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Generating community-built tools for data sharing and analysis in environmental networks

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Abstract

Rapid data growth in many environmental sectors has necessitated tools to manage and analyze these data. The development of tools often lags behind the proliferation of data, however, which may slow exploratory opportunities and scientific progress. The Global Lake Ecological Observatory Network (GLEON) collaborative model supports an efficient and comprehensive data–analysis–insight life cycle, including implementations of data quality control checks, statistical calculations/derivations, models, and data visualizations. These tools are community-built and openly shared. We discuss the network structure that enables tool development and a culture of sharing, leading to optimized output from limited resources. Specifically, data sharing and a flat collaborative structure encourage the development of tools that enable scientific insights from these data. Here we provide a cross-section of scientific advances derived from global-scale analyses in GLEON. We document enhancements to science capabilities made possible by the development of analytical tools and highlight opportunities to expand this framework to benefit other environmental networks.

Key words: community tools, GLEON, open science, open source

Introduction

Technological advances in environmental sensors are generating enormous volumes of publicly accessible data of increasing spatial coverage and temporal resolution (Porter et al. 2009). This data revolution can expand the scope and impact of the science when data are openly accessible (Reichman et al. 2011). The data obtained from these networks can also increase understanding of environmental phenomena and create new research opportunities (Hipsey et al. 2015). Greater volumes and complexity of these data have emphasized a potential bottleneck in computational literacy in science (Wilson 2006). A wide range of skills are necessary to successfully navigate these challenges and produce successful outcomes for the investments in new technology (Guimera et al. 2005, Wuchty et al. 2007, Cheruvelil et al. 2014).

To redefine scales of inquiry in response to this increase in available data, scientists must re-tool traditional analyses and expand collaborations to include diverse networks of people (Hampton et al. 2013, Soranno et al. 2015). Despite demonstrable advantages of this

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network approach to science (Johnson and Johnson 1991, Bennett et al. 2010, Cheruvelil et al. 2014), many disciplines are only beginning to use shared data resources (Reichman et al. 2011) and to adopt practices that promote open and transparent development and distribution of software tools.

The Global Lake Ecological Observatory Network (GLEON), created in 2005 (Weathers et al. 2013), "conducts innovative science by sharing and interpreting high resolution sensor data to understand, predict, and communicate the role and response of lakes in a changing global environment." Here, we detail examples of tools designed to pair with environmental data developed within this grassroots research network. We examine GLEON's approach to encourage data sharing and the development of open tools to assist with scientific understanding of lakes. Finally, we recommend that other environmental networks embody the core values that have supported this growth: diversity, flat collaborative structure, and transparent sharing. Through specific examples, we demonstrate how GLEON's values enhance the network community, research, data, and tools.

GLEON collaborative science innovations

Attracting and celebrating diversity

GLEON attracts and celebrates diversity in members and their scientific outputs. Membership at the time of this writing exceeds 500 individuals representing more than 50 countries (Rose et al. 2016) and includes a full spectrum of career stages ranging from undergraduate students to senior researchers/faculty, as well as citizen scientists and industry representatives. GLEON members bring diverse disciplinary training to the network from the fields of limnology, ecology, biology, climatology, hydrology, computer science, and information sciences (among others). The network's scientific outputs are similarly diverse, including a collection of software tools, teaching modules, and mobile applications (discussed later), in addition to more traditional research publications and data papers (Rose et al. 2016).

GLEON facilitates these diverse outcomes by organizing annual meetings across 6 continents and by implementing a meeting structure that supports sharing from all members of the organization in a variety of formats (e.g., meeting attendees can self-select to give "lightning" style talks on the topic of their choice during the GLEON Cool Things session; discussed later). GLEON provides an environment to encourage collaborative development, which largely relies on voluntary commitments by the membership. To initiate a culture of collaborative sharing and trust, central funding has supported meeting organization and covered some of the travel costs to bring members together (i.e., GLEON funding is used sparingly for salaries, infrastructure, or tool development). Funding is prioritized for students and early career scientists, who have been particularly productive with respect to curated data products, software, and research product development.

Grassroots science carried out by working groups

A collaborative "team science" approach to research within the network has produced important advances (Klug et al. 2012, Read et al. 2012, Solomon et al. 2013) and promoted inclusivity (Hanson 2007, Read et al. 2016). GLEON encourages practices such as clearly defining roles and responsibilities, establishing trusting relationships, peer-to-peer teaching, and an iterative approach to structuring meetings, which are key characteristics of productive interdisciplinary teams (Bennett et al. 2010, Cheruvelil et al. 2014).

In practice, team science in GLEON often begins with small-group discussions (Working Groups) around a research topic (e.g., aquatic metabolism, information technology; Weathers et al. 2013). GLEON's annual in-person meetings typically include formal meeting times for a few distinct Working Groups, with work shifting online (e.g., Skype meetings, email) between meetings. Targeted science outcomes are produced by teams whose membership may shift over time, usually including 5 to 20 active participants. In the early- to mid-term stages of the GLEON project lifecycle, Working Groups identify needs and seek out solutions by querying the community for additional data, recruiting participants with underrepresented expertise/skills, and encouraging development or enhancement of analytical tools/models to meet the needs of the specific project. Gaps between current GLEON capabilities and science needs are quickly converted into opportunities for training activities or future software development efforts.

A culture of transparency and member feedback

GLEON members build tools to fill gaps in common scientific workflows, and these tools are shared freely with other members and with scientists outside of the network (e.g., Cossu and Wells 2013, Kankaala et al. 2013). Although most peer-reviewed journals are not yet requiring data or analytical code to accompany publications (Morin et al. 2012, Joppa et al. 2013), GLEON has effectively increased both by stimulating a culture of open information exchange and sharing (e.g., Read et al. 2011,

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Table 1. GLEON tools created by members to address unique research questions or project goals. Although difficult to quantify at this time, our experience indicates that each of these tools is supporting many new projects intended for publication.

Research question/goal	Data used	Tool developed	Products
Improve the efficiency of data QA/QC	high-frequency sensor data	B3[1]	
Multi-lake comparisons of physical indices	high-frequency instrumented buoy data	Lake Analyzer[2] rLakeAnalyzer[2]	Read et al. 2011, 2012, Klug et al. 2012, Winslow et al. 2014b, Carey et al. 2015
Patterns in lake surface turbulence dynamics	high-frequency instrumented buoy data, meteorological observations	LakeHeatFluxAnalyzer[2]	Woolway et al. 2015
Lake metabolism patterns across a global distribution of lakes	high-frequency instrumented buoy data, meteorological observations	LakeMetabolizer[2]	Solomon et al. 2013, Rose et al. 2014, Dugan et al. 2016, Winslow et al. 2016
Climate change impacts on thermal structure of lakes	Meteorological data and lake metadata	GLM3, glmtools[4]/GLMr[2]	Hipsey et al. 2014, Read et al. 2014; classroom teaching modules
Water quality monitoring	digital imagery, data collection	LakeObserver iPhone/ Android app[5]	Citizen science and engagement
Real-time response of lakes to weather events	data stream from instrumented buoy	Lake Sunapee Protective Association buoy dashboard[6], NTL Lake Conditions Android app7	Citizen science and engagement

[1] https://www.lernz.co.nz/tools-and-resources/b3
[2] https://github.com/GLEON
[3] http://aed.see.uwa.edu.au/research/models/GLM/
[4] https://github.com/USGS-R/glmtools
[5] www.lakeobserver.org
[6] www.lakesunapee.org/live-buoy
[7] https://play.google.com/store/apps/details?id=lter.limnology.wisc.edu.lterlakeconditions

Winslow et al. 2016). The network's "ground rules" related to respect, collegiality, and member-driven research (www.gleon.org; see Operating Principles and Procedures) lead to successful data and analytical tool sharing. The willingness of members to share and work in open teams yields a culture of transparency.

Explicit feedback loops between Working Group projects and the broader network participants are a key element for individual projects and overall network success. GLEON has several forums designed to encourage transparency and inclusiveness in ongoing projects, which create an entry path for new participants and opportunities to provide feedback on project design or goals. These forums include Project Tracker (a web-hosted inventory of active projects in various stages of completion; discussed later), the Cool Things plenary sessions during "all-hands" meetings (a public forum for rapid idea sharing), the Working Groups (discussed later), and the Network Partnership Program (NPP; pairs new-to-GLEON members with members who have attended several meetings; Weathers et al. 2013). These elements are part of the GLEON process to create a transparent, open, and welcoming culture for diverse participants.

GLEON's community-built tools for environmental science

Creating a diverse portfolio of network science products

Diverse scientific project goals have produced a range of software tools and outreach opportunities (Table 1; Smyth et al. 2016). Sharing data from many member sites enable research questions on a global scope (Read et al. 2012, Solomon et al. 2013) and in key areas of lake ecosystem studies, including responses to disturbance and episodic events (Jennings et al. 2012, Klug et al. 2012). Each of these examples was supported by analytical code or a subsequently published concept (Read et al. 2011, Woolway et al. 2015, Winslow et al. 2016), providing attribution for these contributions (Costello 2009). Tool development efforts in the early stages of GLEON created successful prototypes of a data model and data access tools for high-frequency sensor data (Winslow et al. 2008). It became clear with time, however, that GLEON's small-scale information technology operation could not support the needs of a large international network. GLEON now leverages collaborations with the Data Observation Network for Earth (DataONE; https://www.dataone.org) and the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI; https://www.cuahsi.org) to close the data lifecycle. As a result of these partnerships, GLEON's software development has shifted away from infrastructure and toward building tools that support limnological research workflows.

In a thematic research network such as GLEON, tools that support common workflows of data collection, quality control, modeling, and analysis (Fig. 1) provide high value to research teams (Table 1). Dissemination of data analysis tools developed within GLEON has also been occurring through regional spin-off initiatives, such as the NETLAKE COST Action in Europe (www.netlake.org). In addition, several GLEON tools have found utility in outreach activities. The LakeObserver mobile app (https://www.lakeobserver.org/) helps citizen scientists contribute observations of algal blooms for use in research projects and lake management applications. Undergraduate and K-12 classrooms have leveraged Lake Analyzer and the General Lake Model (GLM; Hipsey et al. 2014) to explore limnological concepts in unique ways (see Project EDDIE; http://projecteddie.org/). All of these tools broaden the research portfolio of GLEON and create greater impacts with the general public.

Recognizing tool/software builders as partners

Integrating tool development with research provides deeper, often unintended gains for the network. GLEON's flat network structure supports many different types of leaders and contributors. Although researchers clearly know the needs of their discipline and are often encouraged to develop software and share tools, few have any formal training in software engineering (Wilson 2006, Joppa et al. 2013). For truly interdisciplinary collaborations to occur, technologists must be recognized as first-class citizens in the network, which allows many technological (software engineering, information management, sensor development) best practices to emerge in community-built tools.

Numerous interdisciplinary success stories have grown out of GLEON's flat, collaborative culture established within the network. Information managers, computer scientists, and ecologists collaborated to create a project management system for the network (the GLEON project tracking system: http://gleon.org/research/projects). Conversations between aquatic scientists, engineers, and private industry partners resulted in the development of new technologies that filled a specific sensor need (i.e., the PME MiniDOT logger: http://pme.com/products/minidot). Finally, GLEON Graduate Student Fellows learned version control, continuous integration, and other software development best practices through a series of workshops in 2013–2014 (http://fellowship.gleon.org/; Read et al. 2016). None of these outcomes would have been possible if the contributions from disciplines outside lake ecological science were not valued and encouraged.

Coevolution of tools and research questions

Research tools evolve in concert with the evolution of science questions. A number of project-specific solutions created in GLEON to address research questions were quickly shared or expanded into reuseable tools that provided greater benefit to the network. Solomon et al.

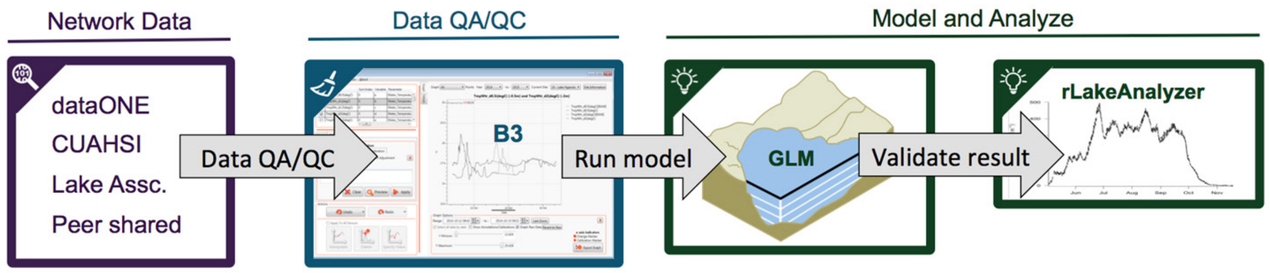

Fig. 1. A hypothetical workflow that leverages GLEON tools sensor data. B3 is a sensor QA/QC tool used to clean data that will then drive the GLM model. Results can be analyzed and compared to field observations with the rLakeAnalyzer tool.

(2013) assembled a large collection of instrumented buoy data to examine respiration patterns in 25 globally distributed lakes. This curated dataset was then used in other publications (e.g., Rose et al. 2014, Dugan et al. 2016), but more important, the original project-specific metabolism code was formalized during each subsequent publication and later resulted in a fully documented package in the R programming language (R Development Core Team 2015) called "LakeMetabolizer" (Winslow et al. 2014a, 2016). We contend that this pattern of fruitful coevolution, which results in data and tools that continue to support future science questions, is a direct product of tight coupling between tool development and research projects that encourages and supports repeatable science.

Despite the important gains from the formalization of analytical code into software, not all GLEON technical contributions are widely shared or published. Informal code and tools are often designed to serve the needs of a single project, and the additional effort to make them more broadly useful may not be worth the investment. This decision is often made by the code creator but can be guided by evaluating the needs outside the immediate research group for such a tool and weighing those needs against the potential cost of current development and future maintenance.

GLEON's community-built process in practice: B3 and Lake Analyzer

The B3 and Lake Analyzer tools are examples of specific software developed to support the workflow process of data collection, quality control, and analysis (Fig. 1). B3 is a customized quality assurance–quality control (QA/QC) tool for rapid visualization of sensor data and record keeping of changes. These data manipulations may include calibration corrections for sensor drift, interpolation between missing data, or removal of erroneous data. B3 provides a flexible and intuitive working environment based on a visual interface for semi-automated editing of outlying data and erroneous measurements (see B3 interface in Fig. 1). B3 records a detailed log of data modifications, including provisions for a user to input reasons for any changes (e.g., calibration adjustments, sensor drift, and missing or erroneous data). The initial software development of B3 took place through one of the GLEON member sites (University of Waikato, New Zealand).

B3 was introduced through the GLEON Cool Things session at the 2012 meeting at Lake Sunapee, USA, followed up by a "hands-on" B3 workshop at the 2012 meeting in Mulranny, Ireland. The latter interactive session demonstrates how GLEON has transitioned into a variety of communication modes to enable effective engagement and uptake of technology, as opposed to conventional conference presentations. The flat organizational structure of GLEON supported rapid uptake of B3 and generated useful feedback for improvements. Students and information technologists were early adopters of the software, and their feedback continues to drive development of B3 capabilities. Recent software additions include sensor error alerts, different interpolation methods to fill missing data, and the alignment of B3 data outputs to Lake Analyzer input requirements to create an interoperable tool framework.

Lake Analyzer is a software tool that calculates indices of mixing and stratification in lakes and visualizes results (Read et al. 2011, Winslow et al. 2014b). Lake Analyzer originated from an international undergraduate student exchange between the University of Waikato (New Zealand) and the University of Wisconsin-Madison (USA). GLEON's Lake Physics and Climate Working Group evaluated the prototype version of Lake Analyzer, and feedback helped steer additional development of the tool and resulted in a publication (Read et al. 2011). To meet the needs of the range of technical skills found in GLEON, the design of Lake Analyzer balanced simplicity for users with future flexibility (e.g., the ease of adding new algorithms or visualizations). Use of the tool quickly spread to other GLEON working groups (e.g., Klug et al. 2012) and to other limnology projects (e.g., Perron et al. 2014) facilitated, in part, by Lake Analyzer training workshops led by graduate students at GLEON meetings. To date, the supporting publication has been cited more than 100 times.

The creation of Lake Analyzer produced a useful tool for its sponsor network (GLEON) but also generated opportunities for undergraduates and graduate students. The developers of Lake Analyzer took on leadership roles in several GLEON software workshops and participated in other spin-off science projects. The code created for Lake Analyzer was leveraged for training graduate fellows in collaborative coding and version control (http://fellowship.gleon.org/) as the students ported the original MATLAB code to the open-source "rLakeAnalyzer" R package (Winslow et al. 2014b). The Project EDDIE (Environmental Data-Driven Inquiry & Exploration; http://www.projecteddie.org/; Carey et al. 2015) used this tool, as well as GLM, as key elements of modules developed to provide undergraduate students the skills to work with large datasets (Table 1). Along with the tools featured here, Lake Analyzer is illustrative of the potential gains community-built tools can provide for environmental networks.

Recommendations for other environmental networks

Embody diversity in participants and products

Research networks have much to gain by explicitly providing on-ramps for early career and underrepresented collaborators. Moreover, recruiting equitable participation from disciplines traditionally relegated to technology support roles improves the likelihood of producing higher quality software within the network. Recognizing and valuing diverse roles and responsibilities is characteristic of high-functioning research teams (Cooke and Hilton 2015). The development of B3 and Lake Analyzer provides examples of the benefits of inclusivity characterized by transdisciplinary teams and the open exchange of information and tools.

It is also important for networks to support multiple definitions of "success" in the network. Successful products from the network should include peer-reviewed scientific manuscripts but also software products, instrumentation, teaching tools, mobile applications, and more. Doing this enables broader participation, broader network impact, improves morale, and results in a more diverse portfolio of project outcomes. Additionally, leveraging the network output across multiple sectors, including teaching, research, and outreach, maximizes the utility of these project investments.

Let the membership steer product development

A Working Group model carried out within an inclusive network (such as GLEON) encourages active participation of people with different skills. Enabling community input from the early stages of idea generation through tool development, data analysis, and publication is important to developing a culture of inclusion. This process also engages new contributors in the community as rapidly as possible and encourages interactions across disciplines and career stages.

Instead of setting a science agenda from the top down, participatory (or grassroots) science networks should rely on the unique assemblage of members to steer science questions and tool development efforts. GLEON refrains from setting the scope of individual projects and instead focuses on providing a collaborative environment from which tools can be developed and research questions can be proposed and answered (Rose et al. 2016). Establishing a framework for member-led initiatives can also provide opportunities for diverse types of leaders to emerge from the network.

Promote responsive tool development that solves real science needs

We recommend a tight coupling between ongoing research projects and tool development efforts to help minimize wasted efforts and allow the network to adapt quickly to opportunities. To support this coupling, technologists must have a seat at the table (i.e., they must be treated as peers to domain scientists in network collaborations), and clear channels for transparent sharing and feedback must be in place. If possible, multiple levels of communication should be supported by the network structure, including peer-to-peer (e.g., Working Groups) and individual-to-network (e.g., Cool Things presentations), and there should be clear opportunities for 2-way communication from outside the network (e.g., participation in larger professional meetings, hosting webinars, etc.).

Research tool developers need to be pragmatic when deciding when code should be formalized into tools or software. The following questions can be used to aid in this decision: Do others have a clear need for this tool? Is there a mechanism to provide formal training for others to use the tool? Have the methods stabilized, or are they rapidly changing, requiring frequent updates and changes? Will there be resources to develop the code from research stage to production stage, including extensive documentation?

Conclusions

New skills and new technologies are required to exploit exponentially increasing data collected from environmental science networks. The collaborative structure of science networks can directly influence their ability to attract and retain the diversity of participants required to build analytical tools and produce data-driven research. Research that integrates and analyzes large and complex environmental data can benefit by engaging technologists with nontraditional research skills as equitable peers. GLEON established the core values of diversity, transparency, and a flat collaborative culture, resulting in numerous tools (Table 1) and research products (Rose et al. 2016). These tools are paired with openly shared data to produce research insights that would otherwise not have been possible. GLEON is an inclusive science network that celebrates diversity in its members and their contributions, values that should be extended to other environmental networks and collaborations.

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References

Bennett LM, Gadlin H, Levine-Finley S. 2010. Collaboration and team science: a field guide. National Institutes of Health.

Carey CC, Klug JL, Fuller RL. 2015. Project EDDIE: dynamics of lake mixing. Available from: http://cemast.illinoisstate.edu/data-for-students/modules/lake-mixing.shtml

Cheruvelil KS, Soranno PA, Weathers KC, Hanson PC, Goring SJ, Filstrup CT, Read EK. 2014. Creating and maintaining high-performing collaborative research teams: the importance of diversity and interpersonal skills. Front Ecol Environ. 12:31–38.

Cooke NJ, Hilton ML. 2015. Enhancing the effectiveness of team science. National Research Council.

Cossu R, Wells MG. 2013. The interaction of large amplitude internal seiches with a shallow sloping lakebed: observations of benthic turbulence in Lake Simcoe, Ontario, Canada. PLoS ONE. 8:e57444.

Costello MJ. 2009. Motivating online publication of data. BioScience. 59:418–427.

Guimera R, Uzzi B, Spiro J, Amaral LAN. 2005. Team assembly mechanisms determine collaboration network structure and team performance. Science. 308:697–702.

Hampton SE, Strasser CA, Tewksbury JJ, Gram WK, Budden AE, Batcheller AL, Duke CS, Porter JH. 2013. Big data and the future of ecology. Front Ecol Environ. 11:156–162.

Hanson PC. 2007. A grassroots approach to sensor and science networks. Front Ecol Environ. 5:343–343.

Hipsey MR, Bruce LC, Hamilton DP. 2014. GLM General Lake Model: model overview and user information. Perth (Australia): University of Western Australia Technical Manual.

Hipsey MR, Hamilton DP, Hanson PC, Carey CC, Coletti JZ, Read JS, Ibelings BW, Valesini FJ, Brookes JD. 2015. Predicting the resilience and recovery of aquatic systems: a framework for model evolution within environmental observatories. Water Resour Res. 51:7023–7043.

Jennings E, Jones S, Arvola L, Staehr PA, Gaiser E, Jones ID, Weathers KC, Weyhenmeyer GA, Chiu CY, de Eyto E. 2012. Effects of weather-related episodic events in lakes: an analysis based on high-frequency data. Freshwater Biol. 57:589–601.

Johnson D, Johnson F. 2014. Joining together: group theory and group skills. 11th ed. Essex (UK): Pearson Education Limited.

Joppa LN, McInerny G, Harper R, Salido L, Takeda K, O’Hara K, Gavaghan D, Emmott S. 2013. Troubling trends in scientific software use. Science. 340:814–815.

Kankaala P, Huotari J, Tulonen T, Ojala A. 2013. Lake-size dependent physical forcing drives carbon dioxide and methane effluxes from lakes in a boreal landscape. Limnol Oceanogr. 58:1915–1930.

Klug JL, Richardson DC, Ewing HA, Hargreaves BR, Samal NR, Vachon D, Pierson DC, Lindsey AM, O’Donnell DM, Effler SW, et al. 2012. Ecosystem effects of a tropical cyclone on a network of lakes in northeastern North America. Environ Sci Technol. 46:11693–11701.

Morin A, Urban J, Adams PD, Foster I, Sali A, Baker D, Sliz P. 2012. Shining light into black boxes. Science. 336:159.

Perron T, Chételat J, Gunn J, Beisner BE, Amyot M. 2014. Effects of experimental thermocline and oxycline deepening on methylmercury bioaccumulation in a Canadian Shield lake. Environ Sci Technol. 48:2626–2634.

Porter JH, Nagy E, Kratz TK, Hanson P, Collins SL, Arzberger P. 2009. New eyes on the world: advanced sensors for ecology. BioScience. 59:385–397.

R Development Core Team. 2015. R: a language and environment for statistical computing. Available from: http://www.R-project.org

Read EK, O’Rourke M, Hong GS, Hanson PC, Winslow LA, Crowley S, Brewer CA, Weathers KC. 2016. Building the team for team science. Ecosphere. 7:1–9.

Read JS, Hamilton DP, Desai AR, Rose KC, MacIntyre S, Lenters JD, Smyth RL, Hanson PC, Cole JJ, Staehr PA, et al. 2012. Lake-size dependency of wind shear and convection as controls on gas exchange. Geophys Res Lett. 39:L09405.

Read JS, Hamilton DP, Jones ID, Muraoka K, Winslow LA, Kroiss R, Wu CH, Gaiser E. 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. Environ Model Softw. 26:1325–1336.

Reichman OJ, Jones MB, Schildhauer MP. 2011. Challenges and opportunities of open data in ecology. Science. 331:703–705.

Rose KC, Winslow LA, Read JS, Read EK, Solomon CT, Adrian R, Hanson PC. 2014. Improving the precision of lake ecosystem metabolism estimates by identifying predictors of model uncertainty. Limnol Oceanogr-Meth. 12:303–312.

Rose KC, Weathers KC, Hetherington AL, Hamilton DP. 2016. Insights from the Global Lake Ecological Observatory Network (GLEON). Inland Waters. 6:476–482.

Solomon CT, Bruesewitz DA, Richardson DC, Rose KC, Van de Bogert MC, Hanson PC, Kratz TK, Larget B, Adrian R, Babin BL, et al. 2013. Ecosystem respiration: drivers of daily variability and background respiration in lakes around the globe. Limnol Oceanogr. 58:849–866.

Soranno PA, Bissell EG, Cheruvelil KS, Christel ST, Collins SM, Fergus CE, Filstrup CT, Lapierre J-F, Lottig NR, Oliver SK, et al. 2015. Building a multi-scaled geospatial temporal ecology database from disparate data sources: fostering open science and data reuse. GigaScience. 4:1–15.

Weathers K, Hanson PC, Arzberger P, Brentrup J, Brookes J, Carey CC, Gaiser E, Hamilton DP, Hong GS, Ibelings B, et al. 2013. The Global Lake Ecological Observatory Network (GLEON): the evolution of grassroots network science. Limnol Oceanogr Bull. 22:71–73.

Wilson GV. 2006. Where's the real bottleneck in scientific computing? Am Sci. 94:5–6.

Winslow LA, Benson BJ, Chiu KE, Hanson PC, Kratz TK. 2008. Vega: a flexible data model for environmental time series data. Albuquerque (NM): Proceedings of the Environmental Information Management Conference 2008. p. 166–171.

Winslow LA, Read JS, Woolway R, Brentrup J, Zwart J. 2014a. rLakeAnalyzer: package for the analysis of lake physics, version 1.7.6. Available from: https://CRAN.R-project.org/package=rLakeAnalyzer

Winslow LA, Zwart J, Batt R, Corman J, Dugan H, Hanson PC, Holtgrieve G, Jaimes A, Read JS, Woolway RI. 2014b. LakeMetabolizer: tools for the analysis of ecosystem metabolism, version 1.1.2. Available from: https://CRAN.R-project.org/package=LakeMetabolizer

Winslow LA, Zwart J, Batt R, Dugan H, Woolway RI, Corman J, Hanson PC, Jaimes A, Read JS. 2016. LakeMetabolizer: an R package for estimating lake metabolism from free-water oxygen using diverse statistical models. Inland Waters. 6:622–636.

Woolway RI, Jones ID, Hamilton DP, Maberly SC, Muraoka K, Read JS, Smyth RL, Winslow LA. 2015. Automated calculation of surface energy fluxes with high-frequency lake buoy data. Environ Model Softw. 70:191–198.

Wuchty S, Jones BF, Uzzi B. 2007. The increasing dominance of teams in production of knowledge. Science. 316:1036–1039.

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