The Promise and Potential of Continental-Scale Limnology Using the U.S. Environmental Protection Agency's National Lakes Assessment

Amina I. Pollard, Stephanie E. Hampton, and Dina M.Leech

Abstract

While there are many local and regional sampling efforts in lakes across the U.S., it is often difficult to compile this information into a cohesive framework to make national- or continental-scale conclusions. To address this gap, the U.S. Environmental Protection Agency partners with States and Tribes to implement the National Lakes Assessment, which is a national-scale, coordinated lake sampling program. The resulting data include colocated biological, chemical, habitat, and human use measures that are available to the scientific community. We provide a brief overview of the program, describe the data, and discuss some of the ways the results have been used. The availability of a consistent data set of this magnitude is an impressive and unique resource for the limnological community.

Introduction

The leading edge in many fields of science increasingly demands data of larger volume and more ambitious scope, exploring phenomena at scales both finer and broader than has previously been possible. Technologies that deliver such data are more accessible than ever, putting tools such as in situ sensors and satellite-derived environmental data into individual researchers' hands. These tools have spurred innovation and also heightened interest in research that is more synthetic across scales, taking advantage of a new era of data availability (Durden et al. 2017). Even so, large gaps in knowledge remain where existing technologies cannot replace human effort, and these gaps are prominent in aquatic science where both the physical properties of water and the micro-scale of the primary producers (and their consumers) stubbornly discourage investigation by sensors (Hampton 2013). Many aquatic scientists are turning toward collaboration for synthesis of existing data, including both sensor and "hand collected," using mechanisms such as synthesis centers (e.g., National Center for Ecological Analysis and Synthesis, Shurin et al. 2002), the Global Lake Ecological Observatory Network (Solomon et al. 2013), LAGOS and CSI Limnology (Soranno et al. 2017), the Global Lake Temperature Collaboration (O'Reilly et al. 2015), and other formal and informal models. For all their successes, in each of these endeavors investigators struggle with the inconsistencies inherent to data that were not collected in a coordinated and consistent manner (Soranno et al. 2015). Here the U.S. Environmental Protection Agency's (USEPA) National Lakes Assessment (NLA) provides an exceptional service

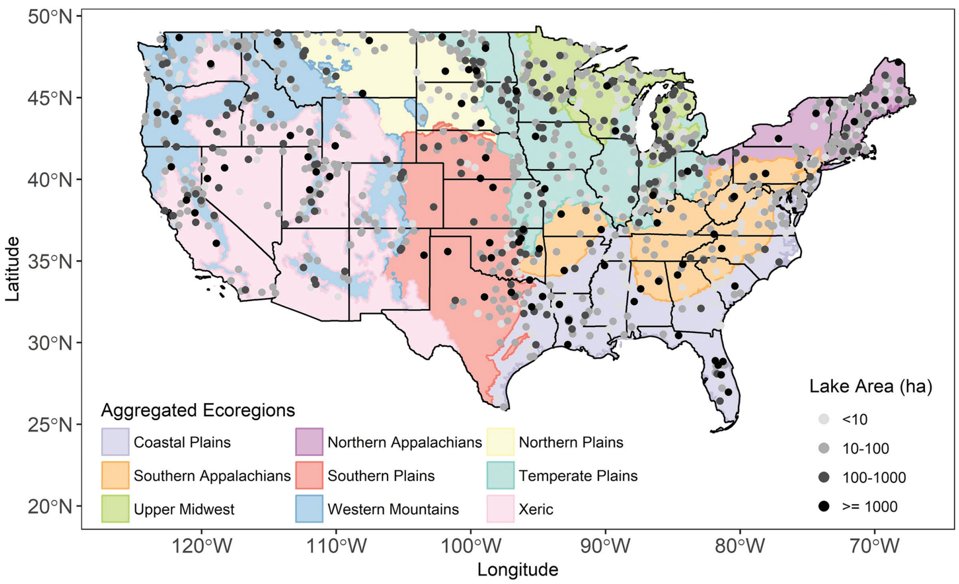

FIG. 1. Location and size of lakes sampled in the 2012 NLA survey, across all Omernik III regions.

to both science and society through its coordinated, intensive sampling of lakes in the United States.

Brief history of NLA and its objectives

The NLA was intended to address a series of critiques between the 1970s and early 2000s that the U.S. did not have the data needed to understand current conditions, track environmental improvements, or to inform decisions at a national scale (e.g., Shapiro et al. 2008). This data need was deemed so important that the U.S. legislature set aside a special budget item to fund national-scale assessments of aquatic resources. Housed within USEPA's Office of Water, the NLA is designed to evaluate the ecological condition of lakes within the conterminous U.S. (USEPA 2009). Specifically, the objective of the NLA is to provide a snapshot of lake conditions in the U.S. that can answer two questions: (1) what is the current condition of lakes? and (2) how is this condition changing over time? Results from the NLA are provided to national policy-makers to help inform environmental decisions. While the NLA focuses on water quality, the breadth of variables sampled enables limnological research well beyond this primary goal. The stratified randomized sampling design facilitates extrapolation to national scales and includes over 1000 lakes in each survey, both natural and man-made. NLA surveys have been conducted in 2007, 2012, and 2017; the first two surveys are available online, and 2017 samples are currently being processed (https://www.epa.gov/national-aquatic-resource-surveys/nla). Thus the NLA provides both spatial and temporal insights.

Standardized methods used by the NLA

Approximately 1000 lakes and reservoirs ≥1 ha are sampled in the summer during each cycle. Lakes are selected from the National Hydrography Database (version 2; https://nhd.usgs.gov) using a statistical design that stratifies based on aggregated Omernik level III ecoregion and lake size (Fig. 1). This design tackles two challenges in the development of the NLA: (1) a project objective to report on condition at both national and regional scales and (2) the numerical dominance of small lakes across the U.S. (e.g., Peck et al. 2013). Lakes are not distributed evenly across the U.S. The design ensures that at least 100 lakes are selected from each ecoregion, which provides sufficient statistical power for NLA to develop population estimates at a regional scale. One hundred of the 900 selected lakes are identified to be sampled twice in the field season. The revisit data are used to examine sampling variability, e.g., signal : noise, as another aspect of the NLA quality assurance checks. The design also imposes a requirement to select an equal number of lakes in each of six size classes (1–4 ha, >4–10 ha, >10–20 ha, >20–50 ha, >50–100 ha, >100), so that NLA represents lakes of different sizes. A total of 1028 lakes were sampled in 2007, and 1038 lakes were sampled in 2012. Lakes are resampled across surveys as well—for example, from 2007 to 2012, approximately 400 lakes were resampled.

Consistency is critical for the successful implementation of NLA. All lakes are evaluated for inclusion in the assessment following established site evaluation guidelines (e.g., USEPA 2011). The design process relies on maps of lake objects from NHDplus, so all selected sites are evaluated to ensure that they meet NLA target population requirements (e.g., ≥1 ha surface area and ≥1 m deep) and are accessible. If not, a site is replaced with a lake from an oversample list following standardized procedures. Sampling methods are identified that can be deployed across a wide array of conditions and are detailed in a field manual (e.g., USEPA 2012*a*). States and Tribes are responsible for carrying out the majority of sampling, maximizing local and regional knowledge involved in the coordinated national effort, with guidance and support from USEPA staff. Before the field season begins, NLA staff provide mandatory in-person training sessions for field crews to ensure the use of consistent sampling protocols. Early in the field season, every field crew is visited and evaluated as they sample to ensure that protocols are consistently implemented. Sample processing procedures are detailed in a lab manual (e.g., USEPA 2012*b*). Finally, in aiming for the highest quality information possible, NLA data undergo thorough quality assurance checks, are compiled by the USEPA, and checked by States and Tribes before public release.

Field sampling occurs across the U.S. from June through September, with standardized sampling methods carried out on a single date for each lake. Approximately 90 field crews of two to four people (i.e., approximately 180–360 individuals) go out each field season to sample for the NLA. Biological, chemical, and physical measurements and samples are taken at a deep, open water location (i.e., <50 m in natural lakes and at a mid-point in reservoirs). First, a dissolved oxygen-temperature profile and Secchi depth are recorded (Fig. 2). Water is then collected from the photic zone (i.e., <50 m in lakes and at the midpoint of reservoirs) with a vertical, depth-integrated sampler (design by the Minnesota Pollution Control Agency) (Section 5.5, USEPA

FIG. 2. A NLA 2012 field crew member starts a sampling event with a Secchi disk reading. Photo by Hilary Snook.

FIG. 3. Water samples from the NLA sampling are sent to the EPA Western Ecology Division National Health and Environmental Effects Research Laboratory in Corvallis, Oregon for chemical analyses throughout the summer survey periods. A total of three baker's racks, like those pictured here, hold the samples four 4-L cubitainers deep, creating a strong visual impact of seeing the variety of color across the Nation's lakes.

2012*a*). Water is transferred from the sampling device to a triple rinsed 4 L cubitainer (Fig. 3). Once full, a sample aliquot is collected for common water chemistry measures including alkalinity, acid neutralizing capacity, conductivity, dissolved organic carbon, total phosphorus, total nitrogen, pH, true color, and a set of ions. Then, separate aliquots are collected for phytoplankton, chlorophyll *a* (Chl *a*), microcystins, and atrazine. Detailed descriptions of all water quality analyses are found in the NLA 2012 Laboratory Operations Manual (Section 9, USEPA 2012*a*).

Phytoplankton are identified, measured, and enumerated in Utermöhl sedimentation chambers under a compound microscope (Section 5.4, USEPA 2012*b*). Phytoplankton abundance (cells mL^{-1}) is estimated from the count data and the volume of water sampled, and for each major taxonomic group, biovolume is calculated based on cell dimension measurements. In an effort to maintain consistency among taxonomists, phytoplankton samples are subjected to within-lab quality assurance and then 10% of samples are sent to an independent taxonomist. This data set goes through a taxonomic reconciliation process before it is released.

Zooplankton are collected during the day with separate fine (50 μm) and coarse (150 μm) Wisconsin mesh nets, each towed vertically for a total length of 5 m, where depth adjustments are made in lakes <7 m deep, to sample the same volume in each lake. Zooplankton are identified to the lowest level of taxonomic resolution, usually species. For quality assurance among taxonomists and between laboratories, a random 10% of all samples are reidentified by independent taxonomists. Any differences among taxonomists are reconciled before the final zooplankton data set was compiled. Zooplankton abundance is estimated from the number of individuals counted and the volume of water sampled, and biomass is estimated based on published, standard length-width relationships (references listed in Section 10.5, USEPA 2012*b*).

Lake shorelines are also assessed for each lake. Ten evenly spaced locations are selected around the perimeter of each lake. Field crews visit each of these locations and gather standardized observations about littoral and riparian habitat. Littoral observations include estimates of the dominant substrate, macrophyte cover, woody debris, and habitat complexity within a plot that is 15 m wide and extends 10 m from the shoreline lakeward. Riparian observations include information about vegetation cover and complexity within a plot that is 15 m wide and extends landward 15 m from the water. The littoral and riparian habitat information are summarized to provide an estimate of habitat condition and

TABLE 1. Selected physical, biological, and chemical variables measured in the NLA, with medians and ranges for values from the 2012 survey.

	NLA 2012 (1038 lakes)					
Attribute	**Minimum**	**First quantile**	**Median**	**Mean**	**Third quantile**	**Maximum**
Physical characteristics						
Latitude (decimal degrees)	26.07	37.81	41.48	40.91	44.86	48.99
Longitude (decimal degrees)	−124.20	−107.60	−95.08	−95.73	−85.45	−67.20
Area (hectares)	1.03	11.04	32.05	871.11	109.40	167,489.61
Elevation (masl)	−53.27	182.27	325.07	623.24	684.75	3594.97
Thermocline depth (m)	0.12	2.12	3.70	4.59	5.80	34.25
Secchi depth (m)	0.02	0.63	1.33	2.03	2.75	28.00
Chemical characteristics						
Dissolved oxygen, 2 m depth (mg L^{-1})	0.30	7.05	8.07	8.12	9.14	31.80
Dissolved organic carbon (mg L^{-1})	0.23	3.40	5.73	8.72	9.43	515.80
Color (PCU)	0.00	12.00	20.00	25.63	30.00	724.00
Total phosphorus (μg P L^{-1})	4.00	21.00	42.00	123.90	106.50	3636.00
Total nitrogen (mg L^{-1})	14.00	331.50	650.00	1201.00	1310.00	54,000.00
Nitrogen : phosphorus (molar ratio)	0.57	18.69	31	45.86	50.12	3736.61
Calcium (mg L^{-1})	0.12	5.76	21.20	30.00	37.94	594.90
Chloride (mg L^{-1})	0.04	2.29	8.52	54.39	21.81	18,012.74
pH	2.83	7.57	8.30	8.11	8.64	10.47
Acid neutralizing capacity (μeg L^{-1})	−3361	446	1705	2920	2998	203,900
Biological characteristics						
Benthic macroinvertebrate richness	0.00	21.00	29.00	28.42	37.00	70.00
Chl *a* (center of lake, μg L^{-1})	0.00	3.06	8.01	27.59	26.20	764.00
Cyanobacteria density (cells mL^{-1})	0.00	956	8632	144,748	57,145	8,757,487
Microcystin concentration (μg L^{-1})	0.00	0.05	0.09	0.69	0.17	66.69
Phytoplankton biomass (μg dry weight L^{-1})	0.33	133.81	385.43	1584.75	1270.26	61,842.46
Zooplankton biomass (μg dry weight L^{-1})	0.13	29.41	83.27	217.31	223.33	5448.9
Watershed characteristics						
Watershed area (km^2)	0.00	2.00	11.00	2388.9	58.9	656,462.3
% Agricultural land use	0.00	0	6.40	19.92	34.21	97.46
% Wetland cover	0.00	0.17	1.81	6.17	7.28	94.99
% Urban development	0.00	0.82	3.90	9.19	8.30	99.42
% Forest cover	0.00	2.63	25.41	32.95	58.53	97.00
Road density (km km^{-2})	0.00	1.04	1.59	2.08	2.36	18.26

disturbance around each lake. An estimate of lake level is also assessed within each plot.

Benthic macroinvertebrates are collected from each of the littoral plots. A 500-μm mesh D-net is swept for one linear meter over the dominant habitat within each plot. The individual samples from each plot are composited to yield a single benthic invertebrate sample for each lake. Benthic macroinvertebrates are subsampled, and 500 individuals are identified and enumerated from each sample. Taxa are identified to the lowest level of taxonomic resolution possible, usually genus. Similar to other biological samples, the benthic invertebrate samples are subjected to within laboratory quality assurance and then a random 10% of samples are reidentified by an independent taxonomist.

In addition to field samples and observations, general landscape characteristics are provided for each lake, including lake area, elevation, and location. Watersheds and predefined buffers are also delineated for all lakes. Furthermore, within the watersheds and buffers, land cover characteristics, like percent forest, percent agriculture, and percent development, are summarized from the National Land Cover Database (NLCD). Other features, such as population density, housing density, road density, mine density, fertilizer use, air temperature, precipitation, mercury deposition and nitrogen deposition, are summarized for each sampled lake. Characterizations of some of these parameters from the 2012 NLA are provided in Table 1, and more data not mentioned here can be found online (https://www.epa.gov/national-aquatic-resource-surveys).

Uses of the NLA data set

More than 11 yr after the initial sampling, and with three field seasons completed, the NLA continues to inform water management at scales from national to local. For example, by participating as partners in the NLA, Vermont has been able to track habitat changes around lakes and compare the condition of habitat in the State to that found regionally and nationally. An analysis of the NLA 2007 data highlighted that lakeshores in Vermont were in worse condition than those in the Northern Appalachian ecoregion and nationally (VDEC 2013). This comparison provided one of the many lines of evidence that State resource managers used to gather support for their 2014 Shoreland Protection Act (http://dec.vermont.gov/watershed/lakes-ponds/permit/shoreland).

To date, researchers have used the NLA data set for a wide variety of limnological studies (e.g., controls of summer CO_2, estimating risks of covarying stressors, occurrence of pharmaceuticals in Minnesota lakes, physical habitat structure, and predicting lake depth), extending its uses far beyond the lake condition assessment for which it is designed. In particular, the comprehensive nature of the data set provides a powerful tool for exploring relationships among explanatory variables and lake status. Several studies, for example, have assessed the predictive power of abiotic factors that contribute to increased primary production, especially cyanobacterial biomass and Chl *a* concentrations (e.g., Beaulieu et al. 2013; Yuan and Pollard 2014). By merging the NLA data with additional public data sets, Read et al. (2015) put lake and watershed predictors into a landscape limnology context. Modeling predictors of water quality at spatial scales ranging from in-lake to basin and region, they highlight the usefulness of lake-specific characteristics, basin-scale land use, and hydrologic connectivity. By combining NLA data with comparable streams data, Stoddard et al. (2016) documented a continental-scale increase in phosphorus levels between 2004 and 2014. The unbiased sampling design used in NLA was critical to the Stoddard et al. findings, where phosphorus increases were evident across the population of lakes and streams and, most surprisingly, in undeveloped catchments.

A full listing of studies utilizing the NLA data set is available online (https://www.epa.gov/national-aquatic-resource-surveys/journal-articles-applying-national-aquatic-resource-survey-data). Please help NLA find your study by using the suggested citation format and acknowledgement statement found here: https://www.epa.gov/national-aquatic-resource-surveys/frequent-questions-about-nars-data#NARScitation.

Conclusions

NLA is a unique project within the U.S. It is a broad-scale synoptic survey of biological, chemical, physical habitat, and recreational measures in lakes, which facilitates the exploration of associations among measures. This data set is specifically designed for extrapolation from the sampled lakes to a broader population of lakes in the conterminous U.S. The sample design ensures that lakes are representative of the landscape rather than being conveniently located. As such, the data reflect the landscape characteristics of the U.S. The project provides a national and regional scale context for lake conditions that is intended to complement more intensive local, State, and Tribal data collection efforts. Standardized sampling methods ensure a consistent data set and rigorous quality assurance contributes to robust data. With all of these unique characteristics, the primary synthetic product for the NLA project is a high-level assessment report. After that, the data set is posted online for public consumption.

Given anthropogenic changes to the natural environment, these types of data sets are essential for supporting environmental decisions and can be used to explore fundamental limnological patterns across broad spatial scales. Several studies have started exploring the NLA data, but there are many opportunities to use this information. For example, detailed zooplankton and benthic macroinvertebrate data are provided, but few researchers appear to be using them. In addition to using the data for developing manuscripts, some professors have used the data as a resource in classes (e.g., how widespread is eutrophication in the U.S.?) and others have used it as an exploration resource for incoming graduate students to generate initial hypotheses. As an additional complementary resource, there are comparable projects within USEPA to collect continental-scale biological, chemical, physical habitat, and recreational data on wetlands, coastal waters, and rivers and streams. All of these data are available online (https://www.epa.gov/national-aquatic-resource-surveys) and provide a unique resource for examining aquatic ecosystem types individually or more comprehensively as a holistic aquatic landscape.

Finally, in addition to the fundamental work that can be done within the NLA data set, countless opportunities exist to build upon the NLA data with additional work. In some cases, researchers have leveraged the NLA sampling effort to explore supplemental measures in both early assessments (e.g., algal toxin measures, water isotopes) and in NLA 2017 (e.g., dissolved gases, fish eDNA, pharmaceuticals, and personal care products). Moreover, complementary efforts in Canada are currently in progress, which would extend the uses of the NLA to truly continental scales.

Whether focusing on existing data sets or looking for newer exploratory data sets, we hope that this brief description will increase awareness of this exceptional resource.

References

Beaulieu, M., F. Pick, and I. Gregory-Eaves. 2013. Nutrients and water temperature are significant predictors of cyanobacterial biomass in a 1147 lakes data set. Limnol. Oceanogr. **58**: 1736–1746. doi: 10.4319/lo.2013.58.5.1736

Durden, J. M., J. Y. Luo, H. Alexander, A. M. Flanagan, and L. Grossmann. 2017. Integrating "Big Data" into aquatic ecology: Challenges and opportunities. Limnol. Oceanogr. Bull. **26**: 101–108. doi: 10.1002/lob.10213

Hampton, S. E. 2013. Understanding lakes near and far. Science **342**: 815–816. doi: 10.1126/science.1244732

O'Reilly, C. M., and others. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. **42**: 10773–10781. doi: 10.1002/2015GL066235

Peck, D. V., A. R. Olsen, M. H. Weber, S. G. Paulsen, C. Peterson, and S. M. Holdsworth. 2013. Survey design and extent estimates for the National Lakes Assessment. Freshw. Sci. **32**: 1231–1245. doi: 10.1899/11-075.1

Read, E. K., and others. 2015. The importance of lake-specific characteristics for water quality across the continental United States. Ecol. Appl. **25**: 943–955. doi: 10.1890/14-0935.1

Shapiro, M. H., S. M. Holdsworth, and S. G. Paulsen. 2008. The need to assess the condition of aquatic resources in the US. J. North Am. Benthol. Soc. **27**: 808–811. doi: 10.1899/08-116.1

Shurin, J. B., E. T. Borer, E. W. Seabloom, K. Anderson, C. A. Blanchette, B. Broitman, S. D. Cooper, and B. S. Halpern. 2002. A cross-ecosystem comparison of the strength of trophic cascades. Ecol. Lett. **5**: 785–791. doi: 10.1046/j.1461-0248.2002.00381.x

Solomon, C. T., and others. 2013. Ecosystem respiration: Drivers of daily variability and background respiration in lakes around the globe. Limnol. Oceanogr. **58**: 849–866. doi: 10.4319/lo.2013.58.3.0849

Soranno, P. A., and others. 2015. Building a multi-scaled geospatial temporal ecology database from disparate data sources: Fostering open science and data reuse. GigaScience **4**: 28. doi: 10.1186/s13742-015-0067-4

Soranno, P. A., and others. 2017. LAGOS-NE: A multi-scaled geospatial and temporal database of lake ecological context and water quality for thousands of US lakes. GigaScience **6**: 1–22. doi: 10.1093/gigascience/gix101

Stoddard, J. L., J. Van Sickle, A. T. Herlihy, J. Brahney, S. Paulsen, D. V. Peck, R. Mitchell, and A. I. Pollard. 2016. Continental-scale increase in lake and stream phosphorus: Are oligotrophic systems disappearing in the United States? Environ. Sci. Technol. **50**: 3409–3415. doi: 10.1021/acs.est.5b05950

USEPA. 2009. National Lakes Assessment: A Collaborative Survey of the Nation's Lakes. EPA 841-R-09-001. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2011. 2012 National Lakes Assessment. Site Evaluation Guidelines. EPA 841-B-11-005. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2012*a*. 2012 National Lakes Assessment. Field Operations Manual. EPA 841-B-11-003. U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2012*b*. 2012 National Lakes Assessment. Laboratory Operations Manual. EPA-841-B-11-004. U.S. Environmental Protection Agency, Washington, DC.

VDEC. 2013. Gauging the health of Vermont Lakes: Results of the 2007 National Lake Assessment. Vermont Department of Environmental Conservation.

Yuan, L. L., and A. I. Pollard. 2014. Classifying lakes to improve precision of nutrient–chlorophyll relationships. Freshw. Sci. **33**: 1184–1194. doi: 10.1086/678465

Amina I. Pollard, US EPA Office of Water, Washington, DC; Pollard.Amina@epa.gov

Stephanie E. Hampton, Center for Environmental Research, Education and Outreach, Washington State University, Pullman, WA

Dina M. Leech, Department of Biological and Environmental Sciences, Longwood University, Farmville, VA