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INNOVATIVE VIEWPOINTS

From concept to practice to policy: modeling coupled natural and human systems in lake catchments

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Abstract. Recent debate over the scope of the U.S. Clean Water Act underscores the need to develop a robust body of scientific work that defines the connectivity between freshwater systems and people. Coupled natural and human systems (CNHS) modeling is one tool that can be used to study the complex, reciprocal linkages between human actions and ecosystem processes. Well-developed CNHS models exist at a conceptual level, but the mapping of these system representations in practice is limited in capturing these feedbacks. This article presents a paired conceptual–empirical methodology for functionally capturing feedbacks between human and natural systems in freshwater lake catchments, from human actions to the ecosystem and from the ecosystem back to human actions. We address extant challenges in CNHS modeling, which arise from differences in disciplinary approach, model structure, and spatiotemporal resolution, to connect a suite of models. In doing so, we create an integrated, multi-disciplinary tool that captures diverse processes that operate at multiple scales, including land-management decision-making, hydrologic-solute transport, aquatic nutrient cycling, and civic engagement. In this article, we build on this novel framework to advance cross-disciplinary dialogue to move CNHS lake-catchment modeling in a systematic direction and, ultimately, provide a foundation for smart decision-making and policy.

Key words: eutrophication; freshwaters; multi-disciplinary; pollution; water quality.

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Introduction

Developing sound environmental policy requires an understanding of the complex interrelationships between human behavior and natural systems. Recent debate over the Waters of the United States rule that defines the scope of the U.S. Clean Water Act is one example that highlights the need to better understand and define the extent of connectivity between people and freshwater systems. Omitting these connections when developing policy alters water protection activities, with potentially adverse impacts on ecosystems and people for decades or longer (Boyle et al. 2017). The potential for long-lived effects underscores the need for a robust body of work that characterizes human–freshwater linkages to increase our scientific knowledge of these systems and to support policymaking and consequent actions to protect freshwater resources.

Coupled natural and human systems (CNHS) modeling provides an important mechanism for understanding the reciprocal linkages between people and freshwater systems: Human actions affect ecosystems, which in turn affect human well-being and future behavior (Liu et al. 2007, Alberti et al. 2011, Kelly et al. 2013). The interactions between humans and ecosystems generate dynamics that operate at multiple spatiotemporal scales and span diverse resource issues, from local wildlife habitat, to regional land use and global climate change (Caraco and Cole 1999, Turner et al. 2003, Field and Raupach 2004, An et al. 2005, 2006, Manson 2005). The complexity of these dynamics, characterized by multiple components and non-linear feedbacks, makes it challenging to identify the many direct and indirect ways in which humans and ecosystems influence one another (Kotchen and Young 2007, Liu et al. 2007, Troy et al. 2015). Yet, understanding the dynamics that arise from interactions within CNHS is critical to generating insights into system behavior and human actions, which will further inform the protection and enhancement of natural systems for future generations.

On a conceptual level, the features of CNHS dynamics and the underlying linkages between human and natural systems are well developed and widely accepted in the scientific literature (Carpenter et al. 2007, Collins et al. 2011). When mapping these conceptual representations into practice, however, there is wide variation among studies in modeling system feedbacks. Moreover, relatively few studies systematically map two-way feedbacks between human and natural systems into practice (Troy et al. 2015, Blair and Buytaert 2016). As a result, existing applications differ in their ability to capture CNHS dynamics.

In this article, we present an innovative conceptual framework that represents the feedback relationships between human and natural systems in freshwater lake catchments. Our objective in developing this framework is to describe a complete CNHS feedback loop that captures human actions, the consequences of those actions for water quality in lake ecosystems, and the effect of ecosystem change on human behavior. We demonstrate how to implement our conceptual framework by coupling a suite of disciplinary models to represent critical relationships between system components. Throughout the article, we use "conceptual framework" to describe the overarching structure that characterizes a complete cycle of linkages and feedbacks between human and natural systems. We use "model" to refer to discipline-specific representations of system components.

With this pairing of concept and practice, we develop an integrated and multi-disciplinary foundation for future CNHS research. We develop this tool in the context of lake catchments, which exemplify a rich set of linkages between human and freshwater systems. An improved understanding of the interaction between humans and lake ecosystems is especially timely given current crises facing freshwater systems worldwide, which suffer degradation due to land-use change, pollution, and increased water scarcity (Green et al. 2015). Furthermore, our conceptual framework can be used to develop practical insights into the protection of water quality and the services humans enjoy from maintaining and improving lake water quality, such as drinking water, recreation, fisheries, and lake esthetics.

Conceptual Framework: Focus on Feedbacks

Our conceptual framework (Fig. 1) provides the overarching structure for modeling a set of core feedbacks that characterize lake-catchment

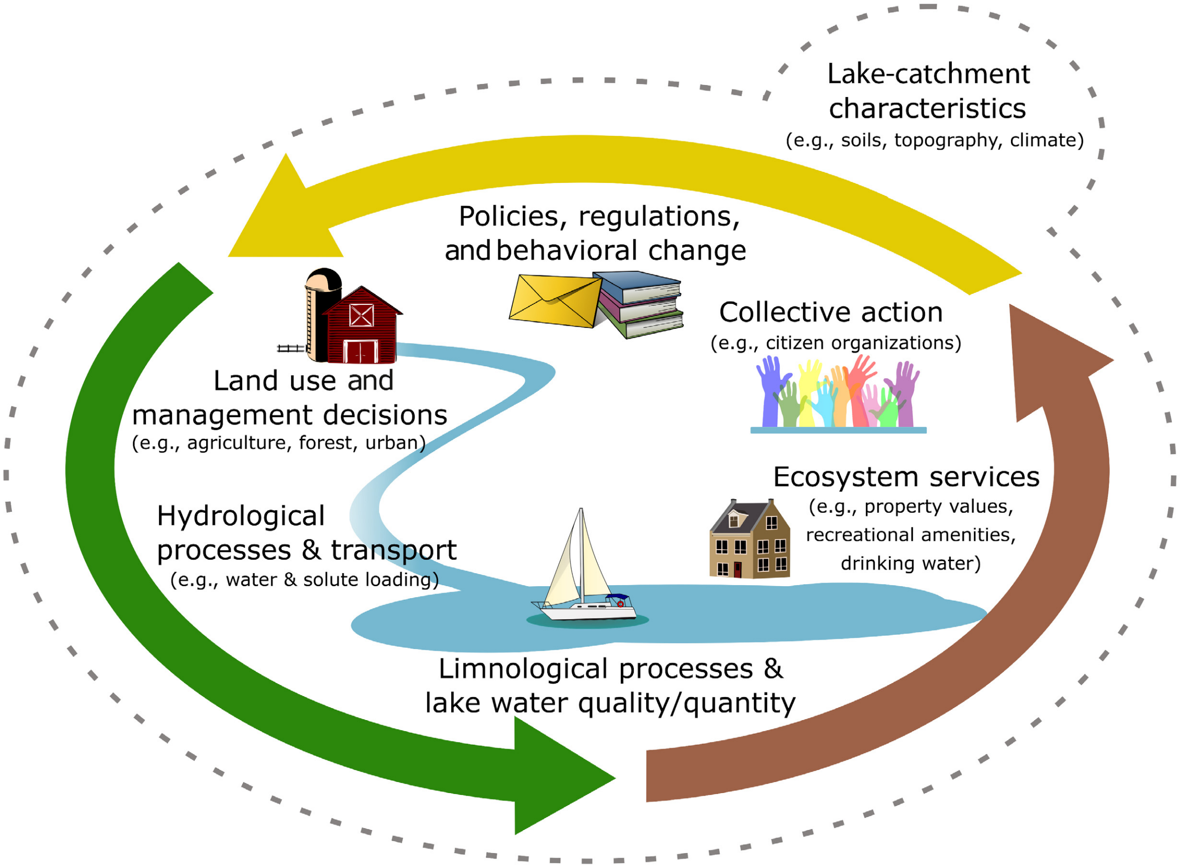

Fig. 1. Conceptual framework for a coupled natural–human system in a lake catchment.

CNHS. Starting in the upper left of Fig. 1 and moving in a counter-clockwise direction, the green arrow captures a critical linkage from human actions in the catchment to the lake via the hydrologic fate and transport of nutrients and sediment (Yaeger et al. 2013, Rabotyagov et al. 2014). The human decisions with the greatest potential to affect lake water quality include land use (e.g., extent of agriculture, forest, and development) and land-management choices, such as farming practices (Ribaudo et al. 2008, Smith and Schindler 2009). Land use and land-management decisions interact with climate and soil through biogeochemical processes that transport sediments and nutrients downstream via surface and groundwater flows. The hydrologic system delivers water, sediments, and nutrients to the lake, where further abiotic and biotic processes result in changes to the lake ecosystem, including altered water quality.

As water quality changes in the lake, the natural system in turn influences human systems. The brown arrow in Fig. 1 captures linkages between lake water quality and human response. In this linkage, we define water quality as an integrated metric of ecosystem characteristics that affect human use and enjoyment of the lake, such as water clarity, the frequency and intensity of algal blooms, and the abundance of desired fish species. Changes in water quality, so defined, influence human systems at the scale of the individual and the community through direct and indirect pathways. A direct pathway involves an immediate connection between freshwater and human systems, as when changes in lake water quality affect the meaning the lake holds for people. An indirect pathway involves an intermediate step, as when water quality drives changes to lake-related factors that people care about, such as home prices and recreational opportunities

(Boyle et al. 1999, Gibbs et al. 2002, Keeler et al. 2015).

While many studies address the linkages from human to natural or natural to human systems, few link these components and even fewer close the feedback loop such that changes in water quality motivate behavioral change (Troy et al. 2015). The yellow arrow in Fig. 1 captures the effect of human response to changes in lake water quality on future decision-making to protect and enhance water quality, beginning the CNHS cycle anew. This component of our conceptual framework captures reflexive behavior in human systems, which occurs when "individuals and societies learn from past experiences and anticipate future occurrences when making current choices" (Kotchen and Young 2007:150). Reflexive behavior often results in self-organization and the formation of human institutions, such as policies, that influence the natural system on a time scale of decades or more (Kandasamy et al. 2014, Sivapalan and Blöschl 2015).

One pathway for reflexive behavior arises as a decline in lake water quality motivates civic engagement in communities. In lake-catchment CNHS, civic engagement often takes the form of lake associations, which consist of groups of individuals for whom a sense of place has developed as a result of their shared experience with the lake (Tuan 1977). These organizations are predominantly groups of citizens who work together to increase awareness, protection, and improvement of local water resources. Some associations are formed by stakeholders themselves as bottom-up, grass-roots organizations, while others take a top-down approach to connecting stakeholders around the lake to work toward a common goal (Kramer 2007, Bell et al. 2013, Thornton 2013).

Lake associations often serve as lake stewards through education and advocacy to maintain or enhance desired environmental outcomes (e.g., water clarity) and social conditions (e.g., limited shoreline development). Organized actions by lake associations can manifest in a number of ways, including education of leaders and neighbors in the catchment and beyond, petitioning for local zoning changes, and working with environmental agencies to develop and support land-use policy. Lake associations also have the potential to serve as boundary organizations that provide a bridge between science, policy, and society, leading to new forms of adaptive governance (Guston 2001). These organizations and their actions thus link the impacts of land use on water quality and humans back to responsive land-use adaptation, completing the feedback loop between human and natural systems in lake catchments.

Lake Catchments as a Prototypical CNHS

Freshwaters provide more ecosystem services per unit area than any other habitat type, but those services are often degraded by human activities (Carpenter et al. 2011). As a result, freshwater systems capture an exemplar suite of the feedback linkages that define CNHS in general. Freshwater lake catchments are particularly illustrative for two reasons: Water serves to integrate terrestrial upstream human actions with downstream lake ecosystem functions; and water quality changes affect humans who can then modify their effects on critical ecosystem services (Bormann and Likens 1979, Adrian et al. 2009, Williamson et al. 2009). An additional advantage to these systems for CNHS modeling is that natural ecosystem boundaries define the extent of the study area (Weathers et al. 2013).

To develop our conceptual framework, we examined three focal lake catchments—Lake Mendota, Wisconsin, USA; Oneida Lake, New York, USA; and Lake Sunapee, New Hampshire, USA (Fig. 2)—to identify common CNHS components and the feedbacks that link them. We strategically chose these three systems because they share common features that support CNHS modeling, but also differ with respect to key variables that influence system dynamics. The commonalities among lakes allow us to instantiate our conceptual framework using the same suite of disciplinary models and coupling linkages. At the same time, these focal systems capture differences in land use, water quality, and civic engagement (Table 1). Using a common modeling framework to study these systems ensures that differences in their dynamics are driven by these features of the systems themselves, and not by our choice of models. Our choice of focal catchments thus yields a flexible conceptual framework that is general in the sense that it

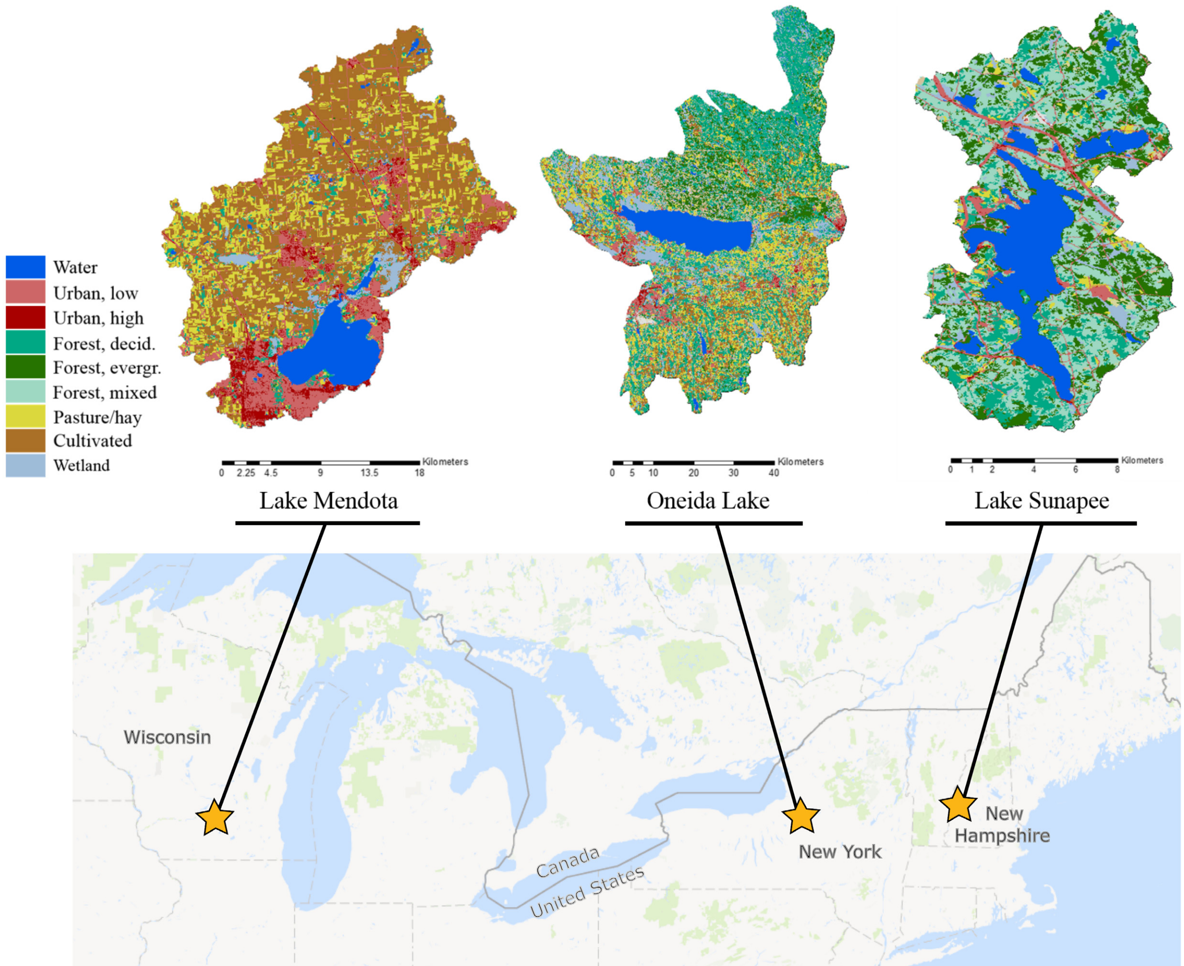

Fig. 2. Three lake-catchment coupled natural–human systems with surrounding land uses (Lake Mendota, Wisconsin; Oneida Lake, New York; Lake Sunapee, New Hampshire, USA).

captures a range of variation in lake-catchment CNHS.

Each of our three focal lakes are glacially formed at a similar latitude, with summer stratification, winter ice cover, and inflows that are predominantly fed by surface waterways. Each of these lakes has extensive historical data on lake water quality that support modeling: All are Global Lake Ecological Observatory Network (GLEON) site members and have both long-term, manually sampled data records and recent data from high-frequency sensor networks (Weathers et al. 2013, Hamilton et al. 2014). All three catchments also have established lake associations that are actively working to engage citizens in maintaining or improving lake water quality.

Despite these similarities, land use differs across the three systems, with important implications for water quality. Lake Sunapee is an oligotrophic lake located in a catchment dominated by forests (81%) and is a drinking water source because of its high water quality (Carey et al. 2014, Richardson et al. 2017). Only 8% of the catchment is developed at present, although impervious surface is increasing near the shoreline and land-use conversion from forest to development is the predominant driver of changes in the lake ecosystem. Though the lake is currently oligotrophic, changing land use

Table 1. Lake-catchment descriptive statistics.

Catchment descriptors	Mendota, Wisconsin	Oneida, New York	Sunapee, New Hampshire
Lake area (ha)	3961	20,770	1669
Watershed : lake surface area ratio	6.2	13.0	3.6
Mean lake depth (m)	12.8	6.8	11.6
Maximum lake depth (m)	25.3	16.8	33.7
Trophic state	Eutrophic	Mesotrophic	Oligotrophic
Mean total nitrogen (μg/L)	1100	500	150
Mean total phosphorus (μg/L)	100	30	5
Mean summer Secchi depth (m)	2.0	3.5	8.0
Major land-use categories	67% Agriculture 1% Forest 22% Developed	33% Agriculture 47% Forest 13% Developed	4% Agriculture 81% Forest 8% Developed
Lake association	Clean Lakes Alliance	Oneida Lake Association	Lake Sunapee Protective Association
Lake association focus	Algal blooms	Healthy fisheries	Water quality

could lead to a deterioration in water quality with the potential to affect property values in the catchment. Threats to Sunapee water quality have motivated a robust and long-lived lake association—the Lake Sunapee Protective Association—that focuses primarily on protecting water quality by influencing human behavior via education, outreach, and advocacy efforts.

In contrast, Lake Mendota is a eutrophic lake in a catchment dominated by agriculture (67%) and development (22%), both of which contribute to large nutrient loads into the lake that degrade water quality. Current and historic agricultural land-management decisions in this catchment are the primary driver of ongoing water quality concerns. Algal blooms, beach closures, and other effects of eutrophication affect catchment residents and property owners, and may reduce property values along the lakeshore (Stumborg et al. 2001). A history of cyanobacterial blooms led to the creation of the Clean Lakes Alliance, a lake association that focuses on reducing blooms to enhance recreation and lake esthetics by modifying agricultural land-management practices via community engagement.

Oneida Lake sits between oligotrophic Sunapee and eutrophic Mendota: Oneida is mesotrophic and is in a mixed land-use catchment with 47% forest, 33% agriculture, and 13% developed land. In this catchment, nutrient loading has declined since the 1970s, but there has been an increase in cyanobacterial blooms and the number of beach closings since 2000. Changes in water clarity have altered fish population dynamics and community structure in the lake, driving a shift away from the currently preferred sport fish species. As a result, the Oneida Lake Association focuses primarily on supporting the lake's recreational sport fishery, which continues to be one of the most heavily fished in New York State (Rudstam et al. 2016). The organization works to address fishery and water quality concerns primarily by influencing top-down policy channels.

From Concept to Practice: CNHS Components and Models

One of the most critical decisions in CNHS modeling is what components must be represented to capture key feedbacks between human and natural systems. As noted by Troy et al. (2015), these linkages vary across systems and depend inherently on the spatial and temporal scales of the CNHS problem. We propose to implement our conceptual framework with an empirical approach grounded in six key CNHS components that we identified using our focal catchments. These components describe human and natural system processes that span academic disciplines, including economics, agronomy, hydrology, limnology, and social psychology, and likely have similar analogues for other CNHS. The CNHS components are (1) agricultural land-management decisions, (2) terrestrial nutrient cycling, (3) hydrologic-solute transport, (4) aquatic nutrient cycling, (5) residential property values, and (6) civic engagement. To represent each component, we chose existing, discipline-specific models based on modeling flexibility to accommodate differences across catchments (Table 2).

We chose to model agricultural land-management decisions, such as crop choice and fertilizer applications, because of the importance of agricultural production and nutrient leaching to water quality in the Mendota and Oneida catchments. We simulate these agricultural land-management decisions using an economic optimization model in which farmers maximize profit subject to constraints on resource availability (i.e., land and water), crop yield functions that capture the relationship between crop productivity and farmer decisions, and land-management policy (Cobourn et al. 2013). The temporal and spatial resolution of this model are by design consistent with agricultural decision-making, in most cases annually and at the level of the farm.

We represent terrestrial nutrient cycling using the agro-ecosystem and nutrient cycling model Cycles (Kemanian and Stöckle 2010), which shares modules with CropSyst (Stöckle et al. 2014) and adds innovations in the representation of coupled carbon–nitrogen cycling and polycultures. Cycles allows for dynamic and flexible changes in agricultural systems management, with model expansions to represent woody systems including forests. Currently, we represent forests in catchments with Biome-BGC, which simulates forest nutrient cycling (Yu et al. 2014). Cycles is a daily time-step model at the spatial resolution of a representative land unit, defined as a land base that shares similar biophysical characteristics (e.g., climate and soils). Cycles represents depth as soil layers that are consistent with the predominant soil profile for a representative land unit.

We represent hydrologic-solute transport using the Penn State Integrated Hydrologic Model (PIHM), which simulates large-scale and fine-resolution transport of water and particulate or soluble nutrients in watersheds and rivers (Kumar et al. 2009). The Penn State Integrated Hydrologic Model overcomes constraining

Table 2. CNHS components and models, including the data flows that link models.

CNHS component	Model/approach	Resolution	Input data	Output data
(1) Agricultural land-management decisions	Economic optimization modeling	Temporal: annual Spatial: representative farmer	Crop yields[(2)] Land-use policy[(6)]	Agricultural land-management practices[(2)]
(2) Terrestrial nutrient cycling	Cycles/Biome-BGC	Temporal: daily Spatial: representative land unit Depth: variable with soil layers	Agricultural land-management practices[(1)] Soil moisture[(3)] Land-use policy[(6)]	Nutrient leaching[(3)] Crop yields[(1)]
(3) Hydrologic-solute transport	Penn State Integrated Hydrologic Model	Temporal: minute Spatial: mesh grid cell (~100 m)	Nutrient leaching[(2)]	Soil moisture[(2)] Stream discharge[(4)] Water temperatures[(4)] Nutrient concentrations[(4)]
(4) Aquatic nutrient cycling	General Lake Model	Temporal: hourly Spatial: lake Depth: dynamic <0.05 to >0.5 m intervals	Stream discharge[(3)] Water temperatures[(3)] Nutrient concentrations[(3)]	Water clarity[(5, 6)] Cyanobacterial blooms[(5, 6)] Anoxia[(5, 6)]
(5) Residential property values	Hedonic property value model	Temporal: multi-year Spatial: catchment	Water clarity[(4)] Cyanobacterial blooms[(4)] Anoxia[(4)]	Water quality price premium[(6)]
(6) Civic engagement	Institutional analysis	Temporal: multi-year Spatial: catchment	Water clarity[(4)] Cyanobacterial blooms[(4)] Anoxia[(4)] Water quality price premium[(5)]	Land-use policy[(1, 2)]

Notes: CNHS, coupled natural–human systems. Input/output data listed are those that form coupling linkages between CNHS models. For each input/output data item, the superscript numeral denotes the model that provides data (for inputs) or the model that receives data (for outputs).

assumptions built into other models, such as the Soil Water Assessment Tool by resolving the topographic, land cover, and soil controls of overland, stream, and groundwater flow in individual lake catchments. The Penn State Integrated Hydrologic Model operates at a fine scale, with spatial resolution defined by a PIHM-generated multi-scale triangular mesh of grid cells (Bhatt et al. 2014). The Penn State Integrated Hydrologic Model generates a denser network of cells close to surface flow paths, capturing heterogeneity in delivery ratios across the landscape. The Penn State Integrated Hydrologic Model algorithms simulate hydrological conditions (water infiltration, runoff, lateral flow, and groundwater recharge) in each mesh cell based on the properties of the landscape and the hydrological regime. Except for the fixed river network, the hydrological conditions in each PIHM mesh cell are an emergent property of the system (i.e., they are not predetermined). The Penn State Integrated Hydrologic Model runs on sub-hourly time steps because hydrological processes in the soil during infiltration and runoff events can occur on short time scales (e.g., minutes).

To capture the underlying dynamics that drive water quality outcomes, we chose the General Lake Model coupled with the Aquatic EcoDynamics library (GLM-AED, hereafter GLM). General Lake Model is an open-source hydrodynamic-water quality model that is widely used to predict phytoplankton blooms and water quality (Hipsey et al. 2017). General Lake Model offers a modeling environment that balances water, mass, and energy budgets at sub-daily time scales and includes biogeochemical cycling and the interaction of trophic levels within the lake. Its modular flexibility enables us to confront the non-linear dynamics that arise in lake CNHS, such as cyanobacterial blooms (Hanson et al. 2011, Kara et al. 2012, Snortheim et al. 2017). General Lake Model is a one-dimensional lake model, with dynamic horizontal layers that range from <0.05 m to >0.5 m. Process equations governing water quality are solved at an hourly time step. General Lake Model supports simulation of three important metrics of lake water quality—water clarity, anoxia, and cyanobacterial blooms. These variables derive from physical–chemical–biological interactions occurring at multiple time scales within the water column of lakes and are influenced by external water, sediment, and nutrient loads.

The economic literature establishes that lake water quality changes that are observable to homebuyers (e.g., water clarity) affect home sale prices (Boyle et al. 1999, Poor et al. 2007). We chose a statistical approach to estimate the relationship between water quality and property values in a catchment—the hedonic property value model (Taylor 2017). The hedonic model involves regressing observed property sales prices over a multi-year time interval against variables describing lake water quality, while controlling for other home attributes, such as structural features, land characteristics, and neighborhood traits. The contribution of each water quality variable to a home's price is the price premium associated with that variable. The temporal resolution of the model is such that an estimated premium applies to the record of available property sales data and a specified change in lake water quality. The spatial resolution is a sub-catchment geopolitical area (or shorefront properties), and price premiums are aggregated at the scale of a community.

Human intervention through lake associations plays a role in maintaining water quality through innovative ecosystem management, the policy process, and by engaging communities through outreach and education (Carpenter et al. 2007). We recognize lake associations as embodying the myriad use and non-use values held for a particular lake and the actions they take to be the manifestation of those values. We use a qualitative approach grounded in organizational behavior to assess lake associations' effectiveness in enhancing lake water quality. Specifically, we adopt the multi-dimensional framework established by Andrews et al. (2010) for studying civic associations using institutional analysis in order to understand the ways lake associations effect change within lake catchments. The basis for the civic association model is investigation of lake associations through historical records and interviews with key informants. The temporal resolution of the institutional analysis depends on the historical information available and the longevity of the lake association. For example, the Lake Sunapee Protective Association was founded in 1898 and has maintained lake association documents from as early as 1950. In the case of the focal catchments, data availability supports an understanding of lake associations on an annual time step (e.g., annual reports). The spatial scale is the catchment, which defines the area over which citizens engage in activities intended to maintain and improve lake water quality.

Capturing Feedbacks through Model Linkages

The most challenging, but also most crucial, part of CNHS modeling is coupling disciplinary models to capture feedbacks in the lake-catchment system. Conceptual and technical challenges arise in linking models due to disciplinary differences in approach (e.g., quantitative vs. qualitative and process-based vs. statistical) as well as spatial and temporal resolution. Developing an implementable version of the full CNHS feedback loop requires choosing a coupling method and defining the variables that link models. With lake-catchment coupling, it is also necessary to address differences in the spatial and temporal resolution of the various human and natural system models at each stage, but not globally (Table 2).

Coupling methods

Different methods may be used to couple models, ranging from a direct approach, in which two or more models are run simultaneously, to a sequential approach, in which output data from one model are passed as input data to another. We chose the latter, which involves undertaking each model individually and specifying data flows between them. This approach offers the benefit of preserving the discipline-specific structure and resolution of each model, while also highlighting the critical model interactions that allow for the expression of system-level emergent properties of the CNHS. We developed a workflow for the exchange of data between each of our models, defining the linkages essential to the empirical CNHS model (Fig. 3).

Exchanging data between models requires choosing the variables, and their resolutions, that define the critical coupling linkages in the system. Our coupling workflow identifies potentially important variables to pass between natural and human systems models, as well as differences in their resolution (Table 2). In our CNHS, natural system models (Cycles, PIHM, GLM) operate on relatively short (sub-hourly to daily) time steps to ensure that they accurately simulate short-term extreme events (e.g., storms) that can have disproportionate effects on annual water and nutrient budgets. In contrast, human system models (economic optimization, hedonic property value model, institutional analysis) operate on relatively long (e.g., annual to decadal) time steps or at a specific point in time. Similarly, the human and natural system models differ in spatial resolution, from integrated over the full catchment and beyond (institutional analysis) to sub-catchment units (economic optimization, Cycles, hedonic property value model), the lake's surface area (GLM), and a finely resolved, multi-scale mesh on the centimeter to meter scale (PIHM). To address mismatch in the resolution of variables passed between models, we present methods of aggregating, disaggregating, or interpolating data flows where appropriate.

Coupling workflow

Starting with the agro-ecosystem in the upper left-hand corner of Fig. 3, we trace the flow of data through the empirical model of lake-catchment CNHS. A two-way coupling between the economic optimization model and Cycles describes the catchment agro-ecosystem, which is itself a coupled human–natural system nested within the broader lake-catchment CNHS. The feedback between these models captures the interdependency between crop yields and human decision-making with respect to agricultural management practices. The economic optimization model relies on output data from Cycles that characterize crop yields as a function of land-management choices and exogenous factors (e.g., climate and soils). In turn, the economic optimization model provides input to Cycles in the form of land-management decisions that affect crop yields and nutrient dynamics.

For the linkage from Cycles to the economic optimization model, it is necessary to aggregate daily crop biomass accumulation to simulate crop yields for the growing season, and to map the spatial correspondence between farms and representative land units. For the linkage from the economic optimization model to Cycles, it is necessary to describe how annual agricultural

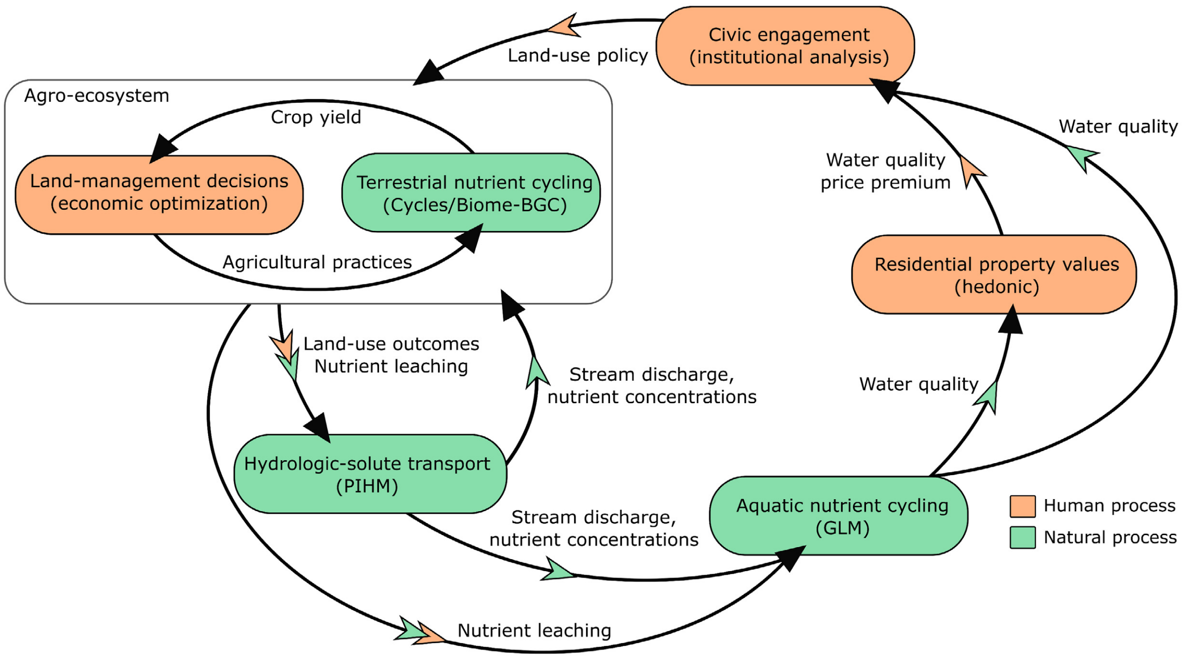

Fig. 3. Coupled natural–human systems components and models (ovals) and the data flows that form coupling linkages (arrows).

land-management decisions influence soil layer mixing and aggregation (and ultimately lake water quality) on a daily scale. This involves passing a set of annual land-management decisions to Cycles to be used as input to simulate associated nutrient dynamics at the daily time step. For example, given simulated fertilizer applications, Cycles generates daily predictions of nitrate leaching from farms in different areas of the catchment.

To simulate hydrodynamics in a watershed, PIHM and Cycles are coupled automatically and sequentially for each mesh grid cell and at a fine scale using the platform C-PIHM. Within C-PIHM, PIHM uses as input nutrient budgets from Cycles to simulate solute transport from terrestrial activities through the catchment's hydrologic system. Output data from PIHM include a water budget for a given time step, which is used by Cycles to simulate biophysical, biogeochemical, and agronomic processes within the terrestrial area of the catchment. Cycles uses these water budgets as boundary conditions for simulating nutrient budgets, redistributing water in the vertical soil column and calculating vapor flux via the soil surface, transpiration, or residue drying. Biome-BGC is similarly linked with the hydrologic-solute transport model to represent these processes in forested areas of the catchment.

Water budgets produced by PIHM also provide the main driver data forcing GLM, creating a coupling that tracks spatial and temporal variation in catchment water storage and fluxes with lake hydrodynamics. These data flows include spatial water storage (e.g., soil moisture) and water fluxes (e.g., stream discharge) across mesh cells at time intervals summarized from minutes to years; water temperatures; and nutrient concentrations in stream discharge into the lake. The primary challenge for coupling PIHM, a three-dimensional hydrological model, to GLM, a one-dimensional lake model, is spatial and temporal aggregation. The PIHM outputs include spatially explicit time series of discharge, water temperatures, and nutrient concentrations for all mesh cells. General Lake Model, like most water quality models, requires water flowing into the lake from the catchment in discrete inflows and at a daily time step, necessitating multiple levels of aggregation (e.g., summing all overland flow into one inflow).

Changes in water quality simulated by GLM drive changes in housing values in communities surrounding lakes, which are captured by the linkage between GLM and the hedonic model. Though the relationship between water quality and housing values is well known, the primary challenge for the hedonic analysis is to identify statistically which water quality variables are observed by homebuyers and incorporated into property values. General Lake Model produces >100 water quality outputs, many of which are unlikely observed or considered by people when purchasing homes (e.g., zooplankton density). Similarly, homebuyers are unlikely to incorporate sub-daily variation in water quality into their decisions. To transform output from GLM into variables that homeowners respond to, we aggregate to a daily, seasonal, or annual time step to create input data for the hedonic model. Examples of variables that may influence home purchasing decisions include those that influence or measure water clarity (light extinction coefficient/Secchi disk depth, turbidity, suspended solids), development of anoxia (dissolved oxygen concentrations), and the development of cyanobacterial blooms (chlorophyll *a* and total phosphorus concentrations).

The trends in property values and lake water quality described by the hedonic model and GLM are often imbedded within the historical knowledge that forms the basis for the institutional analysis. Examining these relationships, which may be either contemporaneous or lagged, involves extracting simulated time series for water quality and property values from the hedonic model and GLM to examine the correspondence between these data and the perceptions, observations, and responses by lake associations, as manifest in the historical record of lake association documents. Access to a time series of records is critical in understanding this linkage in the CNHS, as the effect of changes in freshwater systems on human systems is often evident on a time scale greater than a decade (Kandasamy et al. 2014). Stakeholder interviews, which supplement the time series of written records, provide additional historical knowledge to support understanding of how civic engagement has shaped, and been shaped by, human behavior and water quality in each lake catchment over time.

The institutional analysis generates output that highlights local knowledge about effective strategies tied to successful environmental initiatives by the lake association, its collaborators, and its communications. In tracking lake associations' efforts, we can identify when, where, and the nature by which they leverage their effort to influence water quality. For example, the Lake Sunapee Protective Association regularly meets with local towns to adjust ordinances that benefit water quality (e.g., zoning and the adoption of vegetation buffers around the lake), and the Clean Lakes Alliance works with farmers to implement cover cropping and conservation tillage practices to reduce phosphorus loads. We use this information to generate policy and behavioral scenarios grounded in the real world, and which form a feedback into the CNHS cycle of Fig. 1. Thus, the final CNHS linkage is the role of lake associations in shaping land use and land-management practices that provide input to the economic optimization model, Cycles, and Biome-BGC. These scenarios may be implemented for a year or longer and over a subset of the catchment or its entirety.

Extending the Conceptual Framework

An important challenge for our framework is assessing its potential for understanding dynamics in a larger set of lake-catchment CNHS. Our focal lake catchments are illustrative case studies, but it is unclear how representative they are within their respective regions, which collectively include thousands of lakes. At the spatial and temporal scales in which we study these systems, we emphasize the richness of the data, as well as the richness of the human and natural systems' interactions. As a result, the CNHS modeling approach we propose does not scale well to catchments that do not have the requisite data. Rather, we have chosen the highly contrasting focal systems of Mendota, Oneida, and Sunapee to not only test the robustness of the approach in a diversity of systems, but to better understand how CNHS components affect and feed back to each other and to identify and understand system-level emergent properties. From these details, we can determine the essential characteristics that help us simplify and generalize our approach to a broader set of lake catchments.

Generalizable insight into broad patterns in CNHS drivers and behavior in freshwater lakes can be developed using the linkages in Fig. 3 to extract the variables that most significantly influence each model coupling. Insights into how specific inputs and outcomes vary across lakes can be investigated by conducting sensitivity analyses. For example, by perturbing the economic optimization model and propagating the resulting output through Cycles, it is possible to identify which of the variables or parameters in the former generate the greatest changes in the outcome variables of the latter. Similar such analyses can be conducted for each model coupling linkage in Fig. 3, combining the most critical variables or parameters into a subset of factors that potentially exert the greatest influence on CNHS behavior.

We can describe these critical factors for a set of comparable lakes for which we do not have detailed data available to model the CNHS as we do for our focal systems. To extrapolate to other systems, we identified a dataset of candidate lake systems using the LAGOS-NE database, which includes all 49,000 lakes greater than or equal to 4 ha in size within an area consisting of 17 states in the United States (Soranno et al. 2015). This database draws on diverse data resources to describe the lake water quality and geospatial characteristics that support simplification and generalization of our CNHS modeling. In particular, LAGOS-NE draws on the efforts of groups such as GLEON, lake associations, managers, citizen volunteers, and scientists, which have begun to generate and share data in order to better understand lake ecosystems (Marcé et al. 2016, Smyth et al. 2016). For example, volunteer citizen monitoring efforts, often administered through state agencies, have generated water quality data for thousands of lakes for decades (Lottig et al. 2014, Soranno et al. 2015). By applying statistical models to these data and differing configurations of extrapolation datasets, we can extend our detailed CNHS modeling effort from our focal lake catchments to identify the extent to which similar conclusions apply to other catchments. Future analysis can thus build on our conceptual–empirical framework to extract a parsimonious set of variables that support the study of lake systems more broadly than a data-rich CNHS modeling approach.

Discussion and Future Research Directions

Here we present an innovative framework for understanding and modeling human interactions and responses within the dynamic natural environment of freshwater lake catchments. Importantly, we propose a mechanism to close the feedback loop between human and natural system models, capturing the reflexive human response that is widely recognized as important in these systems, yet remains critically understudied in the scientific literature. We propose a methodology to instantiate the complete feedback loop that fundamentally defines CNHS modeling by linking a series of disciplinary models that capture key processes within lake catchments. Our approach has the flexibility to incorporate additional CNHS components and alternative disciplinary models to represent those components.

Using coupled models and their feedbacks to visualize lake response to social and natural system drivers can be a powerful tool to influence decision-making in order to maintain and improve lake water quality. For example, lake water quality is likely to be affected by future physical, chemical, and biological perturbations, such as an increased frequency and intensity of storm events, changes in land use, groundwater drawdown, or invasive species introductions. The ability to visualize how these perturbations propagate throughout the catchment and within the lake will assist scientists and lake associations in co-developing strategies for outreach and education initiatives as well as highlight future research needs and perhaps even inspire revisions of lake association missions. Further, participatory modeling is one tool that can be used to explore potential outcomes and help stakeholders develop their preferences into social values for ways to manage and adapt to environmental change.

As with all models, and especially with coupled models, one of the most important outcomes is understanding what we do not know about systems, or system interactions, and which data and information are most critical for refining the model. This extends to the identification of the emergent properties of systems as well as the strength, magnitude, and direction of feedbacks. For example, as land is converted from native vegetation to agriculture, the impact per unit area in the catchment is reflected in lake nutrient loading as a trend with a long, gradual time scale. Over time, this trend may reach a nutrient threshold where much more serious effects emerge in the lake (Collins et al. 2011). By understanding the often non-linear spatial and temporal dynamics of the drivers that result in the greatest responses, whether human or natural, it is possible to identify policy and management actions that are most likely to result in desired ecological changes (Pouyat et al. 2010).

In developing and presenting our conceptual framework and its mapping into practice, our primary objective is to advance cross-disciplinary dialogue about how to move CNHS lake-catchment modeling toward a systematic body of work that forms a solid foundation for decision-making and policy. Developing this understanding requires determining the features of lake-catchment CNHS that arise from the fundamental connections between critical system components. In this study, we model a particular set of human and natural systems, but there are biophysical and social system components that we have not explicitly modeled in this framework that may prove important to understanding the dynamics of lake-catchment CNHS. Even so, our framework provides an extendable foundation to advance scientific understanding of CNHS with specific insights for lake catchments. Furthermore, we provide an integrated framework where the critical variables linking system components provide crucial insight to advance lake management efforts to protect and improve water quality. In these ways, we advance the fundamental understanding of a natural resource that is foundational to healthy aquatic ecosystems and human well-being.

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