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Modeling Alternative Collaborative Governance Network Designs: An Agent-Based Model of Water Governance in the Lake Champlain Basin, Vermont

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Abstract

With the widespread use of collaborative governance mechanisms for mitigating water pollution, an opportunity exists to test alternative institutional designs based on collaborative governance theory using computer simulation models, particularly when there is a clear relationship between governance networks, observable resource allocation decisions, and measurable outcomes. This is especially the case for wicked problems like nonpoint source water pollution where there are compelling questions regarding how best to design policies, allocate funds, and build administrative capacity to meet water quality standards. We present an agent-based model (ABM) of water governance for the Lake Champlain Basin to simulate the impacts of alternative collaborative governance arrangements on the development of suites of water quality projects. The ABM is connected or coupled with land use and phosphorus load accumulation models that are informed by existing hydrologic models, project datasets, and state-set load reduction targets. We find that regionally arranged collaborative governance in water quality project planning and implementation can lead to better water quality outcomes, thereby affirming one of the central premises of collaborative governance regime theory. We also find that externally mandated collaboration, as opposed to voluntary, self-initiated collaboration, can lead to better water quality outcomes, adding to our understanding of which type of collaborative governance arrangement is best suited to the specific contexts of this case. Further, without adequate administrative capacity in the form of human resources located in central network actors to manage project funds, "administrative bottlenecks" may form and money can go unspent. This research demonstrates the efficacy of using simulations of alternative institutional design for theory testing and tuning, and policy prototyping.

Introduction

Over the last 20 years, theoretical frameworks have been advanced to inform the design and implementation of effective collaborative governance arrangements

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(Ansell and Gash 2008; Bryson, Crosby, and Stone 2015; Emerson and Nabatchi 2015). Those advancing collaborative governance theories often posit that collaboration among policy actors tends to produce better results (Booher 2004; Emerson and Nabatchi 2015; Koontz and Johnson 2004; Pahl-Wostl et al. 2007), and there is building evidence to suggest this is so (Booher and Innes 2010; Rogers and Weber 2010; Scott 2015). As collaborative governance networks are increasingly pursued as key strategies to drive "collective impact" (Kania and Kramer 2011) and improve outcomes, policymakers, rulemakers, and public managers are also increasingly interested in questions of collaborative institutional design and operation (Kamensky 2019).

Calls for the development of experimental collaborative platforms to aid in this development through the testing of "design rules" have been made (Ansell and Gash 2018). While computer simulation models have long been used to help stakeholders envision possible policy solutions, the use of simulations to model alternative governance design arrangements using meso-level theories of governance originating from the field of public administration has begun to take root (Eckerd, Campbell, and Kim 2012; Kim 2007; Koliba, Zia, and Merrill 2019; Maroulis 2016; Scott and Thomas 2017; Zia and Koliba 2013). Drawing on a case involving collaborative governance design for nonpoint source water pollution mitigation, we employ an agent-based modeling approach to test specific design elements found in collaborative governance theories, and inform actual policy design in the process.

This manuscript highlights how an agent-based model (ABM) constructed to simulate alternative institutional design configurations is used to test aspects of collaborative governance theory and inform public policy. Taking an ABM approach to modeling different institutional designs allows us to estimate performance outcomes (in the form of reduced phosphorus loads) relative to different design parameters. These performance outcome estimates are determined on a regional as opposed to local scale. With the ability to manipulate the collaborative dynamics of simulated actors (in this case municipal and state government actors) through generating different collaborative (and non-collaborative) pathways, the ABM platform enables the aggregation of individual actor decision criteria to larger scales of operation, allowing for the emergence of variations in outcomes that are contingent upon different governance designs.

The ABM highlighted here integrates spatial context and dynamics of the collaborative water governance system being employed and considered for the Lake Champlain Basin (LCB) in Vermont, United States. This water governance model and the framing of initial scenarios were informed by stakeholder input, including consultation with key policymakers in the LCB as part of a transdisciplinary research project that studies this social-ecological system as a complex adaptive system (Koliba et al. 2016). Using this model, we explore and test specific collaborative governance questions relating to the efficacy of collaborative governance over "non-collaborative" governance arrangements (H1); the efficacy of self-initiated, voluntary collaboration versus externally mandated collaboration (H2); the extent to which the functional aims of collaboration (planning and/or implementation) impacts performance (H3); and the role that the persistence of administrative bottlenecks in the lead organization hinders mitigation (H4).

Testing and Tuning Collaborative and Network Governance Theory

The use of collaborative governance to address environmental problems has long been documented empirically through comparative case study analysis (Imperial 2005; Koontz et al. 2010), a large-N comparative study (Scott 2015), social network analysis (Berardo and Lubell 2016; Knieper and Pahl-Wostl 2016), and observed in historical assessments of eras of environmental policy, specifically found in the increased uses of partnerships and incentives beginning in the 1980s (Gerlak 2005). Collaborative governance theory has been widely applied to environmental policy and governance situations and is increasingly being considered more intentionally by policy and rulemakers (Booher 2004; Emerson and Nabatchi 2015; Koontz and Johnson 2004; Pahl-Wostl et al. 2007; Scott 2015). Collaborative governance can be realized as a form of institutional design, leading to the question: "How best to design an effective and usable collaborative governance platform to mitigate environmental pollution?"

Emerson and Nabatchi (2015, 18) define collaborative governance as "the process and structures of public policy decision-making and management that engage people across boundaries of public agencies, levels of government, and/or the public, private and civic spheres to carry out a public purpose that could not otherwise be accomplished." Theories of collaborative governance focus on the critical inputs, processes, and outcomes associated with effective collaborative governance (Ansell and Gash 2008), the internal dynamics of collaborative actors and nature of collaborative life cycles (Emerson and Nabatchi 2015), and the critical challenges and exogenous factors that support or hinder effective collaborative governance arrangements (Bryson, Crosby, and Stone 2015). Collaborative governance is said to be initiated and evolved within a "multi-layered system context," which includes resource conditions, policy and legal frameworks, power relations, and network characteristics (Bryson, Crosby, and Stone 2015, 27)

The key premise of collaborative governance regime theory is the notion that principled engagement "will produce determinations that are fairer and more durable, robust, and efficacious" (Emerson and Nabatchi 2015), and we may infer, lead to better performance outcomes. Most collaborative arrangements call for the intentional use of institutional design (Emerson and Nabatchi 2015, 69; see also Ansell and Gash 2018; Koliba et al. 2018; Ostrom 1990) and the utilization and exchange of resources (Emerson and Nabatchi 2015, 73; see also Rhodes 1997; Emerson and Gerlak 2014; Koliba et al. 2018). Across the collaborative governance literature, the role of networks as the dominant structure shaping institutional rules and resource exchange is fairly consistent (Bryson, Crosby, and Stone 2015; Emerson and Nabatchi 2015; Keast and Mandell 2014; Koliba et al. 2018).

Both collaborative governance (Ansell and Gash 2008; Emerson and Nabatchi 2015) and network governance theories (Provan and Kenis 2007) project typologies relating to idealized states. Both collaborative and network governance arrangements may be externally initiated and led, independently convened and network administratively organized, or self-initiated and governed through shared leadership arrangements. Collaborative governance regime theory tends to emphasize how collaborative networks emerge, whereas network governance theory stresses the relatively stable structures that exist to govern goal-directed networks (Provan and Kenis 2007; Milward and Provan 2006). The extent to which a particular arrangement fits a given context is a question that many theorists and researchers in this space have asked (Emerson and Nabatchi 2015; Keast and Mandell 2014; Milward and Provan 2006).

One of the common critiques of collaborative governance theory is the "black box" treatment of network structures in these models (Koliba et al. 2018), despite the fact that network characteristics are viewed as being an essential feature of collaborative governance regimes (Emerson and Nabatchi 2015; Keast and Mandell 2014). To model the structures of collaborative governance regimes, we need a more fully explicated model of network structures to empirically track and describe resource flows over time and between organizational actors.

In network governance theory, the unit of analysis is the interorganizational governance network. The network is multi-layered (or multi-level) and is comprised of actors that can include public, private, and nonprofit actors (Koliba et al. 2018; Rhodes 1997). Network architecture allows for the explicit identification of actors as being linked or tied to other network actors. The functions carried out by the whole network, sub-network, or network cliques can include formal or informal processes of principled engagement, deliberation, and decision-making. In essence, processes of collaboration unfold as interactions or exchanges between network actors. Network governance hinges on the efficacy of resource exchanges (Rhodes 1997) that lead to network outputs and performance (Turrini et al. 2009).

The multi-scale, multiplex water governance network in the LCB contains a large number of actors who possess multiple objectives and engage with one another through different types of ties (Koliba et al. 2014; Scheinert et al. 2015). The State of Vermont has flexibility in the development and application of policies to meet Total Maximum Daily Load (TMDL) targets set by the US Environmental Protection Agency (USEPA). In this framework of "pragmatic federalism" (Gerlak 2005), the state has considerable control over the shape of the collaborative governance response by choosing how it codifies requirements, structures (dis)incentives, and facilitates coordination. Figure 1 illustrates possible alternative configurations of the water governance network. In figure 1A, we show a traditional top-down, "non-collaborative" governance structure, where the State generates policy tools to directly manage or incent municipal behavior through mandates, grants, and matching funds. The edges in the network are formed by the legal requirements for clean water actions flowing from the State (S) to all municipalities (M), forming the basis of a typical hub and spoke or star network. This configuration represents the current business-as-usual arrangement that involves an, essentially, formal, non-collaborative governance arrangement. Vermont does not have strong county-level governance, making figure 1A the norm. In figure 1B, an alternative network structure describes regional water districts (D) that coordinates the involvement of municipalities and serves as an intermediary for regulation and funding streams. In this instance, we can imagine a legal framework that mandates municipalities to participate in districts that collectively manage water quality into the regional jurisdictions, a scenario that was eventually enacted by the state. Within a district, total phosphorus (TP) mitigation efforts could be prioritized at a regional scale, whereas municipal planning and implementation capacities could be pooled at the regional scale. Funding mechanisms (e.g., block grants) could further take advantage of the network to reduce the administrative burden on the state government and on specific municipalities. Such a configuration may create new inefficiencies in distributed governance and in principal-agent relationships. However, it may also surface local knowledge and develop social capital to better facilitate project feasibility. This scenario best aligns with the externally directed type of collaborative governance regime outlined by Emerson and Nabatchi (2015). Finally, in figure 1C we see a hybrid of A & B, with some districts in place, but direct state-municipal interactions also present. Such a structure may indicate a voluntary regionalization policy based

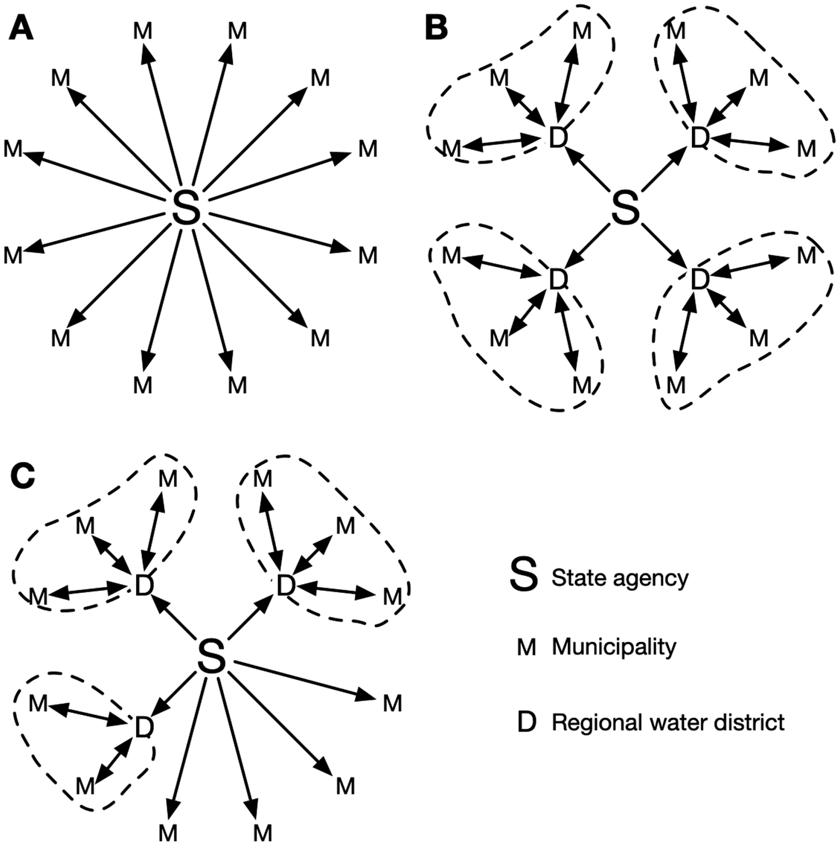


Figure 1. Alternative Network Configurations of Water Governance. In panel A, the state agency directly communicates requirements and funding to municipalities. In panel B, regional water districts act as intermediaries between state and municipal actors. In panel C, the adoption of regional districts is incomplete, and the state must manage relationships with both districts and municipalities.

on a "self-initiated" collaborative governance regime (Emerson and Nabatchi 2015), in which the propensity of a municipality to voluntarily collaborate with others at the regional scale can vary.

Across these three scenarios, the State (S) serves as the central actor responsible for the distribution of resources across the network. As the network actor with the highest degree centrality, the resources of the state, both in terms of financial and human capacity, are critical to the overall performance of the network, regardless of its configuration. Municipalities (M) rely on state funds to pay in part for the planning and implementation of stormwater projects. The two capacities of human and financial capital are very often coupled—as it takes human resources to process requests for funding, and limitations on funding will predicate the number of projects that may be planned and enacted. In essence, the resources available to the central actor in the collaborative governance network configurations studied here likely matters a great deal to the performance of the whole water governance network. The degree to which the state's human resource capacity limits or enables the flow of funding through each type of network is likely to matter a great deal.

To better understand how and to what extent collaborative governance arrangements work best and under what conditions, computer simulation modeling is increasingly being used to test and tune theory (Johnson 1999; Schlüter et al. 2017). Recently, the notion of "collaborative platforms" has been advanced to answer the question of "how can collaborative governance be purposefully extended and scale-up?" (Ansell and Gash 2018, 16). Ansell and Gash propose the collaborative platform as a "generic organizational logic" (Ansell and Gash 2018, 17) or as a strategy for societal problem-solving (Nambisan and Baron 2009). These platforms can serve one of three different functions: to explore and frame the nature of problems, to experiment with potential solutions, and then execute specific solutions using collaborative governance frameworks (Ansell and Gash 2018; Nambisan and Baron 2009). In promoting the concept of collaborative platforms, Ansell and Gash observe that "more needs to be done to translate the logic of platforms from the domain of technology, software development and even organization theory to that of governance and public administration" (Ansell and Gash 2018, 17). The use of computer simulation models to experiment with alternative collaborative designs is increasing, particularly in the experimental stages of collaborative development in which stakeholders may prototype and test the efficacy of these governance arrangements against performance targets. Although Ansell and Gash's interpretation of collaborative platforms extends well beyond the prototyping phase and into the realms of actual implementation, we focus here on one example of constructing and using a computer simulation model to test the efficacy of specific collaborative governance arrangements. As we will note, stakeholder engagement around the design of the model and the use of model output to initialize new collaborative governance arrangements (e.g., moving from experimentation to execution) is discussed. Borrowing from Ansell and Gash's language, this experimental collaborative platform can test a series of alternative design rules.

To better understand which design rules are more or less likely to be effective, we formulate a series of hypotheses to test in our model.

H1: The Collaborative Governance Hypothesis: Those alternative water governance arrangements that are premised on collaborative governance designs will generate higher nutrient load reductions than those water governance arrangements that are not premised on collaborative designs. Findings from prior studies of collective action problems for water governance have found that greater coordination among governance actors leads to more effective outcomes, underscoring the assumptions of collaborative governance regime theory that collaborative governance leads to better outcomes (Koontz and Johnson 2004; Scott 2015). However, other studies have found that collaboration can sometimes reinforce existing power relations (Scott and Thomas 2017) and lead to reduced effectiveness. Our first hypothesis centers on whether collaboration leads to greater phosphorus mitigation. We postulate that greater rates of municipal collaboration in water districts will lead to greater phosphorus mitigation.

H2: The Collaboration for Planning and Implementation Hypothesis (H2). Collaboration in both the planning and implementation phases of project development will result in higher nutrient load reductions than those networks that only collaborate around the planning of projects. Our second hypothesis focuses on the functional goals of collaboration. In the realm of municipal stormwater management, clean water projects, like all engineering or capital improvement projects, must follow a clear planning-to-implementation, "end-to-end" process. Planning phases include the scoping and design of potential projects and involve the coordination of engineering firms, public works departments, and planning offices. While the implementation phase of stormwater projects can include that same group as well as private contractors. We expect that water districts that regionalize both project planning and implementation will be more effective than districts that only regionalize planning. In other words, extending the value proposition of collaboration from an "end-to-end" perspective is likely to better amplify the positive impacts of collaborative governance on performance.

H3: The Mandated Collaboration Hypothesis. Mandated collaborations for planning, and for planning and implementation will generate higher nutrient load reductions than voluntary collaboration for planning, and for planning and implementation. The results of studies of mandated, externally directed collaboration have provided mixed results relative to the value and efficacy of mandated collaboration. A comparative case study of mandated health care delivery networks by Rodriguez et al. (2007) found the mandated collaborative approach failed to enhance interorganizational relationships, particularly in cases when there is a lack of multiple governance mechanisms to enable well-resourced coordination. While Brummel et al.'s (2012) study of wildland fire planning found that mandated collaboration among service providers provided more consistent and higher quality services because of the ability to allow for flexibility and resource sharing. It is clear that the specific design of the mandated collaboration is critically important. We anticipate that mandated collaboration will allow for lower capacity municipalities responsible for higher nutrient loads to receive aid in their phosphorus mitigation efforts. thereby increasing the impact of mandated collaboration arrangements. The challenges associated with the limited capacity of particularly smaller municipalities are a clear concern to emerge during discussions with local municipal leaders.

H4: The Administrative Bottleneck Hypothesis. The administrative capacity of the State (S) will be a significant factor in load reductions results of all configurations of water governance design considered here. Drawing on qualitative assertions made by policymakers operating in the region, as well as the logic of coupling of financial and human resources, the administrative capacity of the State (S) to evaluate water quality projects operates as a constraint on the allocation of resource. This assertion is supported by prior studies of regional governance that have found that the flow of financial resources to infrastructure projects is hindered by a lack of administrative capacity to scope, design, and implement projects (Milio 2007).

Case Study: Stormwater Project Planning and Implementation in the Lake Champlain Basin

The wicked problem of nonpoint pollution provides a context to study the relationship between alternative institutional designs and specific outcomes, in this case, reductions in nutrient loads. In the LCB in the northeastern United States, challenges of nutrient pollution and harmful cyanobacteria blooms in Lake Champlain are met by a variety of cooperating and competing governance actors that operate at federal, state, regional, municipal, and even international levels (figure 2B). Collectively, these actors comprise multiscale, multiplex water governance networks (Koliba et al. 2018; Lubell, Robins, and Wang 2014; Scheinert et al. 2015; 2017). It is well-recognized that the multi- and-cross-scale nature of environmental problems—including water-related issues of quantity, quality, and the degradation of concomitant ecosystem services—requires governance approaches that themselves span similar scales (Bodin, Sandström, and Crona 2017; Hamilton and Lubell 2018; Koontz et al. 2010; Pahl-Wostl et al. 2010; Scott and Thomas 2017). Yet, understanding how the actors in water governance networks might react and adapt to novel policy or environmental pressures (e.g., regulations, global climate change) requires dynamic modeling techniques that integrate geographic context, spatial and temporal lags, and the complex structure of the social-ecological network.

Harmful cyanobacteria blooms (sometimes grouped with harmful algal blooms, or HABs) are a significant water quality problem in Lake Champlain and many other freshwater lakes all over the world. HABs close beaches, threaten public health, negatively impact regional economies, and reduce property values (USEPA 2018). In Lake Champlain, HABs occur most frequently during late summer in shallow bays where climate has a greater influence on nutrient mixing and bacteria have easier access to nutrients in lake sediment (Isles et al. 2017; Zia et al. 2016). Blooms in Lake Champlain are fed by nutrient nonpoint runoff (primarily phosphorus) from multiple sources, including agriculture, urban stormwater, streambank erosion, and forested land use (Lake Champlain Basin Program 2018). Each nutrient source represents a potential target for policy tools aimed (directly or indirectly) at reducing nutrient runoff, and ultimately bloom severity and frequency.

A TMDL regulation, put in place by the USEPA, currently regulates the maximum amount of phosphorus that is allowed to reach Lake Champlain and still meet water quality standards. The amount of phosphorus reaching a waterbody is termed "load" and is measured in units of mass per time (e.g., kg/day, Mt/year) (figure 2A). Thus, the TMDL does not directly regulate the presence of HABs in Lake Champlain, but rather one of the main causal inputs (Koliba et al. 2014).

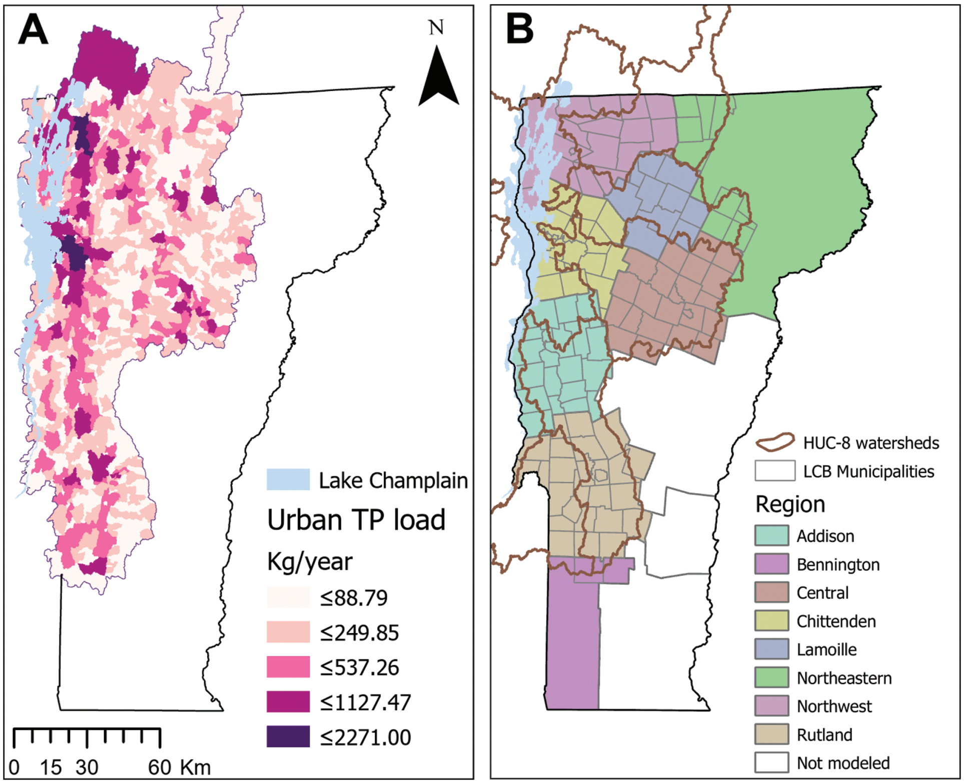


Figure 2. One View of the LCB Water Governance System. Panel A shows the spatial distribution of TP loads at the NHDPlus catchment scale. Panel B shows the mismatch between hydrology (broadly represented by HUC-8 watersheds), municipal jurisdictions, and the modeled regions to which municipalities are assigned.

USEPA used a physics-based SWAT (Soil and Water Assessment Tool) model (Arnold and Fohrer 2005) combining land use, hydrological, and erosional processes to estimate the contribution of various land uses in a spatially explicit manner across the LCB (figure 2A).

On June 15, 2015, Act 64, colloquially the "Vermont Clean Water Act," was signed into law to address degrading water quality in Lake Champlain and its tributaries. The law set forth new rules for managing water quality in the state, including restrictions on agricultural practices and permitting processes for existing and new development. It created the Clean Water Fund, a pool of financial resources to be distributed by the state to fund projects related to clean water goals. Subsequently, on June 6, 2018, Act 76 was signed into law outlining the expectations to design and implement a system through which every watershed in the LCB be assigned a Clean Water Service Provider (CWSP) to provide regional coordination of non-regulatory water quality improvement projects (Vermont General Assembly 2019). These new CWSPs would coordinate actions to collectively develop clean water priorities and to apply for state funding. While implementation details are not yet finalized, this collaborative governance arrangement is in part due to the findings stemming from the sharing of these modeling results.

Agent-Based Modeling of Water Governance

ABMs have been proven to be useful tools as experimental collaborative platforms that can help policy-makers make informed decisions (Ligmann-Zielinska and Jankowski 2007). ABMs are a "bottom-up" method of simulating the interactions among heterogenous actors and their environment, commonly in a spatially explicit manner. Agent-based modeling has been called "the only technique available today to formalize models based on micro-foundations, such as agents' beliefs and behavior and social interactions, all aspects that we know are of a certain importance to understand macro outcomes" (Squazzoni and Boero 2010). ABMs often reflect the dynamics in real-world systems, including how system structures change due to internal processes or outside disturbances (Batty et al. 2011). One strength of ABMs lies in their ability to simulate emergent system-scale dynamics from the repeat interactions of individual agents on a landscape (Parker et al. 2003). Through the application of relatively simple rules that govern individual agent behavior, patterns of collective group behavior, including cooperation in environmental management, can emerge (Goldstone and Janssen 2005; Scott, Thomas, and Magallanes 2018). This ability to link multi-scale actors, processes, and structures means ABMs are particularly well-suited to the study of resilience and sustainability in complex social-ecological systems (Bitterman and Bennett 2018). For example, ABMs have been used to study land use change in the Yucatán peninsula (Manson 2005), the movement of elk as affected by land management practices in Yellowstone National Park (Bennett and McGinnis 2008), the transmission of disease across livestock production chains (Wiltshire et al. 2019), and in common pool resource management situations (Deadman 1999; Schlüter and Pahl-Wostl 2007). ABMs have been explicitly used to model alternative institutional designs in other settings including models of hazardous waste remediation (Eckerd, Campbell, and Kim 2012), school district governance (Maroulis 2016), the diffusion of fraudulent claims across service delivery networks (Kim 2007), and the prioritization of transportation projects (Zia and Koliba 2013).

In their work on Balinese water temples, Lansing and Kremer (1993) demonstrated how simulation models could be used to understand the relationship between water resources and collaborative governance. Their work showed how self-organization emerged in specific collaborative governance arrangements. Building on this legacy, a suite of models and research programs have emerged at this nexus of water, land use, collective decision-making, and governance. Schluter and Pahl-Wostl (2007) developed an ABM to simulate the resilience of different water-management institutions to changes in environmental conditions in a semi-arid Amu Darya river basin in Central Asia. Smajgl et al. (2009) used an ABM to simulate water trading markets and alternative market configurations in Australia, whereas Bellaubi and Pahl-Wostl (2017) modeled corruption in a water management system in Kenya and Ghana. While governance actors can be modeled as agents, their internal dynamics can have substantial influence on collective and individual decision-making as well, as illustrated by the ABM in Watkins et al. (2013). Recent communications behavior-focused research has also shown how ABMs can be used to test behavioral theories (Janssen and Baggio 2017; Bucini et al. 2019) and how different policy-targeting can impact flood mitigation and coping (Erdlenbruch and Bonté 2018). In many cases, ABMs are calibrated to historical patterns (e.g., land use, migration) (Grimm 2005; Magliocca and Ellis 2013) such that the model can be used to create scenarios of future system trajectories. When calibration targets are sparse or unavailable, or when the subject of the study is novel, ABMs are commonly more "stylized" and used not for prediction, but to improve understanding of system dynamics. In this study, the alternative water governance regime embodied by districts in Vermont would be novel to this system. Thus our ABM is conceived as a stylized, exploratory model grounded in collaborative governance theory and not subject to model validation expectations. We purposefully simplify agent decision-making process and have not, for example, included political or legal motivations of behavior. Given these assumptions, the simulations explore model sensitivity to policy-relevant inputs.

While the above models capture many of the key dynamics that can be found in watershed governance, a gap remains in modeling the translation of policy objectives to policy tools in a manner that is both spatially explicit and incorporates environmental feedbacks. Effective reduction of nonpoint pollution has proven to be extremely difficult. The extent to which these difficulties stem from challenges associated with the design and operation of explicit water governance networks is the subject of this study.

Materials and Methods

An adaptive management perspective guided the development of this governance ABM (Norton 2005), with a key feature of this approach being the pursuit of collaborative learning between social and natural scientists and policymakers and other stakeholders (Daniels and Walker 2001). At the start of this project, the research team undertook a series of focus groups and interviews with key informants in the LCB, and source document analysis of major pieces of legislation, rules, white papers, and TMDL memorandums of understanding. This phase of research was used to develop a qualitative appreciation of the multi-level governance networks operating in this region. A Policy and Technical Advisory Committee (PTAC) met with the research team at regular intervals to inform the model development. Observations about model assumptions, data sources, and intended uses of model outputs were made, summarized and drawn on by the research team. Additional data were collected through a survey that went out to all municipalities across the State (Clark, Hurley, and Koliba 2018).

As detailed in figure 3, the coupled (connected) model platform has three primary components: (1) a land use model that places municipal stormwater projects on the LCB landscape, (2) a simplified load accumulation model, and (3) the ABM of networked water governance. Communication among model components is facilitated by an infrastructure that tightly couples the models at an annual timescale, meaning that the land use, phosphorus load, and governance models can generate outputs that can be aggregated across specific and consistent scales of temporality.

Within the ABM, agent–agent interactions occur at sub-annual intervals. Agent–environment interactions occur when municipalities or districts react to the state of the environment and make decisions that lead to the creation of stormwater projects, which are then instantiated on the simulated landscape. When implemented, these projects differentially affect annualized phosphorus loads that accumulate to the lake. The changes in loadings are read by the governance actor agents, affecting their behavior in future timesteps and closing the environment-agent portion of the feedback loop. In addition to the modeling framework shown in figure 3, the Overview Design Concepts, and Details (ODD) model specification (Grimm et al. 2010) for the ABM is included in the Supplementary Material. The ABM framework is built upon the MASON Multiagent Simulation Toolkit (Luke et al. 2005) and its extension GeoMason, which provides additional geospatial support capabilities.

Together, the ABM, land use, and load accumulation models trace the lifecycle of clean water projects as they proceed from an initial state of unknown/unplanned to a final state where the project is implemented on the

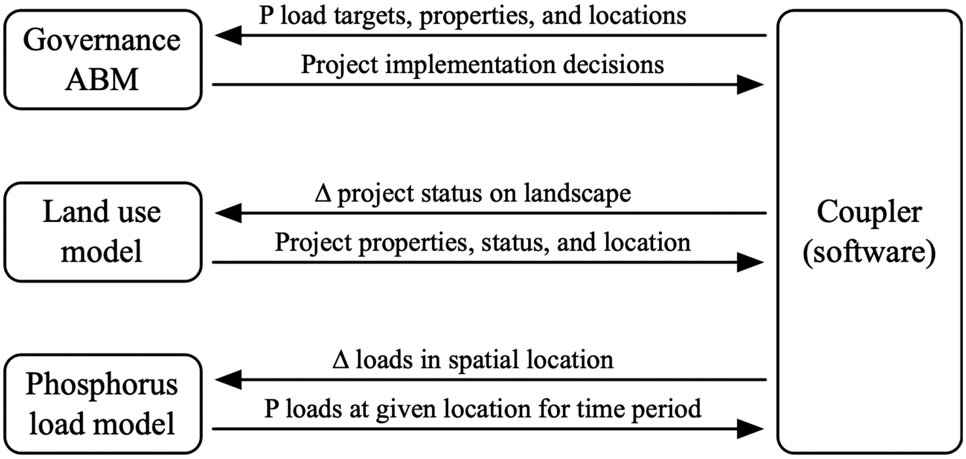


Figure 3. Generalized Schematic of the Coupled Model. The Coupler is a software architecture that facilitates communication among connected models—in this instance the governance ABM, the land use model, and the phosphorus load accumulation model

landscape. When municipalities utilize their project-planning capacity, they may coordinate with other actors to prioritize clean water projects according to their individual characteristics (e.g., available capacity) and rules put in place by policy. The state agency agent evaluates and prioritizes projects, allocating funds and utilizing its state-level capacity. Finally, agents implement projects "on the ground," affecting land use and fulfilling the lifecycle of a project. Once agents implement clean water projects, these changes to the landscape are then translated to the environmental model, affecting the amount of phosphorus reaching Lake Champlain.

The ABM simulates the interactions among three agent types: municipalities (i.e., towns and cities), regional water district agents, and state agencies in the LCB. Each municipal agent represents one of the 126 Vermont towns or cities whose centroid falls within the Vermont portion of the LCB. Eight regional water district agents each correspond to actual regional planning district (RPC) boundaries, with each municipal agent assigned to its corresponding geographic region. Due to our focus on the CWIP process, we simplify interactions among multiple government agencies by using a singular state agency agent that is tasked with improving water quality and managing the allocation of public funds. Within each annual timestep, municipal agents may: (1) plan clean water projects, (2) prioritize projects, and (3) implement projects. When undertaking each of these steps, real-world municipalities are subject to dynamic budget and staffing constraints, regulatory requirements, and public will. We have simplified municipal decision-making and resource constraints to five key municipal variables and functions (table 1).

The objective of a municipal agent is to reduce the amount of phosphorus load generated by land use within its borders to the target level specified by the "reasonable assurance" scenario generated by the USEPA during the TMDL process (US Environmental Protection Agency 2016). A municipal agent's planning capacity corresponds to the number of projects they can take from concept to a "shovel ready" state that is ready to be funded. The distribution of municipal planning and implementation capacity parameters were estimated using empirical data from the VTANR CWIP database. We estimated each municipality's implementation capacity by calculating the annual mean number of projects it completed over the last 4 years (the length of the dataset). As data for planned, but not funded, projects are currently unavailable, we assume that planning capacity is twice that of implementation capacity. Additional parameter estimation details can be found in the supplemental ODD protocol. Municipal agents randomly select among unplanned projects in their boundaries, representing the (at times) disordered process of managing multiple priorities from various constituencies and interest groups. Agents then use their planning capacity to "discover" properties of the project (e.g., estimated load reduction potential, estimated implementation cost, location) in a simulated planning process. Municipal agents then rank planned projects according to prioritization criteria. We follow a simplifying assumption that municipal agents seek to maximize utility by prioritizing projects that provide the greatest load reductions per dollar. All municipal agents follow this institutional rule logic, maximizing project efficiency as defined in equation (1).

$$\max \sum_{i=1}^{\substack{municipal\\capacity}} \frac{est.\ phos.\ reduction_i}{est.\ implementation\ costs_i} \qquad (1)$$

Once projects are planned, they are passed to the state agency agent to be ranked and funded (see below), then passed back to their corresponding municipality. Unfunded projects are queued, and funded projects are available for implementation. Municipal agents then rank funded projects according to equation (1), again optimizing for load reductions per dollar. The top n projects are then implemented, where n corresponds to an agent's implementation capacity. Projects that are

Table 1. Variables and Functions Governing Behavior of Municipal Agents

Variable	Description	Range
Planning capacity	The number of clean water projects a municipality can plan in a year.	2–14
Implementation capacity	The number of clean water projects a municipality can implement in a year.	1–6
TMDL load reduction target	Target value of phosphorus load reduction for urban land use in the municipality to meet TMDL. Estimates generated by EPA. (kg/year)	15.4–1,179.7
Probability of collaboration	The probability that a municipality will collaborate with other municipalities in regional water districts. Empirical distributions generated using survey data of municipalities in the Lake Champlain Basin.	0–1
Prioritization criteria	The algorithm used by municipal agents to rank projects prior to submitting them for funding and before implementation.	NA

funded but not implemented are returned to the corresponding municipal agent's implementation queue. Once municipal agents have met their phosphorus reduction targets, they stop all activity.

In some scenarios (described below), state policy is altered to mandate collaboration among municipal agents at a regional scale. Stakeholder anecdotes drawn from focus groups suggest that regional cooperation varies greatly among regions and their constituent municipalities. This is confirmed by a 2017 survey of Vermont municipalities (Clark, Hurley, and Koliba 2018) that drew on responses to determine the probability that a municipality will collaborate with their regional planning commission (RPC) along four dimensions: (1) information sharing, (2) technical assistance, (3) sharing human/physical assets, and (4) receipt of monetary support. This survey was sent to all 249 municipalities in Vermont, with a response rate of 55% across Vermont, and 64% of those municipalities in the LCB. Each municipality's response was coded 1/0 for yes/no, then summed to estimate a "coordination capacity score" for each municipality. An empirical distribution was generated for each region. At the state scale, these scores follow a normal distribution, though distributions vary at the regional scale. Accordingly, we estimate the distribution for each region in the simulation and normalize to the interval [0,1]. In those scenarios where policies allow for regional coordination, we sample from these distributions and assign a probability of collaboration for each municipality. Mean values are shown in table 2.

At the state level, the responsibility of water policy-rulemaking primarily falls on the state Vermont Division of Environmental Conservation (DEC). Accordingly, we model a second agent type representing a state agency tasked with managing water quality. This singleton agency agent takes allocated funds, evaluates municipal projects, and ranks funding priorities as specified by policy scenarios. The state agent prioritizes projects using the same efficiency criteria from equation (1). This agent's capacity to evaluate projects is a scenario-driven parameter and corresponds to its throughput, or the number of projects it can evaluate in an annual timestep. Finally, the state agent sets the rules of the CWIP action arena, thereby affecting the allowed behavior of municipal and regional agents (table 3). The final class of agents is regional facilitators that, depending on policy scenario, coordinate the planning and implementation of municipal agents at broader scales. We model these agents on RPCs and utilities, but the framework can be scaled to other geographic extents (e.g., watershed boundaries) or network configurations.

Table 2. Mean of Probability Distribution for Each Municipality in a Region

Region	Mean
Chittenden	0.671
Addison	0.585
Central	0.568
Rutland	0.545
Lamoille	0.521
Bennington	0.500
Northwest	0.429
Northeastern	0.298

Note: Regions derived from Regional Planning Commission (RPC) jurisdictions in the LCB.

The land use model provides a bridge between governance actions and water quality impacts. This connection takes the form of the clean water projects that are planned, prioritized, funded, and implemented by municipalities in the LCB. While each municipality is itself a governance actor in the ABM, each is also connected to a spatial feature corresponding to its municipal boundaries. Empirical data from VTANR were used to generate a realistic set of possible projects for the simulation. Additional detail can be found in S7.2 of the Supplementary Appendix.

The environmental model is a simplified load accumulation model based on an EPA-created SWAT model (Arnold and Fohrer 2005; Gassman et al. 2007) that calculated average annual phosphorus contributions to Lake Champlain (US Environmental Protection Agency 2016). As projects are implemented on the landscape, the contribution of phosphorus to the lake is reduced in a spatially explicit manner. This simplified model excludes nutrient transport and the role of climate and assumes all phosphorus eventually reaches the lake. The resultant model is a simplified representation of nutrient export from the landscape (S7.1 of the Supplementary Appendix). However, the relative lack of complexity reduces computational overhead while isolating the effects of governance dynamics on the landscape.

Through collaboration with policymakers at state, regional, and municipal scales, we identified a set of scenarios that included alternative policy configurations, state-level capacity, and funding allocations to explore via simulation. The scenarios that alter policy rules (table 3) modify the degree and geographic scale of cooperation among municipal and regional water district agents. In the current state of this social-ecological system, municipalities are statutorily required to individually meet regulatory and non-regulatory load reductions and must participate in clean water improvements, but have a choice as to whether work directly with the state (figure 1A) or engaged in mandated collaboration with other municipalities in their region to form a district (figure 1B). This second scenario also

Table 3. Scenario Parameters Include Coordination Policies (District Function), Resource Levels (Funding and Capacity), and Landscape Configuration

Resource Parameters			
Parameter	Values		
Allocated funds	1, 2, 3, 4, 5, 6, and 7 million USD		
State agent capacity (throughput)	50, 75, 100, 125, 150, 200 and 225 projects/year		
Initial landscape configuration	5 alternative distributions of projects on landscape		
Coordination policy	1. No district 2. Voluntary planning district 3. Mandated planning district 4. Voluntary planning and implementation district 5. Mandated planning and implementation district		
Coordination policies			
Water district function	Municipal aggregation rule	Aggregated planning?	Aggregated implementation?
No district	none	no	no
Voluntary planning district	probability-based	optional	no
Mandated planning district	all in region	yes	no
Voluntary implementation and planning district	probability-based	optional	optional
Mandated implementation and planning district	all in region	yes	yes

Note: Each coordination policy is composed of rules that govern municipal and regional behavior.

regionalizes planning capacity but imagines a policy tool that mandates municipal participation (probability of coordination = 1). A third scenario is posited in which municipal agents have chosen to voluntarily cooperate with others in the region or not (figure 1C). The voluntary participation of municipalities is probabilistic, according to table 2. The fourth and fifth scenarios extend the previous scenarios to also include collaboration for project implementation. Again, voluntary and mandated policies allow for different levels of participation. These scenarios approximate a regional utility authorized to regulate the municipalities in its jurisdiction. In some scenarios, collaboration is mandated by the state agent, and regional facilitators manage all municipal planning and implementation in their jurisdiction.

In addition to alternative policy scenarios, we modify the capacity (financial and human resources) of the state agency agent to evaluate and allocate funds to stormwater projects (table 3). The State is tasked with evaluating and prioritizing the projects identified by municipalities. Administrative capacity bottlenecks may emerge at the project evaluation stage because the State retains approval of all projects. A constrained administrative capacity can limit the throughput of the approval and funding to municipalities leading to reduced load reductions on the landscape. Further, as Acts 64 and 76 are implemented and as state, regional, and local capacities come online, there is uncertainty in the amount of funds that should be optimally allocated to the problem. At a most basic level, if funding is low, loads will likely remain high. However, if too much money is allocated and there is insufficient capacity to implement projects, the funds sit unused. In our scenarios, we alter the throughput of the state agent and the overall fund allocation to explore these dynamics. The parameters are based on past project funding data and were developed in consultation with agency stakeholders. In total, we simulate 1,225 scenarios. Model stochasticity is introduced in (1) the generation of projects, (2) the selection of projects by municipalities to plan, (3) municipal participation in regional cooperation, and (4) the initialization of municipal capacity. A simulation runs for 50 model years, and each scenario was repeated for 30 Monte Carlo iterations.

Results

Hypothesis 1, the Collaborative Governance Hypothesis, and hypothesis 2, the Collaboration for Planning *and* Implementation Hypothesis, are closely related. We expect collaborative policies to perform better than non-collaborative policies, and we further expect that collaboration across several stages of project planning and implementation will perform better than partial efforts. We first compare the overall efficacy of the different collaborative governance design scenarios by comparing the cumulative load reductions for each scenario over the full simulation period. As shown in figure 4, the most effective (highest cumulative reduction) design was the creation of *mandated planning and implementation* districts. The *voluntary planning and implementation* districts perform nearly as well, followed by *act alone, mandated planning (only), and voluntary planning (only)* districts in that order. The difference among outcomes was confirmed to be significant by a Kruskal-Wallis test ($p < .001$). The clustering of outcomes shown in figure 5A is a result of multiple scenarios with similar levels of funding and state-level capacity. However, statistically significant differences ($p < .001$) among collaborative governance scenarios hold when controlling for funding and capacity. In figures 4B and 4C, we see how differences in policy efficacy change as funding and capacity are increased. There is little difference among policy outcomes at low resource levels, whereas disparities become evident as resources increase.

While these findings partially confirm H1, our results are mixed with respect to the lower efficacy in policies that incentivize regionalized planning schemes. Collaborative arrangements only sometimes lead to greater load reductions, specifically when resources are relatively high, and both planning and implementation capacity are shared. Additional analysis confirms three-way interactions among policy, funding, and capacity scenario parameters (table 4).

The mixed findings of H1 are relevant for evaluating the Collaboration for Planning and Implementation Hypothesis. Our findings very clearly prove H2—the coupling of collaboration for planning and implementation—leads to more efficacious outcomes. In our simulations, municipal water districts that only collaborate around planning functions are the least effective (as measured by cumulative load reductions) collaborative governance scenarios. These results are explained by a spatial mismatch between planning and implementation capacities caused by the newly enabled structure

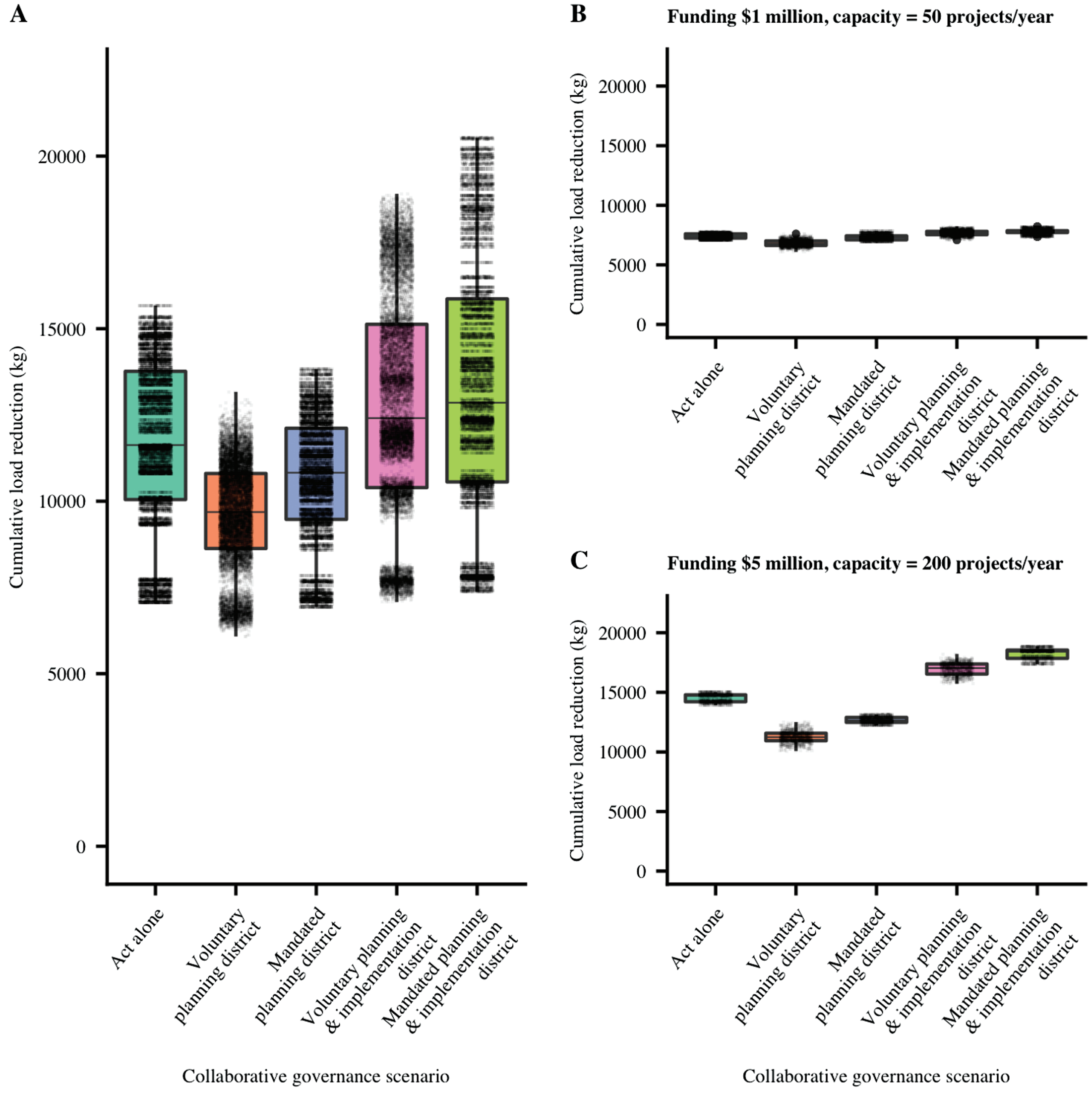
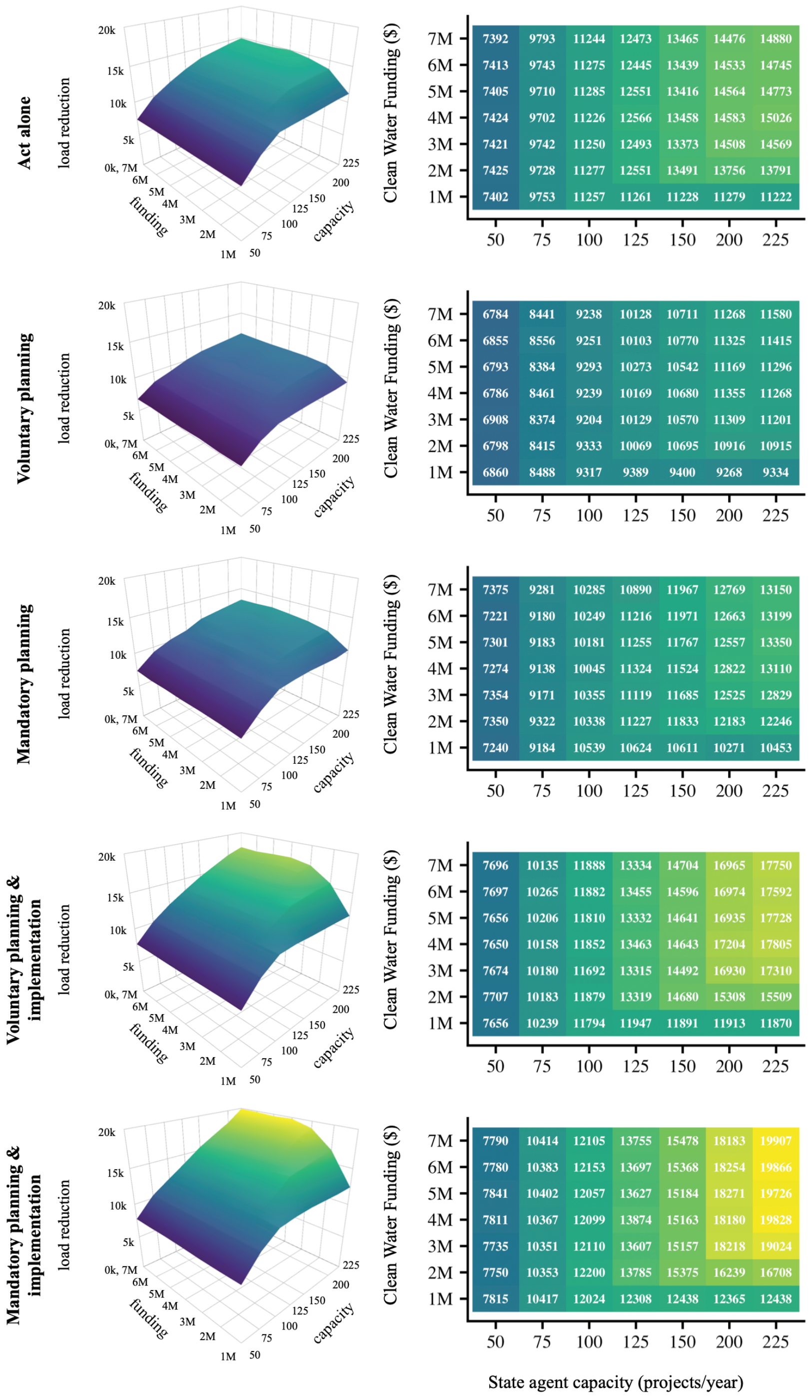


Figure 4. Box-and-Whisker Plots of Cumulative Load Reductions. Panel A shows all scenarios by policy, obscuring the differences among policies at various funding and capacity levels. Panel B shows little differences among policies at low capacity and funding levels, whereas panel C shows that at higher levels of funding and capacity, reductions are greater in policies where both planning and implementation capacity are aggregated.



Act alone

Clean Water Funding ($)	50	75	100	125	150	200	225
7M	7392	9793	11244	12473	13465	14476	14880
6M	7413	9743	11275	12445	13439	14533	14745
5M	7405	9710	11285	12551	13416	14564	14773
4M	7424	9702	11226	12566	13458	14583	15026
3M	7421	9742	11250	12493	13373	14508	14569
2M	7425	9728	11277	12551	13491	13756	13791
1M	7402	9753	11257	11261	11228	11279	11222

Voluntary planning

Clean Water Funding ($)	50	75	100	125	150	200	225
7M	6784	8441	9238	10128	10711	11268	11580
6M	6855	8556	9251	10103	10770	11325	11415
5M	6793	8384	9293	10273	10542	11169	11296
4M	6786	8461	9239	10169	10680	11355	11268
3M	6908	8374	9204	10129	10570	11309	11201
2M	6798	8415	9333	10069	10695	10916	10915
1M	6860	8488	9317	9389	9400	9268	9334

Mandatory planning

Clean Water Funding ($)	50	75	100	125	150	200	225
7M	7375	9281	10285	10890	11967	12769	13150
6M	7221	9180	10249	11216	11971	12663	13199
5M	7301	9183	10181	11255	11767	12557	13350
4M	7274	9138	10045	11324	11524	12822	13110
3M	7354	9171	10355	11119	11685	12525	12829
2M	7350	9322	10338	11227	11833	12183	12246
1M	7240	9184	10539	10624	10611	10271	10453

Voluntary planning & implementation

Clean Water Funding ($)	50	75	100	125	150	200	225
7M	7696	10135	11888	13334	14704	16965	17750
6M	7697	10265	11882	13455	14596	16974	17592
5M	7656	10206	11810	13332	14641	16935	17728
4M	7650	10158	11852	13463	14643	17204	17805
3M	7674	10180	11692	13315	14492	16930	17310
2M	7707	10183	11879	13319	14680	15308	15509
1M	7656	10239	11794	11947	11891	11913	11870

Mandatory planning & implementation

Clean Water Funding ($)	50	75	100	125	150	200	225
7M	7790	10414	12105	13755	15478	18183	19907
6M	7780	10383	12153	13697	15368	18254	19866
5M	7841	10402	12057	13627	15184	18271	19726
4M	7811	10367	12099	13874	15163	18180	19828
3M	7735	10351	12110	13607	15157	18218	19024
2M	7750	10353	12200	13785	15375	16239	16708
1M	7815	10417	12024	12308	12438	12365	12438

Figure 5. Load Reductions as a Function of Policy, Funding, and Capacity Scenarios. Response is generally nonlinear, as the amount of funding has little effect in lower capacity scenarios.

of the water districts. Because planning capacity is regionalized at the district level, but implementation capacity is not, projects can be identified and planned in areas where there is insufficient ability to implement them. Essentially, municipalities can become "over-planned" when the number of to-be-implemented projects exceeds a municipality's implementation capacity. The regionalization policy creates a new bottleneck at the implementation stage. We measure the depth of this backlog using the average number of projects that have been planned and funded—but not implemented—for each collaborative governance scenario.

The municipal-scale bottleneck becomes increasingly apparent in scenarios with greater state-level capacity (table 5). As the state processes additional projects, municipal capacity is exhausted, and the implementation backlog increases. The backlog of delayed projects is much larger (confirmed by analysis of variance [ANOVA], $p < .001$) when planning capacity is regionalized separate from implementation capacity, resulting in lower efficiency in the planning-only regionalization scenarios. The issue is exacerbated as capacity (throughput) of the state agency agent increases. Here, planning capacity, implementation capacity, and prioritized policy targets (greater required load reductions) are mismatched spatially and temporally. Therefore, the regionalization hypothesis is supported only when that mismatch is reduced.

Hypothesis 3, the Mandated Collaboration Hypothesis, tests how municipalities with low operational capacity but high TP loads are affected by an externally initiated mandate to collaborate. To test this case, we created a subset of municipal agents possessing both low capacity (implementation capacity ≤ 1) and the highest 20% of TP loads. Given the implementation bottlenecks discussed above and illustrated in table 5, we only tested differences between the mandated and voluntary planning-and-implementation policies. In the mandated policy, we expect that in aggregate the mitigated loads will be greater, as municipal agents with greater capacity can "lend" their resources to low-capacity collaborators. Accordingly, we performed the non-parametric Kruskal-Wallis analysis of variance of each group individually, reported in table 6. This Table should be read as *what percent more effective is the mandated policy in mitigating TP loads than the voluntary policy?* We find that in all cases, the mandated policy performs better among the low-capacity, high-loads municipalities (all comparisons significant at $p = .01$). The relative effectiveness of the mandated policy does not always improve as state-level resources increase. This is sensible given that the prioritization schemes in both policies optimize for load mitigation independent of resource constraints. To confirm our findings, we also compared policy mandates among municipal agents with low-capacity and *low* TP loads (not shown here). In this alternative case, the result was the opposite, as the voluntary policy performed better (Kruskal-Wallis test, $p = .01$). This is also as expected, as low-load areas are disfavored in a collaborative scheme, independent of local capacity. Thus, those municipalities with relatively low TP loads can improve their local conditions by *not* collaborating under a voluntary policy regime.

Our fourth hypothesis, the Administrative Bottleneck Hypothesis, tests whether the human resource capacity at the state scale (as indicated by the number of projects that State administrators can

Table 4. Analysis of Variance of Interactions Among Model Input Parameters

	df	Sum Sq.	Mean Sq.	*F*	*p* (>*F*)
Policy	4	1.5e11	3.6e10	40,214.9	<.001
State-level capacity	1	3.7e11	3.7e11	413,945.0	<.001
Funding	1	1.2e10	1.2e10	13,168.5	<.001
Policy:Capacity	4	4.3e10	1.1e10	11,972.6	<.001
Policy:Funding	4	2.3e9	5.7e8	628.6	<.001
Capacity:Funding	1	1.4e10	1.4e10	15,584.4	<.001
Policy:Capacity:Funding	4	2.9e9	7.1e8	792.9	<.001

Table 5. Project Implementation Backlogs, Measured as the Mean Number of Projects that are Funded but Unable to be Completed due to Constraints on Implementation Capacity

		State Agency Evaluation Capacity						
		50	75	100	125	150	200	225
Policy scenario	Compete	1.24 (0.26)	1.89 (0.52)	2.95 (0.99)	3.90 (1.50)	5.51 (2.59)	10.33 (6.91)	12.88 (9.33)
	Voluntary planning	13.00 (2.70)	19.09 (4.59)	23.42 (6.78)	25.57 (8.21)	27.44 (9.54)	33.62 (14.32)	37.41 (17.47)
	Mandated planning	5.42 (1.64)	8.56 (2.50)	11.88 (3.62)	14.72 (4.86)	17.93 (6.66)	24.18 (10.66)	26.59 (12.43)
	Voluntary planning and implementation	1.18 (0.21)	1.73 (0.44)	2.73 (0.87)	3.80 (1.42)	5.03 (2.12)	9.24 (5.65)	12.03 (8.22)
	Mandated planning and implementation	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)	1 (0.00)

Note: SDs in parentheses. Differences among regionalization policy, state evaluation capacity, and funding levels (not shown here) confirmed to be significant ($p < .001$).

process) constrains the efficacy of the program and the allocation of funds. When measured using the cumulative load reductions funded by alternative collaborative governance scenarios, we find this to be the case. Interactions among policy, capacity, and funding were confirmed by the ANOVA results (table 5). We plot these interactions among policy, capacity, funding, and load reductions in figure 5. Load reductions in all collaborative governance scenarios exhibit some degree of non-linear response, as indicated by the surfaces on the left-hand side of the figure. In general, when the state's human resource capacity to evaluate projects is relatively low (less than 100 projects/year) the effects of additional funds are minimal. For example, in scenarios that model a voluntary planning district with a capacity of 100 projects/year, our model indicates that that increasing funding from 1 to 7 million dollars will result in little-to-no change in load reductions. As capacity increases, however, additional funds do lead to greater TP load reductions. The locations of thresholds differ by active policy but are generally found in the 100–150 projects/year range in this model. The response surface for planning-only districts is fairly flat, indicating a less-responsive system. Planning-and-implementation districts, on the other hand, respond more strongly to changes in capacity and clean water funding. The "act alone" scenarios fall in between. The relationships among load reductions, funding, and state capacity support the bottleneck hypothesis.

Finally, we can also explore the suite of options available to policymakers from the perspective of overall "bottom-line" performance indicators. As we have shown, load reductions respond strongly to state-level capacity. A likely question within VTANR may be "what is the right level of staffing (capacity), and how might we measure the effectiveness of our actions?" In figure 6, we plot two alternative metrics for planning-and-implementation districts against various levels of state capacity. In Panel A, we see that as human resource capacity to evaluate projects increases, so does a performance metric based on the total kilograms of phosphorus mitigated. However, we also see in Panel B that as capacity increases, the effectiveness of spending (kg / $1,000) decreases. This is a result of the prioritization process—as the governance network implements additional clean water projects, it necessarily funds more marginal projects, shifting the distribution and lowering return on investment.

Discussion

Our model findings generally support the supposition that designing for collaborative governance leads to better performance outcomes in the form of reduced phosphorus loads, affirming H1. We also find that H2, the Collaboration for Planning and Implementation Hypothesis to be affirmed, as well as the Mandated Collaboration Hypothesis (H3). These findings are likely intuitive in cases where all capacities and objectives are aggregated, and processes are optimized using collaborative governance mechanisms and norms. In these scenarios, the policy essentially structures the collaborative governance regime as a scale-based linear optimization that maximizes utility at a broader scale. While a useful benchmark, this type of governance requires the participation of all finer-scale entities (here, municipalities) that is only achieved through mandated collaboration. These results also support the Administrative Bottleneck Hypothesis (H4) in which we see the value of matching the administrative capacity of the State to levels of funding.

As the real-world policy reality deviates from a mathematically optimal configuration, the resultant social and environmental outcomes are less predictable. For example, voluntary participation scenarios led to lower reductions in load reductions and less-efficient spending of funds. Further, new bottlenecks and project backlogs were created by planning-only districts at the municipal level, again leading to less-efficient performance. We can conclude, therefore, that the system is not strictly dependent on scaling effects—rather, collaborative design considerations of how and

Table 6. The Relative Performance of The Mandated Planning-and-Implementation Policy Over the Voluntary Policy

		State-Level Capacity (Projects/Year)						
		50	75	100	125	150	200	225
Annual funding (in millions of dollars)	1	22.9	13.4	13.9	23.1	23.2	23.3	22.5
	2	22.7	20.2	19.3	26.6	27.8	20.5	24.1
	3	18.5	22.0	20.7	21.8	23.8	31.5	22.5
	4	20.5	19.3	24.9	20.5	18.5	15.2	33.6
	5	23.5	15.6	23.1	23.4	22.2	31.7	29.0
	6	17.2	23.8	19.8	18.0	26.1	24.2	35.5
	7	11.2	13.3	11.2	20.6	20.4	21.2	37.4

Note: Values in the table are percentages, and should be read, for example, as "the mandated policy on average mitigates 22.9% more load than the voluntary policy". All comparisons confirmed significant by a Kruskal-Wallis analysis of variance.

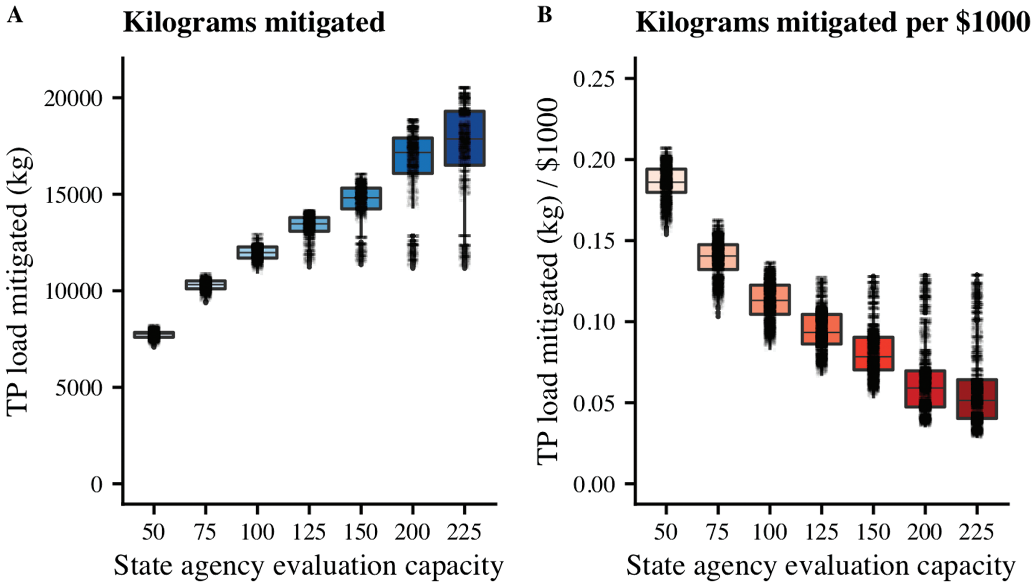


Figure 6. Metrics of Policy Efficacy for Planning-and-Implementation Districts. As capacity increases, amounts of mitigated phosphorus increase, but per-dollar efficiency decreases.

where to regionalize governance capacity is important in achieving goals as well.

These findings demonstrate the complex trade-offs that can surface when collaborative governance mechanisms are employed. Collaboration for collaboration's sake is not a panacea. Our model results demonstrate that the links between planning and implementation, and the need for administrative capacity to address bottlenecks are critically important considerations.

Our model indicates that the efficacy of instituting a collaborative governance approach to municipal stormwater management is highly dependent on the capacity of the state agency agent to evaluate clean water projects and allocate funds. The parameter ranges for our scenarios are based on empirical data from the Vermont DEC clean water projects database, which shows that approximately 57 urban land use projects are funded annually (VTDEC 2019). Our simulations show that significant increases in state capacity will have greater immediate impacts than short-term increases in funding. As shown in figure 6, system response to an increase in capacity is non-linear. Across all modeled scenarios, at lower capacity levels (100 projects/year or less), funding can increase by 700% and the response of the policy target (i.e., load reductions) remains flat, as the system cannot utilize all of the funding from the state. Though increased capacity and funding improve the state's ability to process projects, this model holds municipal (and regional) capacity constant. Thus, additional resources eventually shift a bottleneck from the state agent to the municipalities (or to their regionalized districts). The values in figure 6 heatmaps point to possible "sweet spots," or combinations of capacity and funding levels that could lead to more efficient policy outcomes. While the assumptions and simplifications in the model limit normative predictions, the model allows for the exploration of alternative scenarios with stakeholder input.

The ability of the water governance ABM to both test hypotheses and provide some practical considerations to policymakers offers us a unique ability to test variations of collaborative governance theory. This study contributes to the growing body of research that has demonstrated the efficacy of collaborative governance arrangements to address wicked environmental problems (Booher 2004; Emerson and Nabatchi 2015; Koontz and Johnson 2004; Pahl-Wostl et al. 2007; Scott 2015). This assertion is rendered at a coarse-grain level, as found in Hypothesis 1. The variation of differences between collaborative and non-collaborative designs is measurably higher, but not always decidedly so. The non-collaboration scenario illustrated as the star network found in figure 1A provides an opportunity for municipalities to directly access resources from the state. The lack of any intermediaries that may provide buffers against the state may place greater burdens on municipalities to "fend for themselves." For municipalities with higher capacity to plan and implement stormwater projects, these arrangements provide them greater ability to comply with water quality standards. But as we have noted, the problem locations or drivers of nonpoint source pollution are not evenly distributed, driving the potential for projects with lower returns on investment to get implemented over other projects. Pooling resources and aggregating project planning and implementation at the district scale should lead to higher net load reductions. However, this was not the case for either voluntary collaboration scenarios. In this case, voluntary collaborative governance regimes for planning alone and planning and implementation both scored lower mean load reductions than the non-collaborative scenario. We should judge this particular outcome not as a generalizable outcome, but as a property of the particular relationship between a municipality's propensity to collaborate and the geospatial distribution of nonpoint pollution. This finding should rather be explained as a specific set of contingencies shaped by municipal willingness to collaborate and the geophysical properties of the environmental problem. By incentivizing or motivating municipalities to increase their propensity to collaborate, we may find that load reduction measures would increase. Mandating collaboration for the planning and implementation of stormwater projects leads to generally higher levels of load reductions because it allows for a stronger prioritization of projects with higher ROIs.

These findings suggest that in the context of nonpoint pollution mitigation, at least, the efficacy of collaboration governance regimes is contingent on the specific properties of both institutions and ecosystems (Raab, Mannak, and Cambré 2013). Taken more broadly, we can conclude that in circumstances when governance networks carry out specific regulatory and capital-intensive projects that the use of collaborative governance regimes should be considered as contingent upon actor's propensities to collaborate and the administrative capacities of central actors. This latter point highlights the importance that network structures play in determining the optimal collaborative governance regime type. Here, the properties of the network matter, signaling the need for deeper integration of collaborative and network governance theories.

The contributions of this study to theory development include the demonstration of the relationship between network governance and collaborative governance. As noted earlier, there is compatibility between collaborative governance typologies of origins and network governance typologies of relatively stable governance design. Future theory development should focus on the relationship between specific structural properties of networks and collaborative capacity.

The ability of social-ecological systems to be resilient is contingent on their ability to adapt and transform as conditions change (Folke et al. 2002; Gallopín 2006). There is congruence among dimensions of collaborative governance and adaptive capacity theories, suggesting that as institutions enable collaboration, their ability (and that of the system) to adapt may be increased (Emerson and Gerlak 2014).

This study demonstrates the value that ABMs can have for theory testing and institutional design and contributes to the growing literature regarding the use of simulation modeling to test alternative design rules. Although we cannot anticipate or model all possible futures or conditions, the examination of various configurations of collaborative governance platforms can increase learning and adaptive capacity (Ansell and Gash 2018; Daniels and Walker 2001; Emerson and Gerlak 2014). As we have seen, not all collaborative governance schemes may lead to desirable outcomes. Thus, the value proposition of collaborative governance is very likely contingent upon the specific design of the collaboration network.

Conclusion

With the nuances of modeling complex governance arrangements recognized, there are a number of key observations to make relative to some of the core questions that concern public managers and policymakers. The first conclusion is one that is well-trodden, but here is empirically validated, is that you simply cannot "throw money at the problem" of nonpoint source pollution. A rush to fund at the expense of proper planning, targeted focus, and appropriate levels of administrative capacity can leave a system rich in financial capital, but poor in knowledge, human and physical capital, and ultimately, results.

The second main conclusion to be drawn here pertains to the importance of administrative capacity. The kind of process-based modeling demonstrated here can be very useful in determining where and how administrative bottlenecks occur, and their relation to program performance. Strategic investments in administrative capacity are critically important, and an assertion that is likely not lost on practicing public managers. This fact may, at times, be lost on policymakers who are setting the policy agenda and making resource allocation decisions. ABMs and other process-based models of alternative governance design can be used to inform policy decisions and ensure that administrative capacity is dully considered.

The third main conclusion to be drawn pertains to designing for collaborative governance and the efficacy of collaborative and network governance theories to inform this process. The apparent inefficiencies of voluntary collaboration at both the planning and implementation stages are worth noting again. When agency is provided to actors such as municipal agents at a finer, localized scale, their limited perceptions of the whole system and the collective goals tied to that system, may be lost in the specifics of local politics, resource constraints and the like. The apparent value of mandated collaboration, not just in planning, but in project implantation as well, suggests the need to "level the playing field" by pressing for stronger coordination across scales of government. In this regard, our study provides some very important insights regarding mandated versus voluntary collaboration.

This study highlights the potential uses of dynamic models of governance networks (Koliba, Zia, and Merrill 2019) to inform actual public policy. The State of Vermont is set to enact mandated water districts, and this governance model has been credited with helping to shape this legislation (Kamman 2019). That this model was able to draw on actual project data, projected nutrient load reductions of those projects, and hydrological modeling estimates used by the USEPA and the State to set TMDL targets, demonstrates the practical use of coupled modeling approaches that incorporate alternative governance designs. That policymakers in the State of Vermont were involved in the design and analysis of this model also underscores the potential value of using dynamic modeling to shape legislation and governance arrangements. In this manner, policy implementation and governance design can be understood as key components of a wider situational awareness of a social-ecological system.

Supplementary Material

Supplementary material is available at the *Journal of Public Administration Research and Theory* online.

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