Cover

Federal Agency and Organization Element to Which Report is Submitted:

4900

Federal Grant or Other Identifying Number Assigned by Agency:

1517823

Project Title:

CNH-L: Linking Land-Use Decision Making, Water Quality, and Lake Associations to Understand Human-Natural Feedbacks in Lake Catchments

PD/PI Name:

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- **Kevin J Boyle, Co-Principal Investigator**
- **Cayelan C Carey, Co-Principal Investigator**
- **Christopher J Duffy, Co-Principal Investigator**
- **Paul C Hanson, Co-Principal Investigator**

Recipient Organization:

Virginia Polytechnic Institute and State University

Project/Grant Period:

01/01/2016 - 12/31/2018

Reporting Period:

01/01/2017 - 12/31/2017

Submitting Official (if other than PD\PI):

- **Kelly Cobourn**
- **Principal Investigator**

Submission Date:

12/31/2017

Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)

Kelly Cobourn

Accomplishments

* What are the major goals of the project?

The overarching goals of this project with respect to intellectual merit are to:

1. Understand how human land-use decisions alter nutrient fluxes through lake ecosystems;
2. Represent the consequences of those nutrient fluxes as changes in lake water quality attributes that are meaningful to people;
3. Determine how changes in water quality affect human systems by altering property values and by motivating citizen engagement in lake associations;
4. Scale in-depth coupled natural-human systems (CNHS) modeling results for focal lake catchments to understand natural-human system feedbacks at a sub-continental scale.

In terms of broader impacts, the project's overarching goals are to:

1. Engage lake associations in CNHS modeling of focal lake catchments to support science-based monitoring, advocacy, and volunteerism;
2. Provide integrative, interdisciplinary graduate education to cultivate the next generation of CNHS researchers focused on freshwater issues.

* What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

Major Activities:

Team meetings and workshops.

The all-hands CNH project Year 2 workshop was held from May 30th to June 2nd at the University of Wisconsin, Madison, WI. The workshop was designed as a platform for team building across disciplines and institutions. The workshop included breakout group brainstorming sessions to develop cross-disciplinary research and outreach products. Representatives from the Clean Lakes Alliance attended and provided input on how the project could support their mission and activities. Team discussion focused on identifying essential management variables (EMVs) that form the linkages between disciplinary CNHS models and the generalizable foundation for scaling up efforts.

A workshop titled “Modeling Lakes and Reservoirs with GLM-AED” was designed and led by project personnel from January 9th to 12th. Participants in the workshop gained in-depth understanding of GLM parameters, developed a workflow for calibrating the model, and calibrated a model for three prototypical lakes.

Cross-cutting manuscript development.

A team-wide manuscript is in preparation for submission as an Innovative Framework contribution to *Ecosphere*. The manuscript translates a high-level, abstract representation of CNHS into a pragmatic approach to study feedbacks in lake catchments. The manuscript contextualizes our project and establishes a foundation for future CNHS research. Postdoctoral researchers and graduate students supported by the project are developing a review of the CNHS literature that focuses on freshwater systems. Weathers (co-PI) is facilitating collaborative manuscript development across early career researchers in different disciplines and institutions. The manuscript has been pre-screened for submission to *Ambio*.

Education and outreach.

To build relationships with our lake association partners, graduate student Fitchett spent a month in summer 2017 housed at the Lake Sunapee Protective Association (LSPA). She acted as a participant observer during association activities, gathering preliminary information for the social science portion of this project. Project personnel (PI Carey, Co-PI Weathers, graduate student Ward, postdoc Farrell) attended the LSPA annual meeting in July to present research results and solicit feedback on CNHS modeling scenarios.

PI Carey led development of education modules for undergraduates, which were delivered as two day long workshops at Virginia Tech on GLM lake ecology modeling. In the first workshop (Oct. 2017), PI Carey and graduate student Ward taught students how to set up a lake model and manipulate driver data to examine how climate may affect lake thermal stratification. In the second workshop (Nov. 2017), student teams manipulated nutrient loads and air temperature in models of Lake Mendota, WI or Lake Sunapee, NH to study how land-use change and climate may interact to affect algal blooms. Teaching materials are available on the macrosystemseddie.org website for other instructors, and are currently being assessed through PI Carey's partnership with the Science Education Resources Center (SERC; serc.carleton.edu) and will be disseminated through GLEON (Global Lakes Ecological Observatory Network; gleon.org).

Project management and communication.

We continued developing the project's wiki-based task management system, project administration, and manuscript development/tracking through the ODS platform (http://www.organicdatascience.org/cnh). The site serves a dual role as an interface with the public by providing open access to information about project activities, models, and team members.

The team collaboratively refined and adapted a project authorship policy to support co-authorship across disciplines. The policy incorporates new understanding about diverse manuscript leadership styles and manuscript types, and is published on the ODS site.

PI Cobourn hired new postgraduate project manager Henson in Nov. 2017. Henson is developing a strategy for increased communication with public audiences via the project website (www.cnhlakes.frec.vt.edu) and twitter feed (@CNHLakes).

Specific Objectives:

Completion and ongoing development of CNHS models.

Year 2 saw completion of numerous CNHS component models for focal lake catchments. Completed work includes: agronomic/soil science modeling (Cycles) for Lake Mendota; economic decision-making modeling (SDP) for Lake Mendota; hydrological fate-transport modeling (PIHM) for Lake Mendota and Lake Sunapee; limnological (GLM) modeling for Lake Mendota and Lake Sunapee; and hedonic property value modeling for Lake Mendota. Models in development include: Cycles modeling online interface that allows users to input parameters and run their own Cycles model; GLM modeling with invasive species modules

for Lake Oneida; data collection and analysis of lake association documents for civic engagement analysis; statistical data mining techniques for scaling up using LAGOS database, with exploration of the relationship between lake nutrient/phosphorus retention and lake connectivity.

Development of linkages between CNHS component models.

In year 2, we developed a workflow to couple: Cycles and SDP for Lake Mendota with a two-way feedback linkage; a 30-year PIHM and GLM model for Lake Mendota; GLM and hedonic property value models for Lake Mendota using observational data; and a qualitative linkage between the civic engagement analysis and SDP using lake association land-use scenarios.

Significant Results:

Agro-economic modeling for the Lake Mendota catchment.

Our work on coupling Cycles and SDP models indicates that a command-and-control policy aiming at overall reduction in nitrogen fertilizer usage at the catchment level may not lead to a decrease in overall nitrate leaching into the lake. Though nitrogen fertilizer use decreases under the policy, the environmental effect is ambiguous and depends on how farmers alter their land allocation among crops in response to the policy.

Coupled hydrologic-limnologic modeling.
A 30+ year simulation of Lake Mendota water quality includes nutrient loads and water balance provided by PIHM catchment models and USGS nutrient observational data. The two models, PIHM and GLM-AED, have been coupled, and we are in the process of quality checking the data and calibrating the lake water quality model. A manuscript describing the details of the model coupling and its application toward long-term oxygen dynamics is in development for submission to a special issue of *Limnology and Oceanography*.
Feedbacks from lake water quality to property values.

To understand how lake water quality influences human systems, we created a coupling between the GLM and hedonic property value models for Lake Mendota. This coupling allows us to examine correlations between various metrics describing water quality changes and surrounding property values. During Year 2, we completed an initial coupling analysis using observed water quality data for Lake Mendota. The results indicate that water quality improvements, measured by Secchi depth and concentration of chlorophyll a, could yield significant benefits to waterfront homeowners. For example, we find that a 9.19% increase in Secchi depth is associated, on average, with a 14.7% increase in home price to waterfront homeowners.

Lake connectivity and nutrient loading.

Another notable result from year 2 comes from our efforts to leverage large data through LAGOS to understand nutrient loading in freshwater lakes. Statistical analysis suggests that connectivity between lakes explains some of the variation in the relationship between phosphorus retention and water residence time. A key parameter in the well-known Vollenweider equation for phosphorus loading (k, the bulk-loss coefficient) is statistically

related to lake connectivity. This result supports scaling up of the CNHS analysis by identifying the key role that connectivity plays in explaining phosphorus dynamics across a broad set of lakes.

Key outcomes or Other achievements:

Component model development and calibration.

During year 2, we made significant progress on development and calibration of a number of our component models. Cycles, SDP, PIHM, GLM, and the hedonic models are fully calibrated and operational for Mendota. PIHM and GLM are calibrated and operational for Sunapee (there is no Cycles/SDP component for the Sunapee catchment, which has negligible agriculture). The hedonic model is in development for Oneida and Sunapee. Scaling up and extrapolation based on land-use and water quality characteristics is in progress. Civic engagement with institutional analysis of lake associations is also in progress for Mendota, Oneida, and Sunapee.

Workflow for fully coupled CNHS model.

Figure 1 illustrates the complete workflow linking all human and natural systems models in the project. Data flows are indicated by arrows. Input and output data for each model are included in Table 1, where boldface type indicates essential management variables (EMVs), which for the basis for linking model components.

* What opportunities for training and professional development has the project provided?

In year 2, the project supported 19 total undergraduates, graduate students (M.S. and Ph.D.), postdoctoral researchers, and research associates/technicians.

Through the year 2 workshop and monthly teleconferences, the project has created an opportunity for graduate students to gain exposure to a wide range of modeling approaches (statistical, process-based, qualitative) that are not available in their home department/institution. Graduate students are collaborating on multidisciplinary elements of the project and developing disciplinary and interdisciplinary journal articles under the guidance of faculty mentors. They are also being mentored on the process of working in a multidisciplinary team environment, and the project has provided new training on how economists, hydrologists, soil scientists, and social scientists study lake catchments and human decision-making.

Through the project, these graduate students, postdocs, and technicians have had opportunities to build networking and presentation skills, learn new research methods, and develop their ability to use relevant software. Such opportunities include presenting research updates at monthly project-wide teleconferences, attending lake association partner gatherings, participating in limnological model (GLM) training and mentoring, and in some cases, presenting at international conferences. The Year 2 workshop included a poster session for project graduate students and research technicians to present their work. The poster session was attended by all project personnel, who discussed the research projects with students individually and provided feedback on site.

* How have the results been disseminated to communities of interest?

PIs Cobourn and Carey proposed a two-part track session on freshwater lake catchment CNHS for the 2018 annual meeting of the Universities Council on Water Resources (UCOWR), a multidisciplinary organization focused on outreach, education, and research. The track session includes a set of research presentations by project graduate students and a panel of senior project personnel who will discuss new directions and challenges in CNHS research. The session was proposed to UCOWR in year 2 and accepted as part of the conference program.

Co-PI Weathers delivered two talks to the LSPA, during which she shared information about the project's objectives and progress with members of the Lake Sunapee community. During this time, she also received feedback from the LSPA on the results and products that would be most helpful to the community.

The year 2 workshop involved engaging and disseminating project results to the Clean Lakes Alliance (CLA) in Madison, WI. Representatives from the CLA were invited to a special workshop session on co-PI Weathers and co-PI Sorice's work with the lake associations in each focal lake catchment. As part of that workshop, the CLA representatives learned of project results and provided feedback on the types of policies they advocate for in the Mendota watershed to improve lake water quality.

Graduate student Stachelek (working with co-PI Soranno) taught a workshop on the basics of geospatial analysis for research computing to a research audience at the Lawrence Berkeley National Laboratory on September 26, 2017. He also contributed to an interactive database of R package datasets on the Comprehensive R Archive Network (https://ropenscilabs.github.io/data-packages/), which is of broad interest to the scientific research community.

PI Carey's teaching materials have been disseminated to audiences of educators via the macrosystemseddie.org website and through GLEON (Global Lakes Ecological Observatory Network; gleon.org).

* What do you plan to do during the next reporting period to accomplish the goals?

Publishing and presenting results.
Once completed, the project's framework paper (led by PI Cobourn) will be submitted as an Innovative Viewpoints manuscript to the journal *Ecosphere* (anticipated submission January, 2018). A graduate student-led literature review of CNHS modeling of freshwater lakes (led by graduate student Ward) will be submitted as a Perspective manuscript to the journal *Ambio* (anticipated submission summer, 2018). Both of these articles have already been reviewed and received editorial permission for submission.
Four articles are currently in development on project research results. The first (led by graduate student Weng) couples limnological data on water quality with a hedonic model for Lake Mendota. This paper is currently in draft form and will be submitted in the second quarter of 2018. A journal article on a 30-year coupled PIHM-GLM simulation of Lake Mendota (led by co-PI Dugan) is slated

for submission to a special issue of *Limnology & Oceanography* in the first quarter of 2018. Another two manuscripts (led by co-PI Soranno) related to phosphorus dynamics in lakes will be submitted in 2018.

Graduate student Weng will complete and publish a dissertation that addresses the use of machine learning to evalutate the variables that connect water quality and property values, based on modeling of Lake Mendota and Lake Sunapee. Weng will also present the hedonic analysis at the World Cpngress of Environmental and Resource Economists. Weng, Ward, and graduate student Fitchett will present research results at the UCOWR meeting in 2018. PI Cobourn, co-PI Weathers, co-PI Kemanian, and co-PI Soranno will discuss future directions and challenges in CNHS research at an invited panel at the UCOWR meeting in 2018.

Data collection and analysis.

Co-PI Sorice and graduate student Fitchett will continue collecting and analyzing documents from the lake associations. They will also begin collecting interview data.

Model data will be posted and archived on the project's data repositories and will be passed between modeling teams to support model coupling. Research technician Henson will maintain these archived data and support coupling analysis through with versioning control and metadata documentation on GitHub.

Model development and calibration.

In year 3, we will complete calibration of PIHM for the Sunapee catchment. Co-PI Duffy plans to continue working on a simplified carbon model applicable to the Mendota and Sunapee catchments. Co-PI Hanson will continue to refine the GLM model for Mendota by investigating other potential components to include in the model. Project collaborator Rudstam will continue working on calibrating the GLM model of Oneida Lake, which includes incorporating the effects of invasive mussels on aquatic nutrient dynamics. Members of the PIHM and GLM teams will continue to refine the tight coupling between the two models for both Mendota and Sunapee.

The Cycles-SDP workflow will be expanded to consider a set of representative farmer types and landscape characteristics in the Mendota catchment. These models will be coupled to PIHM via the data flow illustrated in Figure 1. This workflow through Cycles-SDP-PIHM will be completed and agricultural/land-use policy scenarios will be propagated through the linkages.

The hedonic analysis will be expanded to include both observed water quality data and water quality data generated by GLM for Mendota and Sunapee. The goal is to determine whether the statistical signal that links changes in water quality with property values in each lake catchment is detectable in the modeled output of GLM, which is more comprehensive and covers a longer time span than available observational data. Machine learning techniques will be applied to determine which of the hundreds of water quality variables produced by GLM constitute the most powerful predictor variables in the hedonic model.

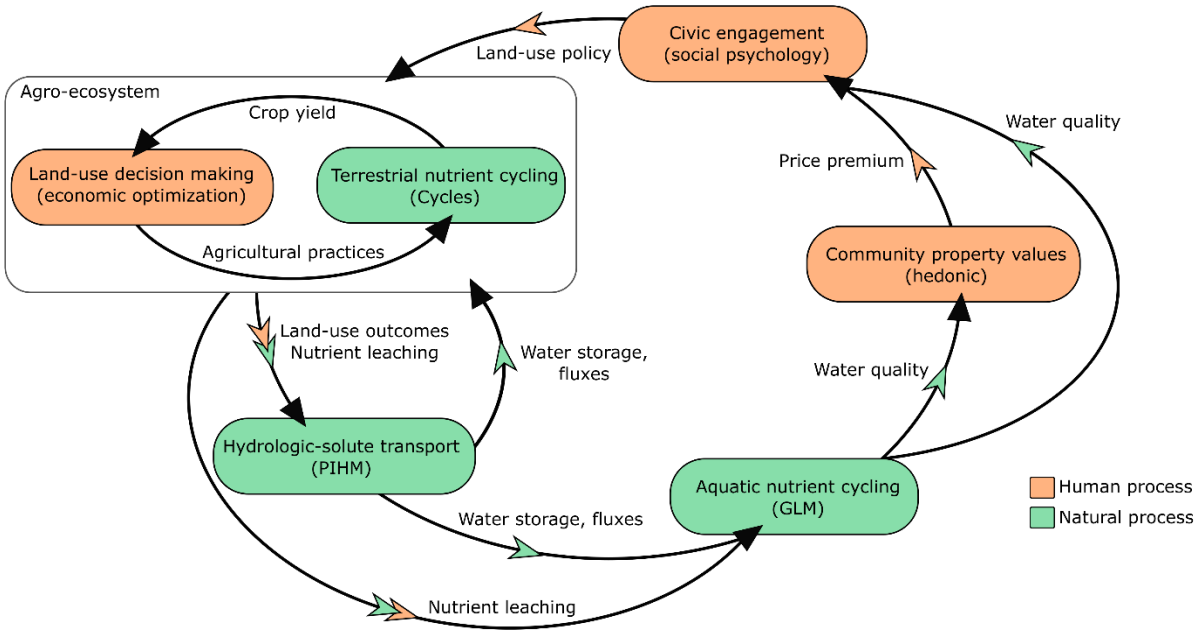

Figure 1. Figure 1 illustrates the coupling workflow between component models, with arrows indicating the flow of model data.

Table 1. CNHS components and model descriptions, including data flows and linkages among models

CNHS component	Model/approach	Resolution	Input data	Output data
(i) Land-use decisions	Economic optimization modeling	*Temporal*: annual *Spatial*: representative farm	– Crop prices – Costs of production – Production practices – **Crop yields** – **Land-use policy**	– **Land use** – **Ag. management practices** – Profit
(ii) Terrestrial nutrient cycling	Cycles	*Temporal*: daily *Spatial*: representative unit *Depth*: XXXm intervals	– Soil characteristics – **Ag. management practices** – **Land use** – **Spatial water storage, fluxes**	– **Nutrient leaching** – **Crop yields**
(iii) Hydrologic-solute transport	Pennsylvania Integrated Hydrologic Model (PIHM)	*Temporal*: minute *Spatial*: mesh grid cell (~100m)	– Soil characteristics – Geology – Topography – **Land use**	– **Spatial water storage, fluxes**
(iv) Aquatic nutrient cycling	Generalized Lake Model (GLM)	*Temporal*: minute *Spatial*: lake *Depth*: 0.05-0.5m intervals	– **Spatial water storage, fluxes** – **Nutrient leaching**	– Thermal regime – Nutrient cycling – **Water clarity** – **Phytoplankton blooms** – **Anoxia** – Water, energy, nutrient budgets
(v) Community property values	Hedonic property value model	*Temporal*: multi-year *Spatial*: catchment	– Home sale prices – Home characteristics, location – **Water clarity** – **Phytoplankton blooms** – **Anoxia**	– **Water quality price premium**
(vi) Civic engagement	Institutional analysis	*Temporal*: multi-year *Spatial*: catchment	– **Water clarity** – **Phytoplankton blooms** – **Anoxia** – **Water quality price premium** – Lake association documents – Stakeholder interviews	– Lake association mission, engagement, outcomes – Organizational effectiveness, capacity – **Land-use policy**

Notes: Input/output data listed are representative, not comprehensive. Variables in boldface type form coupling linkages between CNHS components and models.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers

- Bruce, L. C., M. A. Frassl, G. B. Arhonditsis, G. Gal, D. P. Hamilton, P. C. Hanson, A. L. Hetherington, J. M. Melack, J. S. Read, K. Rinke, A. Rigosi, D. Trolle, L. Winslow, R. Adrian, A. I. Ayala, S. A. Bocaniov, B. Boehrer, C. Boon, J. D. Brookes, T. Bueche, B. D. Busch, D. Copetti, A. Cortés, E. d. Eyto, J. A. Elliott, N. Gallina, Y. Gilboa, N. Guyennon, L. Huang, O. Kerimoglu, J. D. Lenters, S. MacIntyre, V. Makler-Picka, C. G. McBride, S. Moreira, D. Özkundakci, M. Pilotti, F. J. Rued, J. A. Rusak, N. R. Samal, M. Schmid, T. Shatwell, C. Snorthheim, F. Soulignac, G. Valerio, L. v. d. Linden, M. Vetter, B. Vinçon-Leite, J. Wang, M. Weber, C. Wickramaratne, R. I. Woolway, H. Yao, and M. R. Hipsey. A multi-lake comparative analysis of the General Lake Model (GLM): Stress-testing across a global observatory network. *Environmental Modelling & Software*. Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes
- Carey, C.C., B.L. Brown, and K.L. Cottingham. (2017). Cyanobacterial blooms increase the stability and network complexity of phytoplankton communities. *Ecosphere*. 8 (7). Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1002/ecs2.1830
- Carey, C.C., J.P. Doubek, R.P. McClure, and P.C. Hanson. (). Oxygen dynamics control the burial of organic carbon in a eutrophic reservoir. *Limnology and Oceanography-Letters*. Status = ACCEPTED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1002/lol2.10057
- Carey, C.C., R.P. McClure, J.P. Doubek, M.E. Lofton, N.K. Ward, and D. Scott. Chaoborus spp. transport CH4 from the sediments to the surface waters of a eutrophic reservoir, but their contribution to water column CH4 concentrations and diffusive efflux is minor.. *Environmental Science & Technology*. Status = UNDER_REVIEW; Acknowledgment of Federal Support = No; Peer Reviewed = Yes
- Doubek, J.P., and C.C. Carey. (2017). Catchment, morphometric, and water quality characteristics differ between reservoirs and naturally formed lakes on a latitudinal gradient in the conterminous United States. *Inland Waters*. 7. Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1080/20442041.2017.1293317
- Doubek, J.P., M. Lavender, A.K. Winegardner, M. Beaulieu, P.T. Kelly, C.C. Carey, A.I. Pollard, D. Straile, and J.D. Stockwell. Increased reservoir discharge is related to decreased zooplankton density across the continental United States. *Freshwater Science*. Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes

- Duffy, C.J., H.A. Dugan, and P.C. Hanson. The age of water and carbon in lake catchments: a simple dynamical model. *Limnology and Oceanography-Letters*. Status = UNDER_REVIEW; Acknowledgment of Federal Support = No; Peer Reviewed = Yes
- Hart, J.A., H.A. Dugan, C.C. Carey, E.H. Stanley, and P.C. Hanson. Mineralization of autochthony enhances CO2 and CH4 emissions from a eutrophic lake.. *Limnology and Oceanography*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes
- Hetherington, A.L., A.S. Zhao, J.M. Hunn, R.L. Schneider, C.C. Carey, and L.G. Rudstam. Comparison of clearance rates of zebra (Dreissena polymorpha) and quagga (Dreissena rostriformis bugensis) mussels across a wide range of lake temperatures. *Aquatic Ecology*. Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes
- Hollister J., and J. Stachelek. (2017). lakemorpho: Calculating lake morphometry metrics in R. *F1000Research*. Status = PUBLISHED; Acknowledgment of Federal Support = No; Peer Reviewed = Yes; DOI: 10.12688/f1000research.12512.1
- Ji, X., and K.M. Cobourn. The Economic Benefits of Irrigation Districts under Prior Appropriation Doctrine: An Econometric Analysis of Agricultural Land-allocation Decisions. *Canadian Journal of Agricultural Economics*. Status = ACCEPTED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1111/cjag.12165
- Nicolas P. Rougier, Konrad Hinsen, Frédéric Alexandre, Thomas Arildsen, Lorena Barba, Fabien C. Y. Benureau, C. Titus Brown, Pierre de Buyl, Ozan Caglayan, Andrew P. Davison, Marc André Delsuc, Georgios Detorakis, Alexandra K. Diem, Damien Drix, Pierre Enel, Benoît Girard, Olivia Guest, Matt G. Hall, Rafael Neto Henriques, Xavier Hinaut, Kamil S Jaron, Mehdi Khamassi, Almar Klein, Tiina Manninen, Pietro Marchesi, Dan McGlinn, Christoph Metzner, Owen L. Petchey, Hans Ekkehard Plesser, Timothée Poisot, Karthik Ram, Yoav Ram, Etienne Roesch, Cyrille Rossant, Vahid Rostami, Aaron Shifman, Joseph Stachelek, Marcel Stimberg, Frank Stollmeier, Federico Vaggi, Guillaume Viejo, Julien Vitay, Anya Vostinar, Roman Yurchak, Tiziano Zito (2017). Sustainable computational science: the ReScience initiative. *PeerJ*. Status = PUBLISHED; Acknowledgment of Federal Support = No; Peer Reviewed = Yes; OTHER: arxiv.org/abs/1707.04393
- Read E.K., L. Carr, L. De Cicco, H.A. Dugan, P.C. Hanson, J.A. Hart, J. Kreft, J.S. Read, L.A. Winslow (2017). Water quality data for national-scale limnological research. *Water Resources Research*. Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1002/2016WR019993
- Richardson, D. C., S. J. Melles, R. M. Pilla, A. L. Hetherington, L. B. Knoll, C. E. Williamson, B. M. Kraemer, J. R. Jackson, E. C. Long, K. Moore, L. G. Rudstam, J. A. Rusak, J. E. Saros, S. Sharma, K. E. Strock, K. C. Weathers, and C. R. Wigdahl-Perry. (2017). Transparency, geomorphology and mixing regime explain variability in trends in lake temperature and stratification across northeastern North America (1975–2014). *Water*. 442. Status = PUBLISHED; Acknowledgment of Federal Support = No; Peer Reviewed = Yes; DOI: 10.3390/w9060442
- Snortheim, C.A., P.C. Hanson, K.D. McMahon, J.S. Read, C.C. Carey, and H.A. Dugan. (2017). Meteorological drivers of hypolimnetic anoxia in a eutrophic, north temperate lake. *Ecological Modelling*. 343. Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1016/j.ecolmodel.2016.10.014

- Stachelek, J., C. Ford, D. Kincaid, K.King, H. Miller, and R. Nagelkirk. (2017). The National Eutrophication Survey: lake characteristics and historical nutrient concentrations. *Earth Syst. Sci. Data Discuss.* Status = PUBLISHED; Acknowledgment of Federal Support = No; Peer Reviewed = Yes; DOI: 10.5194/essd-2017-52
- Subratie, K., S. Aditya, R. Figueiredo, C.C. Carey, and P.C. Hanson. (2017). GRAPLEr: A distributed collaborative environment for lake ecosystem modeling that integrates overlay networks, high-throughput computing, and web services. *Concurrency and Computation: Practice and Experience*. 29 (13). Status = PUBLISHED; Acknowledgment of Federal Support = Yes; Peer Reviewed = Yes; DOI: 10.1002/cpe.4139

Licenses

Other Conference Presentations / Papers

- Hanson, P.C. (2017). *Crossing boundaries.*. Numerical modelling of lakes and reservoirs conference. Brisbane, Australia. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Stachelek, J., Soranno, P.A. (2017). *Does Connectivity Control Lake Phosphorus Retention?*. Global Lake Ecological Observatory Network Meeting. New Paltz, NY, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Weathers, K.C. (2017). *Ecological Puzzles and a Passion for Lakes: Cyanobacteria, sensors, citizens, and scientists.* University of Saskatchewan Workshop. Saskatoon, Canada. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Carey, C.C., A.L. Hetherington, R. Figueiredo, and P.C. Hanson (2016). *GRAPLE: GLEON research and PRAGMA lake expedition*. Global Lake Ecological Observatory Network (GLEON) 18 All-Hands and NETLAKE Meetings. Lunz and Gaming, Austria. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Ward, N.K., B. Steele, K.C. Weathers, K.L. Cottingham, H.A. Ewing, P.C. Hanson, R. Wood, J. Fichter, and C.C. Carey. (2017). *Identifying early warning indicators of eutrophication in an oligotrophic lake with messy data, ecosystem modeling, committed citizen scientists, and remote sensing to inform real-world management.* Ecological Society of America Conference. Portland, OR, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Ward, N.K., B. Steele, K.C. Weathers, K.L. Cottingham, H.A. Ewing, P.C. Hanson, R. Wood, J. Fichter, and C.C. Carey. (2017). *Identifying early warning indicators of eutrophication to inform real-world management: engaging long-term datasets, ecosystem modeling, committeed citizen scientists, and remote sensing.* 32nd PRAGMA Conference. Gainesville, FL, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Ward, N.K., B. Steele, K.C. Weathers, K.L. Cottingham, H.A. Ewing, P.C. Hanson, R. Wood, J. Fichter, and C.C. Carey. (2017). *Improving lake water quality with citizen scientists, high-frequency sensors, and ecosystem modeling.* Global Lake Ecological Observatory Network Meeting. New Paltz, NY, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Hanson, P.C. (2017). *Integrated catchment modeling for lake water quality.* Water@UW Conference. Madison, WI, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

- Hetherington, A.L., C.C. Carey, K.M. Cobourn, R.J. Figueiredo, and P.C. Hanson (2016). *Modeling effects of human decision-making on lakes in coupled human natural systems*. Global Lake Ecological Observatory Network (GLEON) 18 All-Hands and NETLAKE Meetings. Lunz and Gaming, Austria. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Carey, C.C., and N.K. Ward. (2017). *Overview to CNH-Lakes project, Sunapee modeling, and data.*. Lake Sunapee Protective Association (LSPA) Workshop. Sunapee, NH, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Carey, C.C., A.I. Krinos, K.J. Farrell, J. Sukumar, K. Subratie, A. Hetherington, P.C. Hanson, and R. Figueiredo. (2017). *Simulation modeling reveals non-linear lake water quality responses to climate and land use change.* Ecological Society of America Conference. Portland, OR, USA. Status = ACCEPTED; Acknowledgement of Federal Support = Yes
- Nowosad, J., Teucher A., Stachelek, J., Cotton, R., Vitolo, C. (2017). *The State of Data on CRAN: Discovering Good Data Packages.* rOpenSci Unconference. Los Angeles, CA, USA. Status = ACCEPTED; Acknowledgement of Federal Support = No
- Hanson, P.C., H.A. Dugan, and C.J. Duffy. (2017). *The age of water and carbon in lake catchments: a simple dynamical model.* Ecological Society of America Conference. Portland, OR, USA. Status = ACCEPTED; Acknowledgement of Federal Support = No

Other Products

- *Databases.*

  A searchable database of dataset metadata taken from R packages on CRAN. Citation: Nowosad, J., Teucher, A., Stachelek, J., Cotton, R., & Vitolo, C. (2017). The State Of Data On CRAN: Discovering Good Data Packages. Zenodo. http://doi.org/10.5281/zenodo.1095831

  Databases on http://cnhlakes.limnology.wisc.edu provide hourly resolution NLDAS climate data, water level data, and water quality observational datasets for Lake Mendota, Lake Sunapee, and Oneida Lake.

  The National Eutrophication Survey database is only available as portable document files (PDF) scanned from printed records with no embedded character information, which limits its searchability and the ability of current and future scientists to systematically evaluate its contents. To create a database, the authors use a combination of automated optical character recognition and manual quality assurance to make these data available for analysis.

  Citation: Stachelek J., Ford C., Kincaid D., King K., Miller H., Nagelkirk R. 2017. The National Eutrophication Survey: lake characteristics and historical nutrient concentrations. KNB Data Repository. http://doi.org/10.5063/F10G3H3Z

- *Software or Netware.*
  The purpose of `lakemorpho` is to provide a suite of tools that can be used to calculate basic lake morphometry metrics from an input SpatialPolygonsDataframe of a lake and a digital elevation model, as a RasterLayer, for the terrain surrounding that lake. These tools are being used to calculate lake morphometry metrics for all "lakepond" waterbodies in the NHDPlus V2. Citation:

Hollister, J., Stachelek, J. 2016. lakemorpho: Lake Morphometry Metrics in R. R package version 1.1.0. http://www.github.com/USEPA/lakemorpho

Other Publications

Patents

Technologies or Techniques

Thesis/Dissertations

- Hart, J.A.. *Greenhouse gas formation and organic carbon dynamics in a eutrophic lake.* (2017). University of Wisconsin, Madison. Acknowledgement of Federal Support = Yes
- Shu, L. *Impacts of urbanization and climate change on the hydrological cycle: a case study in modern and ancient land use change.* (2017). Penn State University. Acknowledgement of Federal Support = Yes
- Dodson, Laura. *Statistical Relationships Between Observational Water Quality and Catchment Agricultural Intensity in Rural Maine*. (2016). Virginia Tech. Acknowledgement of Federal Support = Yes

Websites

- *CNH Lakes Data Repository*
  http://cnhlakes.limnology.wisc.edu

  A website that archives metadata and datasets used by team members.

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Kelly Cobourn	PD/PI	4.0
Kevin Boyle	Co-PD/PI	1.0
Cayelan Carey	Co-PD/PI	4.0
Christopher Duffy	Co-PD/PI	1.0
Paul Hanson	Co-PD/PI	1.0
Armen Kemanian	Co-Investigator	1.0
Lars Rudstam	Co-Investigator	4.0
Patricia Soranno	Co-Investigator	1.0
Michael Sorice	Co-Investigator	1.0
Kathleen Weathers	Co-Investigator	2.5
Hilary Dugan	Postdoctoral	1.0
Kaitlin Farrell	Postdoctoral	2.0
Kristen Holeck	Other Professional	6.0
Virginia Henson	Technician	1.0
Christopher Hotaling	Technician	6.0
Bethel Steele	Technician	1.0
Charles White	Technician	1.0
Leah Fitchett	Graduate student	1.0
Julia Hart	Graduate student	1.0
Lele Shu	Graduate student	1.0
Joseph Stachelek	Graduate student	6.0
Nicole Ward	Graduate student	12.0
Weizhe Weng	Graduate student	12.0
Yu Zhang	Graduate student	1.0
Gabriella Alvarez	Undergraduate student	3.0
Sophie Hearn	Undergraduate student	3.0
Allyson Jones	Undergraduate student	3.0
Arianna Krinos	Undergraduate student	1.0
Amy Li	Undergraduate student	3.0
Aviah Stillman	Undergraduate student	1.0

Full details of individuals who have worked on the project:

Kelly Cobourn
Email: kellyc13@vt.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 4
Contribution to the Project: Project leadership, administration, SDP modeling, model coupling, scenario development and analysis.
Funding Support: n/a
International Collaboration: No
International Travel: No

Kevin J Boyle
Email: kjboyle@vt.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1
Contribution to the Project: Project leadership, hedonic model development, model coupling, scaling up, scenario development and analysis.
Funding Support: n/a
International Collaboration: No
International Travel: No

Cayelan C Carey
Email: cayelan@vt.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 4
Contribution to the Project: Project leadership, administration, GLM modeling (Mendota, Sunapee), model coupling, scenario development and analysis.
Funding Support: n/a
International Collaboration: No
International Travel: No

Christopher J Duffy
Email: cxd11@psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1
Contribution to the Project: PIHM modeling, model coupling, scenario development and analysis
Funding Support: n/a
International Collaboration: No
International Travel: No

Paul C Hanson
Email: pchanson@wisc.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1
Contribution to the Project: GLM modeling (Mendota), model coupling, scaling up, scenario development and analysis
Funding Support: n/a
International Collaboration: No
International Travel: No

Armen Kemanian
Email: akemanian@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Cycles modeling; model coupling, scenario development and analysis
Funding Support: n/a
International Collaboration: No
International Travel: No

Lars Rudstam
Email: rudstam@cornell.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 4
Contribution to the Project: GLM modeling (Oneida), broader impacts
Funding Support: Cornell University; Brown Endowment
International Collaboration: No
International Travel: No

Patricia Soranno
Email: soranno@anr.msu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1
Contribution to the Project: Scaling up and extrapolation
Funding Support: n/a
International Collaboration: No
International Travel: No

Michael Sorice
Email: msorice@vt.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1
Contribution to the Project: Civic engagement analysis, model coupling, scenario development and analysis, broader impacts
Funding Support: n/a
International Collaboration: No
International Travel: No

Kathleen Weathers
Email: weathersk@caryinstitute.org
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 3
Contribution to the Project: Scenario development and analysis, broader impacts
Funding Support: Cary Institute of Ecosystem Studies
International Collaboration: No
International Travel: No

Hilary Dugan
Email: hdugan@wisc.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 1
Contribution to the Project: GLM modeling (Mendota); model coupling
Funding Support: n/a
International Collaboration: No
International Travel: No

Kaitlin Farrell
Email: farrellk@vt.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 2
Contribution to the Project: GLM modeling (Mendota, Sunapee), model coupling, scenario development and analysis
Funding Support: n/a
International Collaboration: No
International Travel: No

Kristen Holeck
Email: kth1@cornell.edu
Most Senior Project Role: Other Professional
Nearest Person Month Worked: 6
Contribution to the Project: GLM modeling (Oneida)
Funding Support: Cornell University, Brown Endowment
International Collaboration: No
International Travel: No

Virginia Reilly Henson
Email: vrhenson@vt.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 1
Contribution to the Project: Project administration
Funding Support: n/a
International Collaboration: No
International Travel: No

Chris Hotaling
Email: cwh65@cornell.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 6
Contribution to the Project: GLM modeling (Oneida)

Funding Support: Cornell University, Brown Endowment; New York State Department of Environmental Conservation
International Collaboration: No
International Travel: No

Bethel Steele
Email: Steeleb@caryinstitute.org
Most Senior Project Role: Technician
Nearest Person Month Worked: 1
Contribution to the Project: GLM modeling (Sunapee)
Funding Support: Cary Institute of Ecosystem Studies
International Collaboration: No
International Travel: No

Charles White
Email: cmw29@psu.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 1
Contribution to the Project: Cycles modeling
Funding Support: n/a
International Collaboration: No
International Travel: No

Leah Fitchett
Email: leahfl2@vt.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1
Contribution to the Project: civic engagement analysis, broader impacts
Funding Support: n/a
International Collaboration: No
International Travel: No

Julia Hart
Email: jhart6@wisc.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1
Contribution to the Project: GLM modeling (Mendota)
Funding Support: n/a
International Collaboration: No
International Travel: No

Lele Shu
Email: lzs157@psu.edu

Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1
Contribution to the Project: PIHM modeling, model coupling
Funding Support: n/a
International Collaboration: No
International Travel: No

Joseph Stachelek
Email: stachel2@msu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6
Contribution to the Project: Scaling up and extrapolation
Funding Support: n/a
International Collaboration: No
International Travel: No

Nicole Ward
Email: nkward@vt.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12
Contribution to the Project: GLM modeling (Sunapee), civic engagement analysis, model coupling
Funding Support: n/a
International Collaboration: No
International Travel: No

Weizhe Weng
Email: weizhe11@vt.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12
Contribution to the Project: SDP modeling, hedonic modeling, model coupling
Funding Support: n/a
International Collaboration: No
International Travel: No

Yu Zhang
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Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1
Contribution to the Project: PIHM modeling, model coupling
Funding Support: n/a
International Collaboration: No
International Travel: No

Gabriella Alvarez
Email: gga8@cornell.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3
Contribution to the Project: GLM modeling (Oneida Lake)
Funding Support: Cornell University, Brown Endowment
International Collaboration: No
International Travel: No

Sophie Hearn
Email: sah326@cornell.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3
Contribution to the Project: GLM modeling (Oneida)
Funding Support: Cornell University, Brown Endowment
International Collaboration: No
International Travel: No

Allyson Jones
Email: asj44@cornell.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3
Contribution to the Project: GLM modeling (Oneida)
Funding Support: Cornell University, Brown Endowment
International Collaboration: No
International Travel: No

Arianna Krinos
Email: akrinos@vt.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1
Contribution to the Project: GLM modeling (Mendota, Sunapee)
Funding Support: n/a
International Collaboration: No
International Travel: No

Amy Li
Email: al974@cornell.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3
Contribution to the Project: GLM modeling (Oneida)
Funding Support: Cornell University, Brown Endowment

International Collaboration: No
International Travel: No

Aviah Stillman
Email: abstillman@wisc.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1
Contribution to the Project: GLM modeling (Mendota)
Funding Support: n/a
International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Cary Institute of Ecosystem Studies	Other Nonprofits	Millbrook, NY
Clean Lakes Alliance (CLA)	Other Nonprofits	Madison, WI
Cornell Biological Field Station	Academic Institution	Shackleton Point, NY
Environmental Data Initiative (EDI)	Other Organizations	Online
Lake Sunapee Protective Association (LSPA)	Other Nonprofits	Sunapee, NH
Oneida Lake Association (OLA)	Other Nonprofits	Syracuse, NY
Pacific Rim Application and Grid Middleware Assembly, PRAGMA	Other Organizations	Online
University of Wisconsin Extension Lakes	Academic Institution	Stevens Point, WI
Virginia Center for Housing Research	Academic Institution	Blacksburg, VA

Full details of organizations that have been involved as partners:

Cary Institute of Ecosystem Studies
Organization Type: Other Nonprofits
Organization Location: Millbrook, NY
Partner's Contribution to the Project:
Financial support
Facilities
Collaborative Research
More Detail on Partner and Contribution: Provided financial support and facilities for Kathleen Weathers (co-PI) and Bethel Steele (Technician). Supported collaboration between Bethel Steele (Technician) and project personnel.

Clean Lakes Alliance (CLA)

Organization Type: Other Nonprofits
Organization Location: Madison, WI
Partner's Contribution to the Project:
Other: Provision of data
More Detail on Partner and Contribution: Provided information and data about the history and mission of the lake association and access to archived lake association documents.

Cornell Biological Field Station
Organization Type: Academic Institution
Organization Location: Shackelton Point, NY
Partner's Contribution to the Project:
Financial support
Facilities
More Detail on Partner and Contribution: Finanial support and facilities for Lars Rudstam (co-I), 2 research technicians (Kristen Holeck and Chris Hotaling), and undergraduate student interns.

Environmental Data Initiative (EDI)
Organization Type: Other Organizations (foreign or domestic)
Organization Location: online
Partner's Contribution to the Project:
Collaborative Research
More Detail on Partner and Contribution: Provided data curation and archiving consultation.

Lake Sunapee Protective Association (LSPA)
Organization Type: Other Nonprofits
Organization Location: Sunapee, NH
Partner's Contribution to the Project:
Other: Provision of data
More Detail on Partner and Contribution: Provided information and data bout history and mission of the lake association and access to archived lake association documents.

Oneida Lake Association (OLA)
Organization Type: Other Nonprofits
Organization Location: Syracuse, NY
Partner's Contribution to the Project:
Other: Provision of data
More Detail on Partner and Contribution: Provided information and data about the history and mission of the lake association and access to archived lake association documents.

Pacific Rim Application and Grid Middleware Assembly, PRAGMA
Organization Type: Other Organizations (foreign or domestic)
Organization Location: online

Partner's Contribution to the Project:
In-Kind Support
More Detail on Partner and Contribution: Provided computing support for simulation scenarios.

University of Wisconsin Extension Lakes
Organization Type: Academic Institution
Organization Location: Stevens Point, WI
Partner's Contribution to the Project:
Other: Provision of data
More Detail on Partner and Contribution: Provided information and data about lake associations and similar organizations across the state and access to a database of lake association information and activities.

Virginia Center for Housing Research
Organization Type: Academic Institution
Organization Location: Blacksburg, VA
Partner's Contribution to the Project:
Other: Provision of data
More Detail on Partner and Contribution: Provided property sales data to support hedonic property valuation modeling.

What other collaborators or contacts have been involved?

Yolanda Gil, Information Sciences Institute, University of Southern California

Corinna Gries, Senior Scientist, University of Wisconsin-Madison, North Temperate Lakes Long-term Ecological Research (NTL LTER) database manager and EDI Principal Investigator

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The project's principal disciplines are economics, agronomy/soil science, hydrology, limnology, and social psychology. Disciplinary impacts to date in each field are as follows:

Economics.

By coupling the SDP model with Cycles, PIHM, and GLM we can improve understanding of how public policy affects human decision-making and environmental externalities. For example, we are developing an understanding of how policies targeting decision-making variables (e.g., fertilizer use) versus environmental externalities (e.g., nutrient leaching and lake water quality changes) affect human welfare. In addition, targeting different types of environmental externalities may either improve or worsen human welfare outcomes. For example, many policies (e.g., the Chesapeake Bay water quality trading program) use nutrient leaching as a proxy for water quality degradation. But the relationship between these two variables is not linear, which implies that there may be welfare losses associated with targeting the wrong environmental indicator. This study sheds light on how the choice of policy target influences policy outcomes and human well-being.

By linking lake ecosystem water quality models and hedonic economic models, we are improving our understanding of the limnological variables that affect property values around lakes. To our knowledge, this is the first time these two types of models have been coupled. Within the freshwater ecology research community, we generally have a common understanding of which water quality metrics likely matter the most to humans as ecosystem services (e.g., water transparency, algal blooms), but we are now able to actually test these hypotheses by coupling our lake model output with hedonic model output.

Agronomy/soil science and hydrology.

The C-PIHM model, which couples Cycles with PIHM, opens up new opportunities for tracking water and nutrients in agricultural watersheds. To the best of our knowledge, no model has accomplished a full coupling of the water and nitrogen cycling while routing water through the landscape. This project provides a perfect platform for the application of this model and its further expansion (e.g. P cycling modeling, in-stream processes, and coupling with CLM-Lakes). A prototype online version of C-PIHM is now in development, which increases access to these models for the scientific community in both fields.

Limnology.

This project is advancing freshwater ecology/limnology by integrating expertise from hydrology and economics into catchment science. Generally most limnologists think of the inflow streams into lakes in a rather simple way, focusing on surface water connections. In this project, we are using a highly spatially-resolved hydrology model to simulate both surface water tributaries, submerged groundwater, and over-land runoff into our focal lakes, which is greatly improving our ability to model

nutrient loading rates. To our knowledge, no existing model couples lakes with their surrounding catchments in this dynamic and spatially explicit way.

Social psychology.

This project offers insight into the formation and activities of lake associations with historical records at a temporal scale of decades to centuries. Our qualitative institutional analysis will inform an understanding of how human systems feed back to natural systems by driving institutional formation and behavioral change. The scientific literature has found that this type of feedback occurs over lengthy time scales, but few researchers have access to institutional records spanning greater than a century. As such, we are uniquely poised to provide insight into long-term insitutional evolution in CNHS.

What is the impact on other disciplines?

The study of CNHS is growing in prevalence within the scientific community, and has the potential to significantly advance our understanding of natural resource management. By documenting the process by which we have worked as a complex, multi-disciplinary team, we help to lay the groundwork for future CNH projects in similar fields and beyond. The methods we employ for project management, model coupling, and interdisciplinary collaboration may be useful to researchers in landscape ecology, oceanography, wildlife conservation, and more. The framework paper developed by the project team is one tool designed to speak to audiences across disciplines about how to practically model and develop insight into CNHS. Moving between process-based, statistical, and qualitative models that use differing spatial/temporal resolutions, methods, terminology, and conceptual approaches is a challenging endeavor. The results of our experiences in making these connections are likely to support CNHS teams working on a broad array of problems.

What is the impact on the development of human resources?

This project is heavily invested in the development of researchers with the expertise to study freshwater systems from a multidisciplinary perspective. To that end, the project is exposing established and early career professionals from disparate disciplines to concepts and modeling techniques from other disciplines, bridging the disciplinary gaps needed to understand CNHS dynamics and modeling methods. Hiring efforts across institutions include advertising to and recruiting a diverse pool of candidates. Additional human resources contributions are as follows:

Co-PI Sorice led a semester-long Independent Study course called “Social and Ecological Systems” with graduate students Fitchett and Ward.

PI Carey organized two day long workshops on GLM lake ecology modeling for undergraduates at Virginia Tech. Approximately n=20 students participated in both of workshops, which taught the students basic skills in programming in R, data manipulation, and visualization.

The project has now engaged 6 undergraduate interns across institutions and disciplines in the project's research activities and broader impacts.

PI Cobourn recently hired technician Henson, who is being trained and mentored in project management and methods to facilitate team collaboration. Cobourn and Henson have completed an Individual Mentoring Plan, and Henson has already begun training in professional skills workshops, such as meeting facilitation.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

Through the creation of databases and software, some of our work is contributing to other researchers' access to data and R packages.

What is the impact on technology transfer?

Nothing to report.

What is the impact on society beyond science and technology?

The results of this project so far offer preliminary implications for lake associations and the management of lake catchments. Primarily, they indicate that hydrological and limnological processes take place on a time scale much longer than the scale at which nearby residents see the effects of change in a lake, and that proactive efforts will be necessary to manage future impacts. As the project continues, it will offer more detailed and concrete recommendations for the management of lakes and catchments that can improve ecosystem services.

Changes/Problems

Changes in approach and reason for change

Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

The project lost postdoctoral research associate Hetherington, who had to depart unexpectedly due to personal reasons. Hetherington's three primary responsibilities were: GLM modeling (Mendota, Oneida) and project administration. We have filled the position with two individuals: postdoctoral research associate Farrell, who will continue work on GLM modeling for Mendota; and project technician Henson, who has taken over responsibility for project administration. Project collaborator Rudstam is leading ongoing efforts in the area of GLM modeling for Oneida.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.