced through the ILUTABM.

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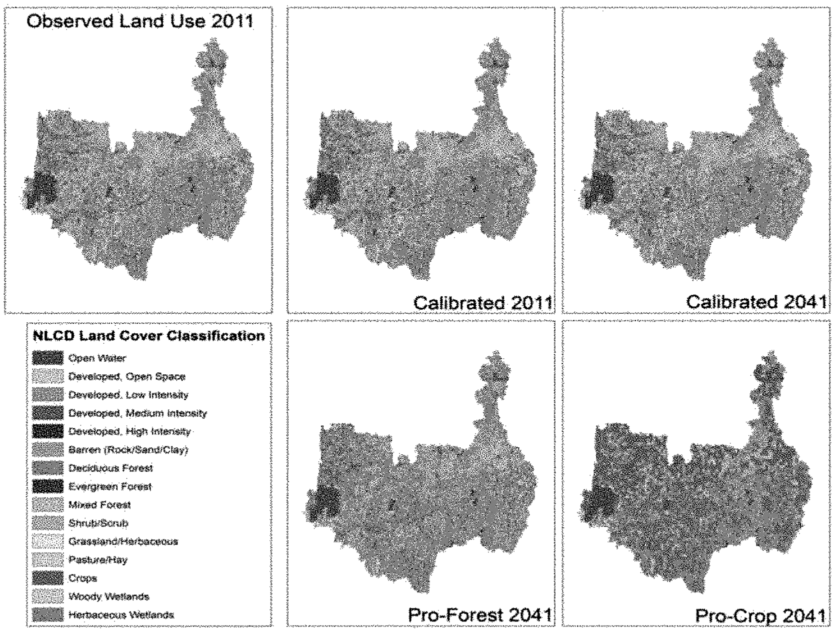
[40] *See generally* Yushiou Tsai et al., *An Interactive Land Use Transition Agent-Based Model (ILUTABM): Endogenizing Human-Environment Interactions in the Western Missisquoi Watershed*, 49 LAND USE POL'Y 161 (2015) (studying human agents at the landowner level).

[41] CHRIS KOLIBA ET AL., RESEARCH ON ADAPTATION TO CLIMATE CHANGE: 2013 WATER QUALITY SURVEY 2–3 (2014), http://www.uvm.edu/~epscor/pdfFiles/documents/Vermont_Water_Quality_Survey_2013_final.pdf [https://perma.cc/3SKA-DDGY]; Asim Zia & Chris Koliba, *The Emergence of Attractors Under Multi-Level Institutional Designs: Agent-Based Modeling of Intergovernmental Decision Making for Funding Transportation Projects*, 30 AI & SOC'Y 315, 315 (2013); Steve Scheinert et al., *The Shape of Watershed Governance: Locating the Boundaries of Multiplex Networks*, 2 COMPLEXITY, GOVERNANCE & NETWORKS 65 (2015).

[42] Tsai et al., *supra* note 40, at 162; Asim Zia et al., Simulating Land-Use Land Cover Change (LULCC) at Watershed Scales Under Heterogeneous Policy Designs: An Agent Based Model of Missisquoi Watershed in the Lake Champlain Basin, 2000-2040, SwarmFest 2015 (July 2015) (unpublished conference paper and presentation) (on file with author) [hereinafter SwarmFest]; *see* Asim Zia et al., Experimental Simulations of Land-Use Land Cover Change (LULCC) Under Heterogeneous Policy Regimes: An Agent-Based Model of Rural-Urban Forest Interface in the Missisquoi Watershed of Lake Champlain Basin, 2000-2050, Conference on Complex Systems (2015) (abstract available at http://www.ccs2015.org/tracks/complexity-in-infrastructure-planning-environment/experimental-simulations-of-land-use-land-cover-change-lulcc-under-heterogeneous-policy-regimes-an-agent-based-model-of-rural-urban-forest-interface-in-the-missisquoi-watershed-of-lake-champlain-ba/ ) (on file with author) (using Agent-Based Model to simulate rural-urban-forest interface).

**Figure yy. ILUTABM Simulated Land Use Scenarios (Figure adopted from Zia et al.[43]**



The ILUTABM includes the decision heuristics of simulated land owners (for instance, the decision of whether to expand a farm into adjacent forests). The model developed by Tsai et al. considers how the economic conditions of farm operations impact land use patterns.[44] It also considers how the enforcement of new and existing land use laws at multiple levels of governance, such as Act 250 at the state level and zoning regulations at the local town, level impact land use patterns.[45] We have found that both the economic conditions of farms and the response of the farms to changing ecosystem service gradients (e.g., changing soil productivity conditions) are significant drivers of farmers' decisions to expand or contract the size of their farm operations.[46] Conjoint analysis studies[47] found that the minimum subsidy threshold that farmers are willing to accept for best management practice ("BMP") adoption is higher than currently being offered by Nature

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[43] SwarmFest, *supra* note 42; Zia et al., *supra* note 42.

[44] Tsai et al., *supra* note 40, at 166.

[45] SwarmFest, *supra* note 42; Zia et al., *supra* note 42.

[46] *See* Tsai et al., *supra* note 40, at 167 (using financial status to predict the likelihood that a farmer will expand operations); SwarmFest, *supra* note 42; Zia et al., *supra* note 42.

[47] Jennifer Miller, Farmer Adoption of Best Management Practices Using Incentivized Conservation Programs 102 (June 6, 2014) (unpublished M.S. thesis, The University of Vermont) (on file with author).

Resource Conservation Service ("NRCS"). It is likely that increased subsidies to farmers are needed to improve the adoption of farm BMPs. We conclude that the economic conditions of famers will likely continue to play a major role in expanding or contracting the distribution patterns of land use within the LCB; however, the economic conditions of farmers are intrinsically tied to the evolution of ecosystem services across the landscape, in particular, soil health and stream protection. A novel contribution of the ILUTABM is the ability to simulate the evolution of fifteen classes of land use and land cover at watershed scales, which requires modeling the competitive land-use dynamics that occur at the cusp of rural-urban-forest interfaces.[48]

Another feature of the ILUTABM concerns the implementation of specific land use management practices. At this juncture, RACC has focused on the use of three specific agricultural BMPs: cover cropping, conservation tillage, and riparian buffer strips. To calibrate our models to historical BMP adoption rates, we have collected survey data, conducted experimental games, and undertaken comprehensive literature reviews. This analysis has led us to render the following additional conclusions about BMP adoption in the agricultural sector: (1) farmers' adoption of BMPs is most likely influenced by their perceived abilities to manage, own, and control the implementation of the BMP themselves; (2) survey data and preliminary results from experimental games suggest that prior knowledge and familiarity with BMPs are major drivers of adoption rates;[49] and (3) the influence of social pressures from peers and family members may also influence adoption rates.[50]

Data are being collected to better understand and simulate how specific incentives (in the forms of cash payments, grants, technical assistance, and tax credits) contribute to specific adoption rates of BMPs. The Q3 team has studied various farmer incentive programs and concluded that the current payment levels of programs such as NRCS's Environmental Quality Incentives Program ("EQIP") are not sufficient to ensure maximum levels of adoption. It is also likely, that there will be a decrease in the rate of adoption, suggesting an optimal return on investment after which return on income ("ROI") declines. In other words, the adoption rates of BMPs will eventually plateau or even decline as the incentive (money) is increased, in part because other factors, such as locus of control and social pressures, are also in play. The goal of these and other Q3 studies is to better understand

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[48] SwarmFest, *supra* note 42; Zia et al., *supra* note 42.

[49] *See* Miller, *supra* note 47, at 21 (stating that knowledge about the impacts of agricultural practices affect a farmer's likelihood to adopt BMPs).

[50] *Id.*

how behavioral triggers (e.g., economic, social, and psychological) contribute to land user/owner decisions. The implications for balancing financial subsidies with technical assistance programs can be derived from fine-tuning the ILUTABM to specific watersheds and sub-watersheds.

A second Q3 focus area concerns the institutional arrangements and resource investments made to mitigate nonpoint pollution. These arrangements are understood as "governance networks."[51] Governance comprises the processes and structures responsible for making critical decisions. Governance of common pool resources processes involve the resolution of trade-offs and to carrying out the implementation and evaluation phases of the policy cycle. Governance networks are the social systems that encompass multi-scale interactions, emergent behavior, pattern formation, and self-organization, and they are often inherently stochastic (operate in unpredictable ways).[52] They possess nonlinear couplings, lags, inertia and feedbacks across multiple processes and scales. They often emerge through a series of incremental policy actions that are undertaken simultaneously at the local, regional, state, provincial, national, and international levels.[53]

Figure zz (below) provides a visual representation of the water quality governance network in place for the LBC. The different planes represent levels of jurisdictional reach: national level entities like the United Stated EPA, and NRCS, and Environment Canada; Basin-wide entities established to provide coordination and focused attention on Lake Champlain, such as the Lake Champlain Basin Program ("LCBP"); state-level agencies such as the Vermont Agency of Natural Resources ("VT ANR"), Agency of Agriculture, Food and Markets ("VT AAFM"), and Vermont Agency of Transportation ("VTrans"); regional entities such as regional planning commissions and regional conservation districts; local governments and municipalities; and individual land owners and land users. These institutional and individual actors interact and impact the landscape (the base layer). The pentagon shapes represent those critical decision-making spaces where regulatory and resource allocation decisions are made. The figure does not include the wider array of advocacy groups, private firms and other stakeholders who all play a role in the region. These actors have been identified and captured in extensive institutional network analysis and intergovernmental programmatic data collected by the Q3 team.

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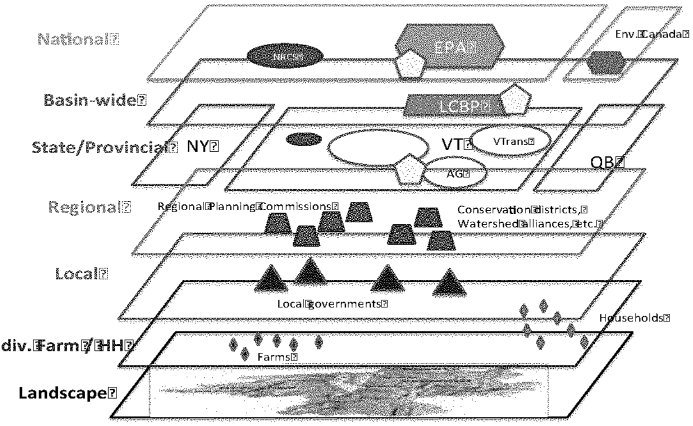
[51] CHRISTOPHER KOLIBA, JACK W. MEEK & ASIM ZIA, GOVERNANCE NETWORKS IN PUBLIC ADMINISTRATION AND PUBLIC POLICY. (2010).

[52] *Id.*

[53] Jouni Paavola, *Institutions and Environmental Governance: A Reconceptualization*, 63 ECOLOGICAL ECON. 93, 94 (2007).

**Figure zz. Water Quality Governance Configuration for the LCB**



The effectiveness of particular regional watershed governance networks to enhance the health, resiliency, and adaptive capacity of regional social ecological systems varies greatly.[54] 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.[55] In RACC we hypothesized that ineffective watershed governance networks may drive watersheds to relatively lower-valued stable states, just as effective watershed governance networks may induce watersheds to stable states that are valued relatively higher by society and policy makers. The kind of "governance informatics" being introduced as part of this project is used 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 and policy interventions.[56]

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[54] *See id.* at 100 (describing factors that influence the effectiveness of governance networks).

[55] Carl Folke et al., *Adaptive Governance of Social-Ecological Systems*, 30 ANN. REV. ENVTL. RESOURCES 441 (2005); *see generally* PANARCHY: UNDERSTANDING TRANSFORMATIONS IN HUMAN AND NATURAL SYSTEMS (Lance H. Gunderson & C.S. Holling eds., 2002) (seeking to develop a theory of changing systems where economic, ecological, and institutional systems all interact).

56 Christopher Koliba, Asim Zia& Brian H. Y. Lee. *Governance Informatics: Utilizing Computer Simulation Models to Manage Complex Governance Networks*, 16 INNOVATION J. ., 2011.

To date, our analysis of the LCB governance network concludes that the region possesses a large number institutional actors involved in the management of water quality for the region.[57] Planning and coordination in response to the TMDL and the LCBP "Opportunities for Action" strategic planning process draw on similar sets of institutional actors and recommendations of policy tools,[58] suggesting a relatively well-coordinated set of actors and common activities. However, as the extent of the nonpoint pollution problem is better understood and some of the intractable challenges associated with this wicked problem are more clearly defined, it is highly likely that new institutional design considerations are warranted. In the realm of transportation-land-use planning, for example, Zia and Koliba found that shifting decision making authority from state to regional planning levels *vis-a-vis* planning and prioritization of road-way projects that implicated water quality (and also related environmental impacts) may induce more equitable resource allocation across regions.[59] The work of the Q3 team to map, simulate, and posit alternative governance scenarios can provide stakeholders with opportunities to consider new watershed or bioregional arrangements, foster new "networks of innovation," and other novel-but-useful institutional arrangements. An instance of such institutional redesign has recently taken place between VT ANR and VT AAFM, in which shared staffing and tighter coordination between regulatory and technical assistance programs is found.

### *D. Tying It All Together: Integrated Assessment Model*

The major focus of the RACC project is on the wicked problem of nutrient loading into Lake Champlain and the implications of these patterns for water quality. One unique contribution to the basic science of fresh lake nutrient loading problems accomplished by RACC is pioneering methods to wrap land use, hydrological, lake, and governance models into the IAM.[60] Although space precludes a detailed overview of the technical components of the RACC IAM here, we will discuss how the IAM is being configured within the context of the social, ecological, and climatological features

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[57] Scheinert et al., *supra* note 41, at 78–79.

[58] KOLIBA ET AL., *supra* note 41, at 2.

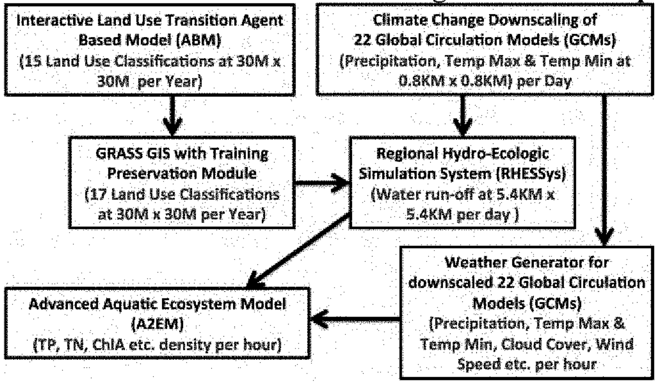
[59] Zia & Koliba, *supra* note 41.

[60] Asim Zia et al., Adaptive Co-Management of "Tipping Points" in Social Ecological Systems: Governing Alternate Stable States in Lake Champlain Basin at the 2014 Norwich Conference on Earth System Governance: Access and Allocation in the Anthropocene, (July 1–3, 2014) [hereinafter Tipping Points]; Asim Zia et al., Quantifying Uncertainty in Modeling the Impacts of Climate Change on Water Quality in Freshwater Lakes: A Bayesian Network Model of Missisquoi Bay (2014) (unpublished manuscript) (abstract on file with Vermont Journal of Environmental Law and manuscript being submitted to Environmental Research Letters) [hereinafter Quantifying Uncertainty].

being addressed within and across the RACC teams. In this sense, the IAM team, comprised of representatives from all of the RACC teams, provides an integrative platform to model the LCB as a complex adaptive system.

At the time of writing this article, a model of Missisiquoi Bay has been fully calibrated, validated, and integrated in the larger RACC IAM, which was a significant accomplishment and the larger team is well-poised to now use the IAM to examine the impacts of climate change and adaptive management scenarios on water quality and algal bloom dynamics over time. Figure ww below shows the configuration of the feedforward version of the RACC IAM: twenty-two ensembles of global climate models ("GCMs") are used to drive three climate scenarios (RCP 4.5, 6.0 and 8.5), and four land use scenarios (BAU, Pro-forest, Pro-Ag and Pro-urban development) through the hydrological and lake models. High resolution spatial and temporal forecasts of hydrological and lake biogeochemical conditions are predicted under alternate climate change and land use change scenarios.[61] Each scenario of RACC IAM requires generation of approximately two terrabytes of data, hence the need to run the model on supercomputing clusters. Delphi panel surveys and mediated modeling workshops have been organized to configure specific governance and policy design scenarios for identifying adaptation to climate change scenarios that best mitigate nutrient reduction in the watersheds and lake systems.

**Figure ww: Feedforward RACC IAM Configuration and Capability**



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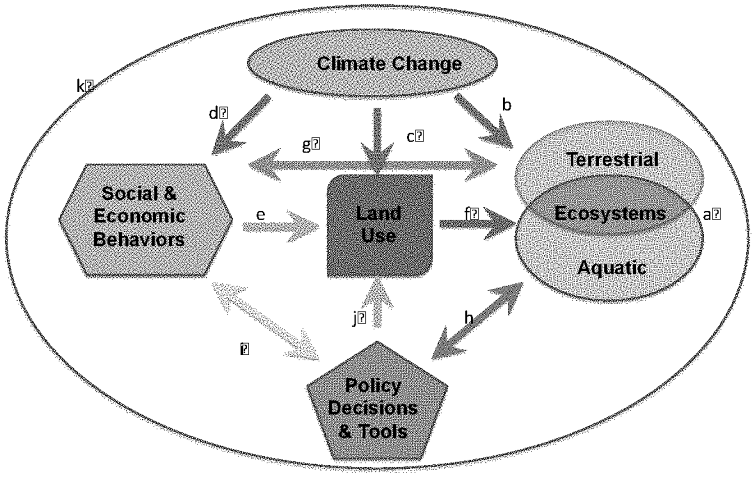
[61] Tipping Points, *supra* note 60; Quantifying Uncertainty, *supra* note 60.

## III. WHAT HAS BEEN LEARNED ABOUT THIS COMPLEX SOCIAL ECOLOGICAL SYSTEM?

The framework for representing the LCB as a complex adaptive system is represented in figure XX. The reader will recognize the major facets of the RACC project found within the coupled terrestrial-aquatic ecosystems, climate change, land use, social and economic behavior, and policy decisions, and tools features. Questions 1 and 2 of RACC encompass the terrestrial and aquatic ecosystems, climate change, and land use features, while question 3 of RACC encompasses the land use, social and economic behavior, and policy decisions and tools features of the project. The entire system modeled through the IAM(k.).

Figure XX. RACC Model: LCB as Complex Adaptive System



A key feature of the RACC approach to modeling the LCB as a complex system lies in the interconnections between the system's component parts. In the next section we briefly highlight the nature of each link, drawing reference back to specific conditions impacting the LCB. These links are described as either feedforward or feedback links in the model.

a. **Coupled aquatic & terrestrial links.** The relationship between an ecosystem's terrestrial and aquatic systems is widely appreciated and serves as a central feature of most models of natural ecosystems. Many of the basic research RACC findings mentioned earlier in this article lie at the interface between the LCB's aquatic and terrestrial ecosystems. Land cover, streambank erosion, and stream and river morphology have direct and critical implications for water quality. Much of the *to-lake* studies being undertaken in the Q2 team are designed to better understand the coupled aquatic-terrestrial links. Likewise, the Q1 team's focus on *in-lake* processes is also very much tied to the coupled dynamics of land and water. Phosphorus enters the hydrological system through sediment. The transportation of sediment facilitates the erosion and reconfiguration of terrestrial features. RACC researchers have built sophisticated models to understand this very dynamic.[62]

b. **Climate change and aquatic and terrestrial ecosystem links.** The role of climate and weather, and changes to the climate over time, upon aquatic and terrestrial ecosystems has long been understood as part of the paleoclimatological and geological history of the planet.[63] Temperature variation and precipitation patterns have always contributed to erosion, sediment transport, and more. As the climate of the LCB changes, as it is predicted to do,[64] better understandings of expected increases in extreme weather events and higher temperatures on algal blooms is critical. It is clearly apparent that as temperatures and precipitation intensity rises, conditions allowing for the advanced eutrophication of Lake Champlain are likely.[65] In the context of current conditions, climate change has led to rising temperatures and more extreme precipitation events, particularly during the spring melt-off and late summer seasons. RACC research has highlighted the role that large storm events play in triggering and, interestingly, shutting down algal blooms.[66]

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[62] *See* Ibrahim Nourein Mohammed, Arne Bomblies & Beverley C. Wemple, *The Use of CMIP5 Data To Simulate Climate Change Impacts on Flow Regime Within the Lake Champlain Basin*, 3 J. HYDROLOGY: REGIONAL STUD. 160 (2015) (using Coupled Model Intercomparison Project phase 5 ("CMIP5") data to study alternative possibilities that might emerge in the Lake Champlain Basin for various climate change scenarios).

[63] *See* FAGAN, *supra* note 2, at xi–xii (describing the author's introduction to ancient climate).

[64] Guilbert et al., *supra* note 11; Guilbert et al., *supra* note 39, at 18.

[65] Mohammed, Bomblies & Wemple, *supra* note 62, at 179; *See* Isles et al., *supra* note 10, at 823 (observing warm temperatures during a pre-bloom phase in Missisquoi Bay); Zia et al., *supra* note 12, at 17–18.

[66] *See* Isles et al., *supra* note 10, at 827 (describing the effects of storms on algal blooms in Missisquoi Bay).

c. **Climate change and land use links**. As archeological studies of climate and environmental impacts on human civilizations have been promulgated,[67] it has been noted how changes in climatic conditions, be they glacial advances during ice ages, intense flooding and drought conditions, or more subtle temperature rises and falls, have helped to shape how human beings use and cultivate the land. Specifically for the present era in the LCB, increasing temperatures have extended growing seasons[68] and will likely continue to extend them in future decades.[69] More persistent flooding events have caused some farmers to abandon fields, relocate pasture lands, and even go out of business.[70] The resilience of the region is predicated on how land use evolves as a result of climate change.

d. **Social and economic behavior and climate change links**. The role of social and economic behavior as a driver of climate change has been clearly recognized by the IPCC and generally recognized by the scientific community. It is likely that as the impacts of climate change become more apparent, human adaptation to climate change will become increasingly evident.

e. **Social and economic behavior and land use links**. Land use is a byproduct of human agency and the tight interaction of human use and value of ecosystem services with human economics needs to be dynamically generated over time. The decisions of land users/owners to transition land from one type of cover and use to another, and to adopt BMPs, can "add up" to watershed scale land use and land cover patterns. By setting in place democratic governance mechanisms and policies in the form of incentives, sanctions, and regulations, policy makers can seek to shape human social and economic behavior that becomes apparent at the landscape scale. This provides a scientific basis to understand the relationship between human agency, ecosystem services, and land use.

f. **Terrestrial and aquatic ecosystems and land use links**. The evolution of human civilizations has depended on how early

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[67] FAGAN, *supra* note 2, at xiii.

[68] VERMONT CLIMATE ASSESSMENT, *supra* note 23, at 13.

[69] Guilbert et al., *supra* note 11.

[70] *See, e.g.*, VERMONT CLIMATE ASSESSMENT, *supra* note 23, at 13 ("Variations in seasonal precipitation combined with the increased frequency of high-energy storms could lead to extreme year-to-year weather variations with implications on farm business viability.").

human societies have, essentially, taken what ecosystems have given them. [71] Geological, aquatic, and other landscape characteristics have limited how and where lands can be cultivated and inhabited. Although extensive efforts have been made to bring ecosystems into some kind of order through the development of irrigation systems, transportation systems, and other forms of built infrastructure, it is clear that land use practices are confined to the capacities of ecosystems and surrounding waterways. RACC researchers are finding that land use clearly impacts stream metabolism—e.g., we see clear signals between urban, agriculture and forested land covers and stream metabolism.[72] The models devised by RACC are built to better understand this interplay, with a particular focus on how these dynamics impact the health of Lake Champlain.

g. **Terrestrial and aquatic ecosystems and social and economic behavior links.** The very nature of a social ecological system must take into account the indelible link between human agency and ecosystems. Ecological economists have advanced the notion of "ecosystem services" as a way to place value on ecosystems and to allow this valuation to intentionally shape social and economic behavior. For instance, the aesthetic and recreational value of Lake Champlain lies in the use of the lake as an ecosystem valued for its swimability and fishability. In this way, the true value of and costs to degrading ecosystems may be understood as consequences and drivers of human behavior. In the RACC project, this direct link between human behavior and ecosystems is understood as a matter of public perception of the value of water quality and other ecosystem services.[73]

h. **Policy decisions and tools and terrestrial and aquatic ecosystems links**. As the more recent history of modern environmental policy and management can attest, the growth of populations and the need for natural resources, such as clean water, fossil fuel, metals and minerals, and food, increases the

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[71] *See generally* FAGAN, *supra* note 2 (describing how societies have adapted to variations in climate throughout history).

[72] Ryan Sleeper et al., Presentation on Ecosystem Metabolism in Streams with Contrasting Land Use at the Society of Freshwater Sciences Annual Meeting in Sacramento, California (May 22-25, 2016).

[73] *See* Tsai et al., *supra* note 40, at 162 (describing how the ILUTABM simulates the relationship between landowners' land use decisions and ecosystem services); Zia et al., *supra* note 12, at 2.

need to place protections on terrestrial and aquatic ecosystems that provide ecosystem services.[74] As the accumulation of air and water pollution impact the quality of human life and compromise biodiversity and wildlife habitat, the link between policy decisions and tools and ecosystem preservation is of critical importance. In the context of the RACC project and the problems of nonpoint pollution in Lake Champlain, the environmental laws in place to protect wetlands, wildlife habitat, and biodiversity play significant roles in ensuring water quality standards are met.[75] While the RACC public opinion polling has concluded that Vermonters, irrespective of their proximity to lake, ideological predisposition, and age, are very much concerned about the health of water quality in the lake and are willing to pay increased fees and taxes to support lake cleanup programs.

i. **Policy decisions and tools and social and economic behavior links**. Public policies are enacted to address particular policy goals and to serve in the public interest. In the context of ecosystem preservation and the intentional development of land use, policy tools such as implementation grants, subsidies and technical assistance contracts, loan and insurance programs, permits, regulations, tax exemptions, and zoning laws are created to, essentially, guide social behaviors.[76] In turn, policy decisions are (or at least should be) informed by how citizens perceive policies such as regulations, incentives, and technical assistance programs.[77] In the context of the LCB, as is likely the case anywhere in the United States, policy makers are sensitive to public perceptions and public and special interest support of and resistance to policy actions plays a role in determining how policy responses to wicked problems like nonpoint pollution are addressed.

j. **Policy decisions and tools and land use links.** Of particular interest to the RACC project and other invested stakeholders is the role that policy tools play in regulating and encouraging certain land use practices. In the Vermont portion of the LCB,

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[74] Folke et al., *supra* note 55; Oran Young et al., *The Globalization of Socio-Ecological Systems: An Agenda for Scientific Research*, 16 GLOBAL ENVTL. CHANGE 304.

[75] KOLIBA ET AL., *supra* note 41, at 16–17.

[76] *Id.* at 2.

[77] STEVE SCHEINERT ET AL., VALUE OF WATER QUALITY AND PUBLIC WILLINGNESS TO PAY FOR WATER QUALITY POLICY AND PROJECT IMPLEMENTATION 1 (2014).

zoning rules are set by localities, devolving critical land use planning to the level of local governance. National and state land use laws, such as the United States Clean Water Act and Clean Air Act, subsequent interpretations of these acts, and state level land use law, also play key roles in shaping the policy environment. In Vermont, Act 250 and the more recent Act 64, posited as Vermont's "Clean Water Act," all play a role in regulating and incentivizing land uses. In addition, significant financial resources are provided through national and state governments to encourage stormwater infrastructure, waste and drinking water treatment, sustainable forestry, and clean water and nutrient management practices for agricultural operations.[78] In the context of the RACC project and the wicked problems of nonpoint pollution, the relationship between policy tool and resource allocation options, and possible land use patterns are being modeled and simulated.[79]

k. **System integration.** When considering the LCB as a complex adaptive system that is bound together as a couple human-natural or social-ecological system, it becomes important to consider how some combinations of feedback and feedforward processes ultimately impact nutrient flows and algal blooms. It should be evident by now that nutrient loading of phosphorus and nitrogen follow a direct pathway (from climate and resultant weather events) into the terrestrial and aquatic ecosystems that are shaped by land use decisions made by social, economic, and policy actors. In turn, we may understand how the terrestrial and aquatic ecosystems and, specifically in the context of the RACC project, the eutrophication of Lake Champlain responds to climatic events and alterations and to land use patterns brought about through policy decisions, tools, and laws. Developing the ability to simulate these kind of complex dynamics lies at the heart of the RACC IAM.

The complexity of interactions of ecosystems, social systems, and climatological systems outlined here bring into clearer focus some of the key drivers of system stability and change. Our focus here has been on the land use and geomorphological drivers of nutrient loading, the biogeochemical drivers of blue green algae blooms, and the social and

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[78] Scheinert et al., *supra* note 41, at 78.

[79] *See* Tsai et al., *supra* note 40 (using an interactive land use transition agent-based model to simulate land use changes); Zia et al., *supra* note 12.

economic behavioral drivers of land use, public policy, and governance arrangements. Although system integration is the larger goal of the RACC project, the effort to identify some of the "component parts" of the larger system can contribute to our understanding of the problem. To suggest that the kind of advanced models being developed by RACC researchers will come up with *the* solution to the water quality problems highlighted here would be an overstatement. Tremendous uncertainty revolves around most of the complex interactions highlighted here. However, by conceiving of and modeling the LCB as a complex adaptive, system we may be in a better position to discover critical leverage points[80] and overarching patterns[81] that, if addressed through creative public policy and market incentives, can effectively mitigate some of the more egregious impacts of nutrient loading on the social ecological system.

RACC research is contributing to what is known about the causes and consequences of nonpoint pollution. Advanced data collection technologies, such as water sensors, certain tracing methodologies, LiDAR, and drone surveillance, can contribute to the adaptive management of the region's water resources, as can advances in modeling human behavior and institutional responses. Advanced computer simulation models, calibrated and validated to historical data, have been devised and are being refined. The extensive monitoring of internal and external processes and drivers and sophisticated holistic modeling are necessary to understand and quantify the relative importance of environmental dynamics that control water quality and algal blooms in this system and project how climate change and management decisions will impact this complex system.

As a result of this research we know much more about the climatological and biogeochemical drivers of algal blooms.[82] As our results indicate, the conditions for the continued persistence of algal blooms are in place despite the well intentioned efforts of policy makers to address the root causes of nonpoint pollution. Substantial reductions in nutrient loading will likely take decades in order to lead to significant reductions in algal blooms and other manifestations of cyanobacteria contamination.[83] Climate

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[80] *See* DONELLA H. MEADOWS, THINKING IN SYSTEMS: A PRIMER 145 (Diana Wright ed., 2009) (defining leverage points as "places in the system where a small change could lead to a large shift in behavior").

[81] *See* Mica R. Endsley, *Toward a Theory of Situation Awareness in Dynamic Systems*, 37 HUM. FACTORS 32, 47 (1995) (emphasizing the importance of situational awareness in recognizing patterns in complex systems).

[82] *See* Isles et al., *supra* note 10 (studying the factors contributing to a severe algal bloom in Missisquoi Bay); Zia et al., *supra* note 12.; *see* Mohammed, Bomblies & Wemple, *supra* note 62 (using models to study alternative effects of climate change on the Lake Champlain Basin).

[83] Zia et al., *supra* note 12, at 17–18.

change is likely to exacerbate algal blooms in both shallow and deep bays. The potential "cancelling out" effects of climate change on policy interventions directed at nutrient management need to be better understood.

Overall, Vermonters are concerned about climate change and highly value water quality.[84] The issue posed is whether the political will and economic resources exist to address nonpoint pollution. Vermonters see it as the role of state government, then individuals, to insure water quality.[85] Our research has found that robust governance networks exist to support water quality management in the LCB and that these networks are dominated by state agencies.[86] Recent coordination between state agencies has resulted in new policy windows for the region (see the development of Vermont Clean Water Initiative).[87] After study of the *2011 Opportunities for Action* and the then-draft TMDL plan, we conclude that both plans recommend a similar balance of regulatory and incentives-based policy tools to advance water quality goals, suggesting a consensus forming around specific suites of policy options.[88] The devolution of power, in terms of allocation and use of programmatic funds from federal and state agencies to local towns and regional/watershed levels, may provide interesting avenues to re-design the intergovernmental relations in this complex adaptive system.

While there are limits, Vermonters appear to support water quality and that this support is not spatially constrained by proximity to Lake Champlain. Our public opinion polling suggests that there is willingness to pay for water quality to certain levels and through certain policy tools.[89] We have also learned more about what it takes for specific land owners and users to adopt water quality BMPs. RACC researchers have found that familiarity with and/or capacity to implement specific BMPs (such as riparian buffers, cover cropping, and conservation tillage) influences an actor's willingness to adopt certain practices.[90]

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[84] KOLIBA ET AL., *supra* note 41, at 2.

[85] *Id.* at 9–10.

[86] Scheinert et al., *supra* note 41, at 78.

[87] *E.g.*, Trey Martin, *The Vermont Clean Water Act: Water Quality Protection, Land Use, and the Legacy of Tropical Storm Irene*, *infra* p. 688.

[88] KOLIBA ET AL., *supra* note 41, at 18–19.

[89] Scheinert et al., *supra* note 77, at 1.

[90] *See* Miller, *supra* note 47, at 22 (arguing that farmers are more likely to adopt BMPs that are low in complexity and highly compatible with the existing farm system); Scott C. Merrill et al., An Examination of the Effect of Information: Awareness of Buffer Strip Effects Increases Adoption Rates (2016) (unpublished manuscript) (a PowerPoint presentation on the findings in this paper is available at http://www.uvm.edu/~epscor/pdfFiles/2016_racc_retreat/21_merrill_RACC%20Retreat%20Feb%202016%20_%20Experimental%20gaming%20research_%20the%20next%20step%20in%20data%20gathering%20and%20complex%20systems%20analysis.pdf [https://perma.cc/67TK-V69M]).

New market mechanisms, such as nutrient cap and trade programs, phosphorous taxes, incentives for agroecological BMPs, incentives for stormwater management, and ecological design of urban towns, may provide viable options to adapt to climate change-induced risks to water quality. Technical assistance programs aimed at improving the perceived behavioral control of farmers to adopt BMPs need to be expanded, which might have large multiplier effects on keeping the nutrients from flowing into the waterways. New performance-based payment for ecosystem programs could be used to improve soil conservation, stormwater management, and use of "precision agriculture" in reducing phosphorous runoff. Decreasing price and increasing accuracy of water quality sensors implies that these sensor networks can be expanded upon throughout the watersheds for increased monitoring and decentralized control of nutrient fluxes. Bottom up town and watershed-scale land use planning, in particular conservation of riparian buffers, wetlands, and forests broadly defined, could go a long way toward protecting Lake Champlain from climate change-induced extreme events, such as floods. This planning process needs to be democratic, bottom-up iterative, and adaptive.

Despite reasons for optimism, there do appear to be real behavioral limits on land users' abilities to fully enact water quality BMPs through the use of incentives and voluntary compliance efforts. We will continue to look into the need for increased regulatory powers and enhanced efforts to stimulate innovation to overcome entrenched behaviors.

## CONCLUSION

Our exploration of the problem of nonpoint pollution as a wicked problem that is resulting from a complex set of climatological, ecological, and social factors has been advanced with a sincere desire to inform the adaptive management of the LCB's nonpoint pollution problems. Viewing the LCB as a complex adaptive system is contributing to the region's capacity to effectively manage nonpoint pollution and its impacts on Lake Champlain and its watersheds. Recalling the nature of wicked environmental problems, we assert that the breadth and complexity of the problem will likely not lead to easy nor quick solutions. Algal blooms and other indicators of compromised water quality in Lake Champlain and in some of its embayments are likely to persist for decades to come. By deepening our understanding of the complex dynamics shaping the problem, we aspire to work with stakeholders to harness this complexity in order to ensure clean waters for future generations.