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## LAGOS-NE: A multi-scaled geospatial and temporal database of lake ecological context and water quality for thousands of U.S. lakes

--Manuscript Draft--

<b>Manuscript Number:</b>	GIGA-D-17-00112	
<b>Full Title:</b>	LAGOS-NE: A multi-scaled geospatial and temporal database of lake ecological context and water quality for thousands of U.S. lakes	
<b>Article Type:</b>	Data Note	
<b>Funding Information:</b>	Massachusetts Water Supply Protection Trust	Environmental Analyst Yuehlin Lee
	U.S. Environmental Protection Agency (US) Office of Research and Development	Not applicable
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	U.S. Environmental Protection Agency (106/319)	Not applicable
	U.S. Army Corps of Engineers (US)	Limnologist Marvin G Boyer
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**Abstract:**

**Background**  
Understanding the factors that affect water quality and the ecological services provided by freshwater ecosystems is an urgent global environmental issue. Predicting how water quality will respond to global changes not only requires water quality data, but also information about the ecological context of individual water bodies across broad spatial extents. Because lake water quality is usually sampled in limited geographic regions, often for limited time periods, assessing the environmental controls of water quality requires compilation of many datasets across broad regions and across time into an integrated database. LAGOS-NE accomplishes this goal for lakes in the northeastern-most 17 U.S. states.

**Findings**  
LAGOS-NE contains data for 51,101 lakes and reservoirs larger than 4 ha in 17 lake-rich U.S. states. The database includes three data modules for: lake location and physical characteristics for all lakes; ecological context (i.e., the land use, geologic, climatic, and hydrologic setting of lakes) for all lakes; and in situ measurements of lake water quality for a subset of the lakes from the past three decades for approximately 2,600-12,000 lakes depending on the variable. The database contains over 200,000 measures of chlorophyll concentration and almost 900,000 measures of Secchi depth. The water quality data were compiled from 87 lake water quality datasets from federal, state, tribal, and non-profit agencies, university researchers, and citizen scientists.

**Conclusions**  
This database is one of the largest and most comprehensive databases of its type

	because it includes both in situ measurements and ecological context data. Because ecological context can be used to study a variety of other questions about lakes, streams, and wetlands, this database can also be used as the foundation for other studies of freshwaters at broad spatial and ecological scales.
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<b>Additional Information:</b>	
<b>Question</b>	<b>Response</b>
Are you submitting this manuscript to a special series or article collection?	No
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**ABSTRACT**

**Background**

Understanding the factors that affect water quality and the ecological services provided by freshwater ecosystems is an urgent global environmental issue. Predicting how water quality will respond to global changes not only requires water quality data, but also information about the ecological context of individual water bodies across broad spatial extents. Because lake water quality is usually sampled in limited geographic regions, often for limited time periods, assessing the environmental controls of water quality requires compilation of many datasets across broad regions and across time into an integrated database. LAGOS-NE accomplishes this goal for lakes in the northeastern-most 17 U.S. states.

**Findings**

LAGOS-NE contains data for 51,101 lakes and reservoirs larger than 4 ha in 17 lake-rich U.S. states. The database includes three data modules for: lake location and physical characteristics for all lakes; ecological context (i.e., the land use, geologic, climatic, and hydrologic setting of lakes) for all lakes; and in situ measurements of lake water quality for a subset of the lakes from the past three decades for approximately 2,600-12,000 lakes depending on the variable. The database contains over 200,000 measures of chlorophyll concentration and almost 900,000 measures of Secchi depth. The water quality data were compiled from 87 lake water quality datasets from federal, state, tribal, and non-profit agencies, university researchers, and citizen scientists.

**Conclusions**

This database is one of the largest and most comprehensive databases of its type because it includes both in situ measurements and ecological context data. Because ecological context can be used to study a variety of other questions about lakes, streams, and wetlands, this database can also be used as the foundation for other studies of freshwaters at broad spatial and ecological scales.

**KEYWORDS**

Lake eutrophication, Nutrients, Water quality, lake trophic state, Ecological context, LAGOS-NE, Open science, Lake database

# 1. Data Description

A major concern for water quality in freshwaters globally is cultural eutrophication, or excess nutrient inputs from human activities that lead to increased plant and algal growth. In many parts of the world, runoff from land, or nonpoint source pollution, has replaced discharges of sewage, or point-source pollution, as the primary driver of lake and reservoir eutrophication [1]. In lakes and reservoirs, eutrophication is expected to become more widespread in the coming decades as the human population increases and climate and land use change commensurately, placing increasing pressures on freshwaters [2,3,4]; although, there is also recognition that eutrophication or its response to management actions does not progress the same in all lakes (e.g., [5,6,7]). Most research to understand lake nutrients and their effects on algae, plants, and aquatic food webs has been conducted in individual or small groups of lakes by studying the complex within-lake mechanisms that control responses to nutrients (e.g., [8,9]). Such relationships and interactions have also been found to be influenced by the ecological context of lakes (i.e., the land use, geologic, climatic, and hydrologic setting of lakes), which varies by lake and region, and is multi-scaled. In fact, it is not always clear whether local or regional ecological context matters more for predicting lake eutrophication (e.g., [10,11,12]). Therefore, determining the current extent of lake eutrophication and predicting how eutrophication will respond to future global change requires water quality data (e.g., nutrients, water clarity, and chlorophyll concentrations) and measures of lake ecological context across regions, the continent, and the globe (e.g., [13,14,15]).

In practice, measures of water quality are often collected from a relatively small number of lakes within individual regions. In the U.S., large investments have been made in water quality monitoring by federal, state, local, and tribal governments; and, many, but not all, of the datasets have been placed in government data repositories such as the USGS National Water Information System (NWIS) and the USEPA Storage and Retrieval (STORET) database. Unfortunately, these data repositories do not currently allow us to study lake water quality at broad scales. Despite the large number of water quality records in these systems, a recent analysis of their stream nutrient data found that over half of the data records lacked the most critical metadata necessary to make the data usable (e.g., chemical form, parameter name, units; [16]); and, we would expect a similar result with lake data because they are typically treated similarly to stream nutrient data. In addition, STORET and NWIS do not include any measures of lake ecological context. Therefore, to study the controls of eutrophication specifically, and water quality in general, requires development of a comprehensive database for lake water quality that is integrated with measures of lake ecological context and sufficient metadata for robust analysis.

We created such a database for thousands of inland lakes in 17 of the most lake-rich states in the upper midwest and northeastern U.S. named LAGOS-NE, the ‘lake multi-scaled geospatial and temporal database’ (Figure 1). We avoided the problem of lack of metadata for the water quality data by contacting the original data providers for water quality data, asking for metadata, and only including data for which sufficient metadata were available. We addressed the problem of lack of ecological-context data by creating our own database of lake ecological context. The detailed methods and approach for building this database have been published previously [17]; here we publish and describe the database for the 51,101 lakes and reservoirs  $\geq 4$  ha in the study area (1,800,000 km<sup>2</sup>).

We had three related motivations for developing this database: (1) to facilitate further development of our basic understanding of lake water quality at broad scales using water quality data on thousands of lakes collected over the last several decades (see [11,17] for details); (2) to build the capacity to apply this scientific understanding to environmental management and policy of inland waters; and, (3) to foster broad-scale research by designing an open-science database that is extensible for future uses and by making the data and methods publicly accessible.

**Figure 1. Map of the study extent of LAGOS-NE.** Map includes 17 states in the upper midwest and northeastern U.S. outlined in white and 51,101 lakes  $\geq 4$  ha shown as blue polygons. Some lakes extend beyond state borders and are included in the database if it was possible to delineate their watersheds. Watershed boundaries rather than state boundaries were used for all analyses of lakes, streams and wetlands. The map is modified from [17].

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4 184 LAGOS-NE is composed of three data modules that, although integrated in the same database,  
5 185 were derived using different data sources and data integration methods, and thus must be version-  
6 186 controlled separately. LAGOS-NE<sub>LOCUS</sub> v1.01 includes lake location and physical characteristics based on  
7 187 an existing national-scale database of lake and streams in the U.S. for all lakes. LAGOS-NE<sub>GEO</sub> v1.05  
8 188 includes measures of land, water, and air (ecological context) obtained from existing national scale GIS  
9 189 (geographic information system) datasets and measured in multiple zones (delineated by different spatial  
10 190 classifications) around all lakes. This module also contains some temporal data for climate, land  
11 191 use/cover, and atmospheric deposition variables. LAGOS-NE<sub>LIMNO</sub> v1.087.1 is composed of in-situ  
12 192 measurements of lake water quality for a subset of the above lakes. These 87 datasets of lake water  
13 193 quality were obtained from a combination of sources including government, tribal agencies, university  
14 194 researchers, citizen scientists, and non-profit agencies. Samples were taken during any season of the year  
15 195 from the most recent decades up until about 2012.

16 196 The largest challenge in building LAGOS-NE was the heterogeneity of the dataset formats,  
17 197 variable conventions and units, and metadata, none which were standardized. Many steps of data  
18 198 integration required manual input from experts in diverse fields and close collaboration among specialists  
19 199 in ecoinformatics, database design, freshwater ecology, and geography; all combined, the effort took six  
20 200 years and involved 10-20 individuals at any one time, spread across numerous institutions.

21 201 We designed the database using principles of open science so futures users could ask new  
22 202 research questions by using the existing database or adding new data modules to the database. To ensure  
23 203 users could do this, we documented the major steps of dataset integration and carefully integrated  
24 204 metadata directly into the database itself, we emphasized data provenance, and we used a database  
25 205 versioning system. In this data paper, we make the following research products available: (1) data tables  
26 206 with the data that make up LAGOS-NE and an R package for accessing the data and integrating the  
27 207 tables; (2) for each of the 87 water quality datasets, we provide the EML (ecological metadata language)  
28 208 metadata files that we authored after receiving the data, the data files that we processed to import into  
29 209 LAGOS-NE, and the R-script that we wrote to process the data; and (3) GIS coverages of the underlying  
30 210 freshwater geographic features (lakes, streams and wetlands) that are linked to the data tables for GIS  
31 211 processing by researchers.  
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## 33 213 **2. Study site: Midwest and Northeast U.S. lakes**

34 214 We selected an area of the U.S. known to have large numbers of lakes, well-developed lake water  
35 215 quality sampling programs, and that spans diverse geographic conditions and thus gradients of ecological  
36 216 context (Table 1). Our study area of 17 U.S. states includes 51,101 lakes  $\geq 4$  ha (Figure 1). These states  
37 217 are in the north temperate climatic zone, which experience cold winters and warm, humid summers. The  
38 218 study area includes part of the Interior Plains, Laurentian Uplands, Appalachian Highlands, and Atlantic  
39 219 Plain geological provinces, and thus encapsulate a range of geological ages, glacial histories, and  
40 220 topography. Land use/cover is highly variable, ranging from regions of intense agriculture in the corn belt  
41 221 that spans portions of Minnesota, Wisconsin, Iowa, Missouri, Indiana, and Ohio, to predominantly  
42 222 forested or urban regions of the northeastern U.S., including the states of Maine, New Hampshire, New  
43 223 Jersey, and parts of New York, and primarily forested regions of northern Minnesota, Wisconsin, and  
44 224 Michigan.

45 225 Although the majority of the data that we provide are for lakes  $\geq 4$  ha (see below for reasons for  
46 226 using this threshold), we do include some data on lakes  $\geq 1$  ha and  $< 4$  ha if data were available. Although  
47 227 there may be water quality data for some lakes in this smaller size range, ecological context variables are  
48 228 not available for these lakes.  
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235 **Table 1: Summary statistics for LAGOS-NE study area.**

State	Area (km <sup>2</sup> )	Number of lakes (≥4 ha)	Mean annual temperature (°C)	Mean annual precipitation (mm)	% Agricultural land	% Urban land	% Forested land	% Wetland
Connecticut	12,878	763	9.7	1253	7.2	24.4	54.5	9.0
Illinois	145,920	2,819	11.3	1005	68.9	11.9	15.0	1.7
Indiana	93,717	1,874	11.2	1072	62.0	10.8	22.5	1.5
Iowa	145,736	903	9.1	881	78.0	7.5	6.9	1.9
Maine	84,123	2,645	5.1	1149	3.7	3.5	66.9	12.1
Massachusetts	21,013	1,698	8.9	1235	5.8	25.2	50.1	12.2
Michigan	150,489	6,511	7.2	841	26.2	10.6	35.5	19.2
Minnesota	218,543	13,984	5.3	709	44.7	5.7	19.7	19.0
Missouri	180,537	1,858	12.7	1100	50.7	7.0	36.6	2.1
New Hampshire	23,980	1,109	6.5	1209	3.8	7.9	74.5	6.4
New Jersey	19,599	1,143	11.8	1188	13.8	31.1	27.9	21.4
New York	126,070	4,461	7.6	1094	21.9	9.3	54.1	7.2
Ohio	106,917	1,279	10.6	1003	50.0	14.7	30.9	1.0
Pennsylvania	117,293	1,755	9.3	1109	22.7	12.3	59.5	1.6
Rhode Island	2,809	253	10.0	1246	4.9	29.5	44.6	13.6
Vermont	24,913	528	5.9	1176	13.3	5.5	70.0	4.7
Wisconsin	145,295	6,009	6.6	831	36.7	7.5	35.5	13.7

This table includes numbers of lakes and geophysical setting of each state and state averages for climate and land use/cover characteristics. Temperature and precipitation data are 30 year climate normals (1981-2010); land use/cover data are from the 2011 National Land Cover Database (NLCD). Note, border lakes are only counted in one state.

### 3. Overview of LAGOS-NE

LAGOS-NE includes some data on all lakes in a study area (above the minimum lake area threshold, which was 4 ha), which we call the ‘census’ population of lakes. The census population of lakes is a critical feature of LAGOS-NE because it allows us to characterize the ecological context of every lake in our study population and to identify whether the lakes for which we have water quality data are biased in any way. LAGOS-NE includes three main categories of variables: (1) variables that describe the physical characteristics and location of lakes themselves; (2) variables that describe in-situ water quality; and (3) variables that describe a lake’s ecological context at multiple scales, and across multiple dimensions (such as hydrology, geology, land use, climate, etc.) based on the principles of landscape limnology [18,19,20,12]. Three factors dictated which data were included: past research and theory about the spatial and temporal controls of lake water quality, data availability and quality, and the time and resources necessary to compile, integrate, or process the original data. In other words, data that were especially time- and resource-intensive to collate, integrate, or process were given lowest priority and in some cases, were not ultimately incorporated into the database.

There were a number of constraints for each of the categories of data that had to be considered. For creating the census population of lakes (i.e., their geospatial location, perimeter, and surface area), we relied on a single source of data (the 1:24,000 National Hydrography Dataset (NHD) [21]). For the in-situ water quality data, we incorporated data only if they were in a digitally-accessible format such as a text or spreadsheet file. Finally, for the ecological-context variables, we included only data for which we could obtain a GIS or raster coverage at the national or state scale for all 17 states.

We organized these three categories of data into database ‘modules’ that had similar data types and sources so that we could develop procedures and set standards for each module (Figure 2). The module structure also facilitates data reuse and extension by accommodating future data modules related to any other lake or ecological-context feature.

**Figure 2. LAGOS-NE data modules and version numbers.** The data modules and versions that are included in LAGOS-NE and are available with this paper include: LAGOS-NE<sub>GEO</sub> v.1.05, LAGOS-NE<sub>LOCUS</sub> v.1.01 (note, that in Soranno et al. [17], this module was called LAGOS-lakes), and LAGOS-NE<sub>LIMNO</sub> v.1.087.1. We include descriptions of the type of data that are included in each module; with the major categories of variables the same as those describing the data tables in Additional File 1. The black connectors among the modules show that the modules are connected to each other through common unique identifiers through the LAGOS-NE<sub>LOCUS</sub> module (either the unique lake ID or the zone ID). P is phosphorus, N is nitrogen, C is carbon, S is sulfur, atm is atmospheric, NHD is the National Hydrography Dataset, IWS is the interlake watershed, WBD is the Watershed Boundary Dataset, EDU is Ecological Drainage Unit. Figure is modified from Figure 1 in Soranno et al. [17].

The design of LAGOS-NE and the workflow for its construction has been described previously in detail [17]. In particular, the database design is based on the CUAHSI ODM as described in [17]. Here, we provide a brief overview. One important guiding principle in creating LAGOS-NE was to ensure data provenance, i.e., that we could trace the original source data through to the final LAGOS-NE database. Because each data module had different types of source data, we developed different procedures for data provenance for each module, described in Soranno et al. [17] and in this paper. The database model is based on the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) Community Observations Data Model (ODM) because it is a flexible data model (i.e., allows the incorporation of wide range of types of data) that allows for the incorporation of controlled vocabulary and, importantly, allows for extensive documentation through a relational database structure of linked tables containing metadata [17]. The database was created and is maintained in PostgreSQL v9.1. However, for researchers to use the database for analysis and modeling, it is necessary to export the data into tables that can be processed by statistical packages or computer code. Therefore, we exported the data into a series of tables (of similar data) that are needed to conduct research on either the census population of lakes, the lakes for which there are water quality data, or some combination. These are the data files that have been used to conduct research on LAGOS-NE to date, and that we make available in this data paper (see Additional File 1 for a list of the tables and associated data that we are making available). Further, we also make our GIS datasets available to facilitate geospatial analyses of lakes, streams, and wetlands used to create some of the major components of LAGOS-NE.

#### 4. Description of LAGOS-NE<sub>LOCUS</sub> v1.01 data module

The LAGOS-NE<sub>LOCUS</sub> module includes data on the physical location, some features and unique identifiers for all lakes in the study area  $\geq 1$  ha, which means this data file has information on 141,378 lakes. Note, that because we detected errors in the digitization of lakes between 1 and 4 ha, we have chosen to define our census population of lakes as only those  $\geq 4$  ha, but we still make data available for lakes smaller than 4 ha when available in this and the LAGOS-NE<sub>LIMNO</sub> data module. However, we recommend caution in analyses, interpretation, and inference for lakes  $< 4$  ha in this database that depend on NHD's spatial representation and detection of water bodies. The data in this module include: lake unique identifiers, perimeter, area, latitude and longitude, GNIS name, and the zone IDs that the lake is located within (e.g., state, county, the hydrologic unit at each level (HU4, HU8, and HU12)). The GIS datasets that we also make available provide the lake polygon features associated with this module, as well as coverages for: lake watersheds, streams, wetlands, spatial classifications, and glaciation history.

Definition of lakes: We defined lakes previously in Soranno et al. [17] as follows. A 'lake' in LAGOS-NE is a perennial body of relatively still water. We include lakes and reservoirs that range from being completely natural to highly modified: lake basins can be entirely natural, modified natural (i.e., a water control structure on a natural lake), or a fully impounded stream or river (i.e., a reservoir). We explicitly exclude: sewage treatment ponds, aquaculture ponds, and detention ponds that are known to contain basins that are entirely artificial and were built for high-intensity human use. In addition, due to their unusual nature and size, we do not include the five Great Lakes in our database. This definition of

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4 319 'lake' for LAGOS-NE has been developed only for the purpose of this database and its applications (e.g.,  
5 320 to answer questions about lake water quality). The intent of LAGOS-NE is not to document and measure  
6 321 the total number of water bodies in our study area, although we are able to perform this calculation for  
7 322 lakes  $\geq 4$  ha, with an acceptable level of uncertainty (see below).

9 323 Definition of lake watersheds: We calculated lake watersheds as 'inter-lake watersheds' (IWSs)  
10 324 defined as the area of land draining directly into the lake as well as the area that drains into upstream-  
11 325 connected streams and lakes  $< 10$  ha (Figure 3). We defined lake watersheds this way to define the  
12 326 drainage basin of lakes that includes connected streams and their drainage basins. However, because  
13 327 research has shown that large upstream lakes can trap nutrients flowing into them, these large lakes can  
14 328 block nutrient transport of nutrients that originate upstream of them to downstream lakes in a connected  
15 329 lake chain (e.g., [22]). Therefore, to calculate a drainage basin for a lake with large upstream connected  
16 330 lakes, we did not include the drainage basins of upstream lakes  $> 10$  ha. See Soranno et al. [17] for full  
17 331 details on how lake IWSs were calculated and the section on LAGOS-NE<sub>GEO</sub> for further details.

19 332 Lakes near and beyond the state borders: For some of our analyses, we delineated boundaries in  
20 333 other ways than political boundaries that were more ecologically relevant, which resulted in the inclusion  
21 334 of some lakes outside of the exact 17 state border. This fact allowed us to include more in situ data  
22 335 collected by state and citizen sampling programs which do not always follow strict state borders and may  
23 336 include lakes that are outside of state lines. Although most of these border lakes have hydrological (i.e.,  
24 337 lake connectivity measures) and topographic (i.e., lake watershed delineations) calculations or water  
25 338 quality data, some measures of ecological context may be missing. For example, for lakes in Canada, we  
26 339 were not able to estimate any data that relied on national datasets that stopped at the Canadian border; one  
27 340 exception is the NHD, which extends into Canada to retain hydrologic boundaries.

#### 30 342 Data sources of the LAGOS-NE<sub>LOCUS</sub> module

31 343 Detailed information on data sources are found in 'Additional File 5' in Soranno et al. [17]. Briefly, the  
32 344 data source for lakes and streams in the 17 state area was the NHD [21]. The hydrologic boundaries (i.e.,  
33 345 for three of the spatial classifications, HUC12, HUC8, HUC4) came from the Watershed Boundary  
34 346 Dataset (WBD; [23]). In addition, we used the digital raster dataset of elevation for watershed delineation  
35 347 from the National Elevation Dataset [24]. All download dates for these data sources are provided in  
36 348 'Additional File 5' in the above citation.

#### 39 350 Data-integration methods of the LAGOS-NE<sub>LOCUS</sub> module

40 351 All methods to create this module are described in Soranno et al. [17]. The most challenging and time-  
41 352 consuming part of building this module was connecting the sampling locations from the lake water  
42 353 quality datasets (which each contained different types of unique identifiers, and sometimes only lake  
43 354 names) to a georeferenced location in the NHD. When data providers included the lake latitude and  
44 355 longitude, we were able to mostly automate the procedure. Nevertheless, even when coordinates were  
45 356 available, there were many cases where the latitude and longitude did not intersect the NHD lake polygon  
46 357 boundary, requiring manual interpretation.

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50 360 **Figure 3. Examples lake watersheds (IWS) in LAGOS-NE.** The watersheds are coded by hydrologic class to  
51 361 which its lake belongs. Data are from the LAGOS-NE<sub>GEO</sub> v.1.01 data module and the GIS data coverages.

#### 55 365 Quality Control of the LAGOS-NE<sub>LOCUS</sub> module

56 366 The full description of error analysis for this module is described in Soranno et al. [17]. However,  
57 367 here we briefly describe our efforts to determine the minimum area of a lake that we could confidently  
58 368 represent using the NHD (further details located in Additional File 9 in Soranno et al. [17]). Although the  
59 369 NHD is a national dataset, it is updated and edited regionally (often at the state level) by local

practitioners familiar with each study region. As a result, there are regional differences in the resolution and digitization of water bodies, particularly for small water bodies, making it difficult to quantify or document even nominal error rates, or rather, the minimum lake size that is well-represented in the NHD. It has been documented previously that the NHD may not successfully identify small water bodies due to a variety of reasons including the resolution of the original underlying data of the NHD database, errors in digitization, hydrologic changes since the time of map creation (e.g., [25, 26]). Because of these documented issues, some programs have set minimum lake area cutoffs for sampling lakes. Most notable is the EPA-National Lakes Assessment of 2007, which chose a minimum size of 4 ha; although a smaller size cutoff was chosen for the EPA-National Lakes Assessment of 2012 [27]. To determine an appropriate size cutoff for our purposes, we conducted an analysis to identify the lakes that are best represented by the NHD across the LAGOS-NE study area.

We selected four states (WI, MI, IA, ME) in which to evaluate error rates of water body identification for lakes  $\geq 1$  ha and seven states (WI, MI, IA, ME, MO, NH, OH) in which to evaluate error rates for lakes  $\geq 4$  ha. We randomly selected three 100 km<sup>2</sup> rectangles from each state then compared the number of lakes occurring in the NHD GIS coverage to the number of lakes in the best available aerial imagery from a range of sources to calculate the percentage of lakes missing from the NHD. The average percentage of lakes missing from the NHD was 58% for the  $\geq 1$  ha four-state test and 13% for the  $\geq 4$  ha seven-state test. Because an average of 87% of lakes  $\geq 4$  ha that are present in high-resolution aerial imagery are also present in the NHD, we chose this surface area as our cut-off and accepted this error rate.

#### **Data in the LAGOS-NE<sub>LOCUS</sub> module**

Figure 1 shows the census population of all lakes  $\geq 4$  ha in the 17-state area, including border areas beyond the 17-state boundary. As expected, the lakes are not evenly distributed, with higher densities in the northern parts of the study area. For those lakes with known lake depth (9,808 lakes with maximum depth values, and 4,090 lakes with mean depth values), there is little regional pattern of lake depth; shallow and deep lakes are found throughout the study area (see [28] for further details). Watershed size varies greatly across the study extent, reflecting the wide range of different lake hydrologic types and connections to upstream water bodies (Figure 3). In fact, the proportion of lakes in different lake hydrologic connectivity classes varies regionally across our study extent (Table 2; see [29] for further details).

**Table 2. Numbers of lakes in each state by lake hydrologic class**

State	Lakes $\geq 4$ ha (#)	Isolated Lakes (#)	Headwater lakes (#)	Drainage lakes (#)	Drainage lakes with upstream lakes (#)
Connecticut	770	40	119	424	187
Illinois	2,831	1,417	279	952	183
Indiana	1,883	760	244	697	182
Iowa	915	339	87	402	87
Maine	2,661	94	619	1,211	737
Massachusetts	1,716	210	269	751	486
Michigan	6,531	2,649	1,087	1,672	1,123
Minnesota	14,031	6,609	1,894	2,673	2,855
Missouri	1,865	435	179	1,113	138
New Hampshire	1,118	70	224	581	243
New Jersey	1,148	219	129	521	279
New York	4,477	629	1,210	1,915	723
Ohio	1,282	543	105	520	114
Pennsylvania	1,757	316	397	840	204
Rhode Island	266	35	40	115	76
Vermont	531	14	74	364	79
Wisconsin	6,026	2,982	823	1,236	985
<b>Total</b>	<b>49,808</b>	<b>17,361</b>	<b>7,779</b>	<b>15,987</b>	<b>8,681</b>

The number of lakes  $\geq 4$  ha in each of the lake hydrologic classes by state, as well as the total numbers of lakes by hydrologic class calculated for the study extent. Note, in this table, lakes are counted for each state in which they occur (i.e., lakes that straddle two states are counted in both states).

## 5. Description of LAGOS-NE<sub>LIMNO</sub> v1.087.1 data module

The LAGOS-NE<sub>LIMNO</sub> module includes in situ measurements of lake water quality. We included variables that are most commonly measured by state agencies and researchers for studying eutrophication (Figure 2, variables labelled as **Water quality variables**). For each water quality data value, we also include metadata as additional columns in the exported data table (Figure 2, variables labelled as **Metadata**) including: the date of the sample, the name of the sampling program, the analytical methods, qualifiers with data flags from the original program (*qual*, which is not standardized for LAGOS-NE), detection limits (if available), and standardized censor codes from our quality control procedures (*censorcode*, standardized for LAGOS-NE).

### Data sources of the LAGOS-NE<sub>LIMNO</sub> module

We acquired individual water quality datasets for LAGOS-NE<sub>LIMNO</sub> by contacting individuals at each of the 17 state and 5 tribal agencies. These contacts helped us to identify the state-agency collected dataset required by the Clean Water Act and which is most likely to be in the public domain. In this way, we were able to acquire at least one (and typically more) dataset from each of the 17 states. Because state and tribal agencies vary in sampling approach and intensity (see below for details), we sought to supplement these datasets with other known sources of water quality data, including university researchers, federal agencies, and non-profit groups to integrate into the LAGOS-NE<sub>LIMNO</sub> module. The full list of data sources acquired is in Soranno et al. [17] in ‘Additional File 17’; however, we incorporated a subset of these datasets in LAGOS-NE<sub>LIMNO</sub> v1.087.1 (the data file *LAGOSNE\_source\_program\_10871.csv* contains the list of sources for this version of LAGOS-NE).

### Data-integration methods of the LAGOS-NE<sub>LIMNO</sub> module

All methods to create this module are described in Soranno et al. [17]. Briefly, for each dataset acquired, we authored LAGOS-NE metadata in EML to aid in data provenance (included in this paper). We also incorporated key metadata features (e.g., methods used, censor codes (if applicable)), and sampling program information) into the database so that future users could easily identify these important attributes. Because each dataset was unique in structure, file format, and naming conventions, we manually processed each dataset and its metadata so that they could be translated into the standard LAGOS-NE vocabulary and data model. Although labor-intensive, we created customized R scripts to process and load each dataset separately (included in this data paper).

### Quality control of the LAGOS-NE<sub>LIMNO</sub> module

The full description of our QAQC procedures for this module are described in Additional File 2. Here, we provide a brief overview of our approach. Our goal for this effort was to identify egregiously high values and values that might be too low, both defined below. Note that our quality control procedures were not designed to identify statistical outliers, which individual users are expected to perform themselves because such analyses depend on the subsequent statistical analysis of each user. There were three major phases in the quality assurance/quality control (QAQC) procedure for LAGOS-NE<sub>LIMNO</sub>. Phases I and II were designed to identify the egregious values that we defined as those that: 1) did not make ecological sense, 2) were far beyond what has been detected in previous studies, 3) were not technically feasible (e.g., SRP > TP), or 4) were a result of a data or file corruption or error in the data loading stage. For these egregious values, we explored the issues that might be underlying the values and removed them from the LAGOS-NE<sub>LIMNO</sub> data export provided in this data paper because we did not have sufficient evidence that they were not scientifically valid data values. We were very conservative in these assessments to avoid removing data values that were high, yet still valid. Phase III was designed to identify and flag values that were lower than analytically possible (i.e., below detection limits) when there was sufficient metadata; however, note that these data are still provided in this data paper because it is not appropriate to remove data that are below detection.



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4 456 For all versions of LAGOS-NE<sub>LIMNO</sub>, Phase I and II are conducted on the entire cumulative  
5 457 dataset to leverage as large of a sample size as possible to detect problem values. In other words, because  
6 458 many of the QAQC analyses outlined here make use of all information from an individual lake or  
7 459 variable, incorporating new data may result in a better assessment of the data than when there is less data.  
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9 460 Thus, for each new version of LAGOS-NE<sub>LIMNO</sub>, new decisions are made about egregious values. In this  
10 461 data paper and this document, we describe the procedures for assessing all major versions of LAGOS-  
11 462 NE<sub>LIMNO</sub>, but we present the results only for this version of LAGOS-NE<sub>LIMNO</sub> (v1.087.1).

12 463 Because there are few accepted practices for conducting such quality control on a large,  
13 464 integrated database, we created our own procedures for Phase I and II by creating tests to identify  
14 465 egregious values that leverage a large, integrated database with multiple measures of water quality and  
15 466 well-established expected relationships among variables. The database that we used to identify egregious  
16 467 values was based on data in the full LAGOS-NE<sub>LIMNO</sub> database for samples taken from all lake depths  
17 468 provided by the source datasets (note, our data exports in this data paper are only for epilimnetic or  
18 469 surface samples). While the quality control procedures that we implemented here were designed to help  
19 470 resolve the large and egregious errors in a combined dataset such as this, there are likely additional  
20 471 extreme values in the database due to the size and heterogeneity of the data. Users may want to check for  
21 472 additional issues in the data values specific to their proposed analyses.  
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### 23 474 Data in the LAGOS-NE<sub>LIMNO</sub> module

24 475 All data in LAGOS-NE<sub>LIMNO</sub> v1.087.1 are from samples that we identified as being collected  
25 476 from either the lake surface or the epilimnion (the well-mixed surface layer of a thermally-stratified lake  
26 477 during the period of stratification). Because we did not have lake temperature data to quantify the exact  
27 478 epilimnion depth in all lakes, we used information from the source datasets to either determine epilimnion  
28 479 depth, or to select data from only the top water layers. Although we received data from different depths in  
29 480 lakes, the majority of the samples were from the surface or epilimnion. The database includes samples  
30 481 from any season of the year. However, most of the published analyses to date have focused on the  
31 482 summer stratified period.

32 483 Lakes are not sampled the same way by all individuals, groups, or agencies; there are differences  
33 484 in the variables measured, the frequency and timing of sampling, and the proportion of lakes sampled. For  
34 485 example, for total phosphorus, the four states with the largest number of unique lakes with at least one  
35 486 value for total phosphorus per state include: Wisconsin (1,920 lakes), Minnesota (1,588), New York  
36 487 (1,289), and Michigan (1,109) (Table 3). However, the states with the highest proportion of their lakes  
37 488 with total phosphorus samples are the smaller states with fewer numbers of lakes, such as New  
38 489 Hampshire (64%), Vermont (58%), and Rhode Island (42%). Notably, there are some states with  
39 490 intermediate numbers of lakes that still have quite large percentages of their lakes with total phosphorus  
40 491 values, including Maine (35% of 2,645 lakes), Wisconsin (32% of 6,009 lakes), and New York (29% of  
41 492 the 4,461 lakes).

42 493 The most commonly measured variable in LAGOS-NE<sub>LIMNO</sub> is water clarity measured as Secchi  
43 494 depth (a relatively easy and cost-effective measure of water quality), with 897,724 measurements taken  
44 495 from 12,034 unique lakes in the 17 states from mostly the mid 1980's to 2011 (Table 3). The second and  
45 496 third most sampled measures of water quality are chlorophyll *a* and total phosphorus, respectively.  
46 497 Although it appears that total nitrogen is sampled far less frequently than total phosphorus, some labs  
47 498 measure total nitrogen directly and report that single value, whereas other labs measure the constituents  
48 499 that make up total nitrogen (total Kjeldahl nitrogen and nitrate+nitrite), and sum them together to  
49 500 calculate total nitrogen. All of our analyses conducted on total nitrogen have used such calculated and  
50 501 measured values of nitrogen together, which increase the sample sizes for total nitrogen markedly.

51 502 Most of our data came from state agencies, either alone or as part of joint programs with citizen  
52 503 scientists or university researchers (Table 4); which highlights the importance of citizen science programs  
53 504 for monitoring lake water quality in this lake-rich area of the U.S.  
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**Table 3. Summary of the water quality variables and the number of values per variable by state.**

State	Number of lakes (≥4 ha)	Variable	Total phosphorus	Secchi depth	Chlorophyll a	True color	Apparent color	Dissolved organic carbon	Total nitrogen	Total Kjeldahl nitrogen	Nitrate + nitrite
Connecticut	763	# of samples:	1294	1943	1160	53	0	74	853	55	397
		# of sampled lakes:	143	168	149	37	0	49	99	26	81
		sample years:	1972-2010	1937-2010	1937-2013	1984-2007	n/a	1984-2007	1973-2010	1999-2009	1976-2010
Illinois	2819	# of samples:	2816	2317	1438	20	0	20	43	1526	2351
		# of sampled lakes:	191	185	167	17	0	17	18	155	188
		sample years:	1999-2011	1999-2011	2000-2011	2007	n/a	2007	2001-2009	1999-2006	1999-2009
Indiana	1874	# of samples:	1232	1303	909	57	0	57	57	1183	1237
		# of sampled lakes:	341	340	320	51	0	51	51	322	341
		sample years:	1988-2010	1986-2010	1990-2009	2007	n/a	2007	2007	1988-2009	1988-2009
Iowa	903	# of samples:	2873	2836	2711	18	0	18	2244	6	2229
		# of sampled lakes:	111	111	103	12	0	16	111	1	111
		sample years:	1997-2011	1997-2011	1997-2011	2007	n/a	2007	2001-2011	2008-2009	2001-2011
Maine	2645	# of samples:	17314	83472	12480	1927	1676	3321	1260	8	1577
		# of sampled lakes:	933	1047	793	601	466	848	461	3	347
		sample years:	1971-2011	1952-2011	1974-2011	1983-2011	1972-2011	1984-2011	1995-2011	1978-1993	1978-2011
Massachusetts	1698	# of samples:	570	760	326	277	228	300	69	69	351
		# of sampled lakes:	211	249	122	122	89	140	37	4	132
		sample years:	1978-2013	1978-2010	1986-2010	1984-2013	1978-2010	1984-2010	2000-2010	1978-2013	1978-2013
Michigan	6511	# of samples:	10143	95283	12243	1811	69	987	749	2651	4850
		# of sampled lakes:	1109	1233	862	836	69	353	200	713	948
		sample years:	1965-2013	1925-2013	1959-2013	1973-2010	2002-2003	1984-2013	1959-2011	1980-2010	1973-2012
Minnesota	13984	# of samples:	10974	497646	81925	406	6683	3382	7717	43054	7725
		# of sampled lakes:	1588	4118	2755	253	1368	811	619	2018	1522
		sample years:	1944-2011	1938-2012	1970-2012	1981-2009	1949-2011	1984-2012	1945-2012	1944-2012	1945-2012
Missouri	1858	# of samples:	11619	11794	11578	27	0	27	11340	0	27
		# of sampled lakes:	208	207	201	23	0	23	207	0	23
		sample years:	1978-2013	1978-2013	1978-2013	2007	n/a	2007	1978-2013	n/a	2007
New Hampshire	1109	# of samples:	9289	2958	154	237	3044	390	22	1209	2445
		# of sampled lakes:	710	618	21	111	603	143	17	535	704
		sample years:	1975-2013	1975-2011	1983-2012	1984-2010	1975-2010	1984-2010	2004-2010	1975-1994	1975-2013
New Jersey	1143	# of samples:	421	461	446	27	0	44	10	443	472
		# of sampled lakes:	175	174	157	25	0	36	8	157	175
		sample years:	1984-2009	1984-2009	2005-2009	1984-2007	n/a	1984-2007	2007	2005-2009	1984-2009
New York	4461	# of samples:	21356	21235	21000	27297	2287	13036	8259	944	27796
		# of sampled lakes:	1289	693	545	1421	47	1158	258	279	1279
		sample years:	1975-2012	1975-2012	1975-2012	1981-2012	1984-2011	1982-2011	1990-2012	1981-2010	1975-2012
Ohio	1279	# of samples:	377	1868	1912	20	0	220	1873	0	447
		# of sampled lakes:	144	144	137	19	0	44	145	0	40
		sample years:	2006-2007	1992-2010	1992-2010	2007	n/a	2006-2010	1994-2010	n/a	1993-2007
Pennsylvania	1755	# of samples:	1170	924	971	163	0	160	638	16	290
		# of sampled lakes:	263	260	160	124	0	124	167	2	147
		sample years:	1980-2011	1984-2011	1980-2011	1984-2008	n/a	1984-2007	1997-2011	1985-2010	1980-2010

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Rhode Island	253	# of samples:	3325	18211	12195	51	6	65	2582	0	2100
		# of sampled lakes:	106	107	102	27	1	32	99	0	102
		sample years:	1984-2010	1984-2010	1986-2010	1984-2007	2003-2010	1984-2010	1992-2010	n/a	1984-2010
Vermont	528	# of samples:	13906	23894	15273	1774	1542	982	8	194	2271
		# of sampled lakes:	307	301	249	94	82	83	8	2	116
		sample years:	1977-2010	1977-2010	1977-2010	1981-2010	1979-2010	1984-2010	2007	1979-1994	1977-2010
Wisconsin	6009	# of samples:	45973	130819	26068	4599	174	4029	1932	9596	9417
		# of sampled lakes:	1920	2079	1024	1281	1	671	180	1160	1216
		sample years:	1933-2013	1948-2013	1933-2013	1974-2013	1976-1998	1977-2013	1986-2010	1933-2013	1965-2013
<b>TOTAL</b>	49592	<b># of samples:</b>	<b>154652</b>	<b>897724</b>	<b>202789</b>	<b>38764</b>	<b>15709</b>	<b>27112</b>	<b>39656</b>	<b>60954</b>	<b>65982</b>
		<b># of sampled lakes:</b>	<b>9749</b>	<b>12034</b>	<b>7867</b>	<b>5054</b>	<b>2726</b>	<b>4599</b>	<b>2685</b>	<b>5377</b>	<b>7472</b>

We include the number of individual values (representing an individual sampling event); the number of unique lakes for which there is at least one data value; and, the earliest and most recent year of sampling, all recorded by state and variable from any time period. Additional variables in LAGOS-NE<sub>LIMNO</sub> v1.087.1, not included in this table, which have relatively low sample sizes include: dissolved Kjeldahl nitrogen, ammonium, nitrite, soluble reactive phosphorus, total dissolved nitrogen, total dissolved phosphorus, total organic carbon, and total organic nitrogen.

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**Table 4. The number of datasets, data values, and lakes from the different types of sampling programs in LAGOS-NE v1.087.1.**

Program Type	Number of datasets	Number of lakes (≥4 ha)		Total phosphorus	Secchi depth	Chl. a	True color	Apparent color	Dissolved organic carbon	Total nitrogen	Total Kjeldahl nitrogen	Nitrate + nitrite
Federal Agency	3	17	# of values:	419	527	324	229	173	215	335	6	30
			# of unique lakes:	17	17	17	13	15	14	16	1	9
Federal Agency/ University	2	2	# of values:	-	799	-	-	-	-	-	-	-
			# of unique lakes:	-	2	-	-	-	-	-	-	-
LTER	3	9	# of values:	2,346	3,529	2,567	-	-	1,872	1,612	507	2,396
			# of unique lakes:	9	9	5	-	-	9	9	4	9
National Survey Program	5	2,244	# of values:	2,320	2,595	243	3,689	703	4,714	431	-	4,204
			# of unique lakes:	1,863	1,891	171	13	142	2,235	398	-	1,997
Non-Profit Agency	4	44	# of values:	1,326	4,798	2,678	-	-	-	214	9	908
			# of unique lakes:	44	41	28	-	-	-	39	1	44
State Agency	33	4,264	# of values:	34,348	42,888	29,993	16,240	5,010	14,528	5,359	7,220	25,684
			# of unique lakes:	3,914	3,186	2,309	2,092	776	1,191	634	1,991	3,216
State Agency/ Citizen Monitoring	11	7,039	# of values:	79,390	645,650	124,766	18,010	8,630	3,195	18,610	52,995	27,826
			# of unique lakes:	3,955	6,629	4,341	1,111	1,508	786	772	3,476	2,782
State Agency/Univ/ Citizen Monitoring	4	1,835	# of values:	31,809	194,177	37,993	439	1,171	1,519	10,844	-	2,112
			# of unique lakes:	1,439	1,812	1,253	302	393	574	712	-	99
Tribal Agency	5	46	# of values:	911	145	905	3	-	357	411	277	463
			# of unique lakes:	33	3	32	3	-	11	18	5	17
University	17	535	# of values:	2,273	4,412	3,939	172	69	723	2,275	-	2,397
			# of unique lakes:	326	500	415	151	69	318	396	-	171

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5 523 **Figure 4. Percentage of lakes by lake area with water quality data.** Percentage of census lakes in each lake area  
6 524 bin (top panel) compared to the percentage of census lakes for which there are limnological data for Secchi (second  
7 525 panel), chlorophyll *a* (third panel), and total phosphorus (TP; bottom panel)  
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10 528 Using the three most sampled variables in the dataset (Secchi depth, chlorophyll concentration  
11 529 and total phosphorus), we found that larger lakes were more likely to be sampled for water quality than  
12 530 smaller lakes (Figure 4). This result was expected given the economic and recreational interest in larger  
13 531 lakes, including easier public access. Previous research has already documented this basic pattern in 6 of  
14 532 the states included in LAGOS-NE [30]. Across all states, almost 80% of lakes > 400 ha have water  
15 533 quality data.

16 534 Lakes are also unevenly sampled through time, depending on the variable (Figure 5). Some  
17 535 programs' focus is on long-term monitoring, whereas others are short-term initiatives. Typically, long-  
18 536 term monitoring programs are localized to a few lakes, although there are exceptions (e.g., monitoring for  
19 537 acid rain in the NE in the 1980's-present has resulted in good temporal and spatial coverage for some  
20 538 variables through time and space [31].

21 539 **Figure 5. The number of years of water quality data by lake.** The number of years for which at least one sample  
22 540 is taken during the summer stratified season (15 June to 15 September) for: Secchi depth in meters, total phosphorus  
23 541 in ug/L, total nitrogen in ug/L (includes both measured and calculated values), and chlorophyll *a* in ug/L.  
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## 26 544 27 543 28 544 **6. Description of LAGOS-NE<sub>GEO</sub> v1.05 data module**

29 545 The LAGOS-NE<sub>GEO</sub> module includes information on the ecological context of the census lakes,  
30 546 their watersheds, and their regions. The information provided in the data tables for this module is  
31 547 organized into three main themes in which data are exported into individual tables: CHAG - climate,  
32 548 hydrology, atmospheric deposition of nitrogen and sulfur, and surficial geology; LULC - land use/cover,  
33 549 impervious cover, canopy cover, slope and terrain indices, and dam density; and CONN - lake, stream,  
34 549 and wetland abundance and connectivity measures (Figure 2). We also provide the GIS coverages that  
35 550 include some of the underlying data for this module, including: lake polygons and their hydrologic  
36 551 classifications defined in [17]; wetland polygons and their classification; streams as a line coverage and  
37 552 their classification by stream order; the zones used for this study (state and county; hydrologic units [at  
38 553 the 4, 8 and 12 scales; [32]]); and, lake watersheds (IWS). We also include boundaries of U.S. states and  
39 554 Canadian provinces for mapping.  
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### 42 556 43 557 **Data sources of the LAGOS-NE<sub>GEO</sub> module**

44 558 Detailed information on data sources are found in 'Additional File 5' in Soranno et al. [17].  
45 559 Almost all data sources for this module are from national-scale datasets and thus use standardized  
46 560 methods throughout the study extent.  
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### 48 562 **Data-integration methods of the LAGOS-NE<sub>GEO</sub> module**

49 563 All methods to create this module are described in 'Additional files 5, 7, 8, 13, and 14' in  
50 564 Soranno et al. [17]. Briefly, we calculated the metrics for this module that describe the ecological context  
51 564 surrounding lakes by developing project-specific GIS tools in the ArcGIS environment, which are  
52 565 referred to as the LAGOS GIS Toolbox (and made available here: [33]). The toolbox outputs multiple  
53 566 individual data tables of calculated values organized by the above three data themes that are then  
54 567 imported into LAGOS-NE<sub>GEO</sub> for different spatial classifications, including values calculated at the level  
55 568 of the individual lake, 100 m and 500 m buffers around each lake, the lake IWS, states and counties,  
56 569 hydrologic units, and ecological drainage units (an ecoregion spatial classification). The unique identifiers  
57 570 for this data module are the zone ID's for each spatial classification for which we calculate these metrics.  
58 571 In other words, we calculate land use around a lake in each of the zones of the many spatial classifications  
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4 573 in LAGOS-NE. However, the data are exported into individual tables by spatial classification. Therefore,  
5 574 there are different numbers of rows in each table; for example, there are 51,101 rows for the land use  
6 575 metrics calculated for the 100 m lake buffer because there are 51,101 lakes that have a 100 m buffer area,  
7 576 but only 17 rows for the land use metrics calculated for the state spatial classification.  
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#### 10 578 **Quality control of the LAGOS-NE<sub>GEO</sub> module**

11 579 The full description of error analysis for this module is described in ‘Additional file 14’ in Soranno et al.  
12 580 [17]. The quality control procedures for this module included procedures to identify possible errors or  
13 581 improbable values as a result of the extensive automated GIS data processing that creates the LAGOS-  
14 582 NE<sub>GEO</sub> data tables and to correct those problems. We assumed that the original data layers had already  
15 583 gone through extensive quality control by the originators of the datasets. We defined errors and  
16 584 improbable values to be: 1) values that did not make ecological sense; 2) values that were well beyond  
17 585 what has been observed in previous studies; 3) values that are not technically feasible; or, 4) null values  
18 586 that indicate an absence of data, when in fact data exist based on the input data coverages. Note, it was  
19 587 not our intention to remove statistical outliers that may or may not be real/true values. Rather, we  
20 588 conducted procedures on each exported table that included: verifying column headers and units, mapping  
21 589 the exported data to evaluate mapping extent and boundary issues using visual inspection, mapping the  
22 590 data distributions of each value, identifying values that were missing or zero, plotting distributions of the  
23 591 data, ensuring that proportions summed to 100 where relevant, and inspecting univariate plots of metrics  
24 592 that are known to be related (e.g., % urban land use versus % impervious surface).  
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#### 27 594 **Data in the LAGOS-NE<sub>GEO</sub> module**

28 595 This module contains the largest amount of data of any of the modules. For example, Figure 6 shows the  
29 596 wide range of ecological context for the LAGOS-NE study area calculated for three different spatial  
30 597 classifications. For those variables that are measured coarsely (e.g., baseflow, runoff, atmospheric  
31 598 deposition, geology), we calculated variables for only the broader spatial classifications. For example, we  
32 599 did not calculate baseflow for spatial classifications finer than HUC12 because the underlying data for  
33 600 baseflow is estimated on a zone generally coarser than the area of a lake watershed.  
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38 604 **Figure 6. Example ecological context variables by spatial classification in LAGOS-NE.** The top four panels are  
39 605 zoomed in to selected regions of Minnesota and Wisconsin so that the zone boundaries can be seen. The upper left  
40 606 panel shows stream density in each lake IWS, and the upper right panel shows the percent of connected wetlands in  
41 607 each lake IWS. The middle left panel shows the 2011 percent urban land use/cover in each hydrologic unit code 12  
42 608 (HUC12), and the middle right panel shows the 2011 percent agricultural land use/cover in each hydrologic unit  
43 609 code 12 (HUC12). The lower left panel shows the 2010 nitrogen deposition in each HUC8, and the lower right panel  
44 610 shows the average percent of streamflow that is baseflow in each HUC8.  
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## 7. Research to date using LAGOS-NE

Prior versions of this database have supported numerous peer-reviewed publications to date. In particular, LAGOS-NE is ideally suited for studying the local to regional controls of water quality through both space and time because of the large of number of lakes with in situ water-quality measurements and its wide gradients of ecological context. The lake census dataset also makes it possible to quantify the types of biases present in the dataset to assess the potential influence of uneven sampling efforts on results across both space and time. Below, we describe the types of research questions that have been and are being addressed using LAGOS-NE, organized according to three main topics related to studying water quality across space and time in thousands of lakes. We have published 10 articles using portions of this database, and 13 articles are in review or preparation presently.

### Methods and database development for macrosystems ecology:

Several of our lines of research have required the development of novel methods and the application of existing methods in novel ways. Much of the impetus for this work on methods and database development has been driven by two needs. The first, was to further develop the database--i.e., creating derived and predicted data as a new data product that is publicly accessible (e.g., [28]). The second was to better understand the spatial and temporal distribution of data contained in LAGOS-NE and to further our understanding of important ecological attributes of lakes across multiple spatial scales. These two needs are not mutually exclusive--analyses that have helped contribute data to LAGOS-NE have also addressed important ecological questions.

Three data gaps were identified early during database development including: (1) a lack of lake depth information (lake depth drives many in-lake processes), (2) the need to develop a flexible method for creating ecological regions from multi-themed mapped data, which are often used in macroscale research to account for broad-scale patterns and processes and, (3) the need for developing ways to measure freshwater connectivity to account for the transport and processing of materials in lakes at broad scales. For the first gap, Oliver et al. [28] used a linear mixed model to predict lake depth for lakes where in situ measurements were lacking, allowing the relationship between surface area and lake depth to vary by region because of the strong regional differences in this relationship. Predictions in some regions were far better than other regions, potentially due to differences in underlying geomorphology. To address the second gap, Yuan et al. [34] developed a novel spatially constrained spectral clustering algorithm that balances geospatial homogeneity and region contiguity, to delineate ecological regions. Cheruvilil et al. [35] has since applied this clustering algorithm across the 17 state study region and tested the ability of newly developed regions to capture variation in lake nutrients and water clarity. Finally, to address the third gap, Fergus et al. [29] developed approaches for determining freshwater connectivity of lakes, streams, and wetlands across broad spatial extents. The resulting freshwater metrics and analysis provide insight into the spatial distribution of surface-water connectivity types across the LAGOS-NE study area and provide LAGOS-NE users with novel metrics of connectivity for use in future research.

A further challenge in large, integrated databases such as LAGOS-NE is the well-known problem with data derived from analytical methods related to the issue of detection limits [36]. Stow et al. (in prep) studied the in situ concentrations that were too low to be quantified by standard analytical practices — measurements that are termed left-censored or below a detection limit of an analytical method. Unfortunately, detection limits were only sometimes reported (although, we do include those data in LAGOS-NE<sub>LIMNO</sub> where available). In some cases, low values were flagged as being censored, with an explanation as to the reason for censoring the data value, but in other cases the reason for censoring was not clear. In some instances, patterns in the data suggested that ad hoc substitutions for censored observations may have occurred without clear documentation. Stow et al. (in prep) describe a statistical approach that can be used to accommodate left-censored data during macroscale statistical analyses. This work also led to refining how censored observations were reported in LAGOS-NE, which have been incorporated into all later versions of LAGOS-NE<sub>LIMNO</sub>, including v1.087.1.

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4 666 Lake water quality is affected by many ecological context features, such as lake physical  
5 667 characteristics, land cover, land use, and climate. The relationship between these features and the water-  
6 668 quality measurements are not always linear. In addition, the data tend to be noisy and often contain  
7 669 missing values, which makes it challenging to fit effective statistical models. To overcome these  
8 670 challenges, Yuan et al. [37] developed a novel algorithm for learning non-linear features to predict lake  
9 671 water quality. The algorithm also enables the missing values to be imputed in a way that preserves the  
10 672 relationship between the predictors and response variables. Furthermore, because many of the lake water-  
11 673 quality variables are strongly correlated with each other, their models are expected to be similar. This  
12 674 similarity information can thus be exploited to build better models especially for the lake water-quality  
13 675 variables that have very few observations because they are not sampled frequently. Yuan et al. (in prep)  
14 676 are developing a machine learning approach known as multi-task learning that can simultaneously build  
15 677 regression models of multiple lake water-quality variables for a large number of lakes, taking into account  
16 678 both the correlation between the variables and the spatial autocorrelation among the lakes. Because we  
17 679 expect many ecological datasets across broad geographic scales to have similar data gaps and challenges  
18 680 as LAGOS-NE, we think these methods will be extremely valuable for other researchers studying  
19 681 different macroscale questions.  
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21 683 *Understanding spatial variation in lake nutrients and eutrophication at sub-continental scales:*

22 684 LAGOS-NE allows investigation of spatial variation in lake nutrients and eutrophication at  
23 685 macroscales. For example, Lapierre et al. (in prep) identify general spatial principles that constrain  
24 686 relationships between ecosystem variables with different spatial structures. In other cases, specific  
25 687 questions regarding spatial patterns have focused on identifying important landscape controls on nutrients  
26 688 and their ratios [38], potential stress induced on phytoplankton communities by high nitrogen levels  
27 689 (Filstrup et al. in prep), and spatial autocorrelation in lake-specific relationships between chlorophyll and  
28 690 nutrients and carbon [39]. In addition, LAGOS-NE contains a wealth of information on a variety of lake  
29 691 ecosystem types. Shallow lakes, in particular, are very abundant across the study area and represent  
30 692 systems that can exhibit hysteresis in response to lake eutrophication. Cheruvilil and Wagner (in prep) are  
31 693 investigating the spatial distribution and temporal dynamics of water clarity in shallow lakes of the  
32 694 LAGOS-NE study area.  
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34 696 An important area of research, and one that was a motivating factor for the creation of LAGOS-  
35 697 NE, is understanding the importance of cross-scale interactions (CSIs) — where ecological processes  
36 698 operating at one spatial or temporal scale interact with processes operating at another scale — in lake  
37 699 ecosystems. Because of their importance ecologically and the challenge of quantifying them over large  
38 700 spatial extents, Wagner et al. [40] evaluated the statistical power of large multi-thematic, multi-scaled  
39 701 datasets, such as LAGOS-NE, to detect CSIs. This work not only helped inform the design of large-scale  
40 702 studies aimed at detecting CSIs, but also focused attention on the importance of considering CSI effect  
41 703 sizes and their ecological relevance.. To extend this work, Fergus et al. (in prep) are investigating the  
42 704 importance of both within- and cross-scale interactions in landscape models predicting lake nutrients, and  
43 705 the role that connectivity among freshwaters plays in these interactions. Understanding and predicting  
44 706 nutrients in lakes at macroscales is important to inform estimates of lake contributions to continental and  
45 707 global nutrient cycles. To date, much of this work has been performed on a nutrient-by-nutrient basis,  
46 708 despite knowing that cycles of nitrogen and phosphorus and other key elements are best understood by  
47 709 considering multiple elements in tandem, *e.g.*, in a stoichiometric framework [41] or through analysis of  
48 710 coupled biogeochemical cycles (*e.g.*, [42, 43, 44]). Currently, efforts are underway to develop spatial joint  
49 711 nutrient distribution models to evaluate how our understanding of landscape-scale drivers of lake  
50 712 nutrients and predictive performance are improved by considering multiple nutrients simultaneously  
51 713 (multivariate models) compared to traditional univariate approaches that ignore that nutrient cycles can be  
52 714 tightly coupled in freshwaters (Wagner et al. in prep).  
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4 717 Understanding temporal and spatial variation in lake eutrophication at sub-continental scales:

5 718 In addition to the vast spatial data contained in LAGOS-NE, temporal data are available for many  
6 719 water-quality variables, and some of the ecological context variables (e.g., land use/cover and  
7 720 atmospheric deposition). This is important information within the context of understanding and predicting  
8 721 how lake ecosystems have and will respond to global change, such as changes in climate and land use,  
9 722 and management activities to reduce nutrient inputs to lakes. Because we do not expect responses to such  
10 723 change and actions to be the same everywhere, these questions must be addressed across both space and  
11 724 time. In particular, recent environmental changes and management efforts have been hypothesized to both  
12 725 improve and degrade water quality in lakes. However, to date, there have been no studies to examine  
13 726 these issues comprehensively across broad scales and to examine which drivers are most strongly related  
14 727 to eutrophication status in lakes. LAGOS-NE is very well suited to answer these types of questions.

15 728 For example, nearly 3,000 lakes were examined for trends in nutrients and chlorophyll from 1990  
16 729 to 2013 using LAGOS-NE [45]. Across all lakes, nitrogen has declined, and phosphorus and chlorophyll  
17 730 have not changed. Nitrogen and stoichiometric changes in lakes were related to atmospheric deposition of  
18 731 nitrogen, providing key insight into large-scale nutrient transport and policies such as the Clean Air Act.  
19 732 Using only citizen-science data in a subset of the LAGOS-NE database, Lottig et al. [46] showed results  
20 733 that suggested little evidence for major declines or improvements in water quality. In addition, Collins et  
21 734 al. (in press) are examining the relationships between a wide range of climate metrics and water quality in  
22 735 ~11,000 lakes in LAGOS-NE to determine, 1) which climate metrics are most related to water quality; 2)  
23 736 whether physical, chemical and biological aspects of lakes respond to climate in the same way; and, 3)  
24 737 how the climate-water-quality relationship varies across space and regions with different ecological  
25 738 context. However, the temporal dynamics of lake ecosystem properties can sometimes be nonlinear and  
26 739 exhibit variability across the landscape--largely because of climate and within-lake processes. Lottig et al.  
27 740 (in prep) have developed models for understanding and predicting the often complex temporal patterns  
28 741 observed in water clarity. These studies point to the importance of considering both space and time when  
29 742 trying to understand broad-scale environmental issues in surface waters.  
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31 744 **8. Using LAGOS-NE for future research, management, and policy**

32 745 To facilitate potential future use of LAGOS-NE, we have thoroughly documented the database  
33 746 and its methods [17]; and, here, we share LAGOS-NE data with the broader research community. In this  
34 747 data paper, we include a wide range of research products, including: the water quality and ecological-  
35 748 context data; the GIS coverages underlying much of the analyses on freshwaters; and, an R package that  
36 749 facilitates use of LAGOS-NE [47]. This package includes functions to retrieve, store, and interact with the  
37 750 LAGOS-NE database that works across many different operating systems. The package should increase  
38 751 the ease with which users of the database are able to access the data and documentation while maintaining  
39 752 a reproducible workflow.

40 753 Key motives for constructing this database included interest in examining lake nutrients and  
41 754 productivity at multiple spatial and temporal scales, fostering broad-scale aquatic ecology and  
42 755 macrosystems research in an open-science platform, and providing new understanding and resources for  
43 756 management and policymakers. To this end, several team members have made presentations at scientific  
44 757 meetings about the structure and use of LAGOS-NE and subsets of LAGOS-NE data have been shared  
45 758 with other researchers and stakeholders and agency personnel in advance of this publication. These early  
46 759 uses of LAGOS-NE data by other researchers outside of our team include an investigation of patterns and  
47 760 causes of shifting distribution of a sentinel fish species (Rypel et al. in prep), developing models to  
48 761 simulate lake temperatures (Winslow et al. in prep) and fish species distributions, and developing a  
49 762 recruitment model for a popular game fish (Hansen et al. in prep). Results from the latter two efforts will  
50 763 inform state-level fisheries management as well as aid in prioritization of lakes for habitat conservation  
51 764 action across a tri-state region.

52 765 Much of the research that we and others are conducting with LAGOS-NE has implications for  
53 766 ecosystem management or environmental decision-making. In addition, we have collaborated with

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4 767 boundary organizations and decision-makers. For example, under development is a dashboard of the  
5 768 ecosystem services provided by lakes for use by land managers (Keeler et al. in prep). In addition, we  
6 769 have helped the state of Michigan determine lake-specific nutrient standards [48]. Our hope is that this  
7 770 database and the associated support tools and documentation serve as a powerful resource and a  
8 771 foundation for future research and decision-making by a broad community of scientists, policy makers,  
9 772 and natural-resource managers. Indeed, our success and experience with database construction and  
10 773 research has inspired us to expand the spatial extent for LAGOS-NE. We have begun to build LAGOS-  
11 774 US, which will include similar data as LAGOS-NE but will be for the continental U.S.  
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## 14 776 **9. Challenges and recommendations for creating large, integrated, and** 15 **heterogeneous databases** 16 777 17 778

18 779 We found that the largest challenge when creating this database was integrating many small  
19 780 heterogeneous datasets that had few common standards. Although creating such large, integrated datasets  
20 781 using fully automated procedures may happen someday, it appears that we are nowhere near such  
21 782 automation today. Until standards in metadata documentation and robust ontologies are created and  
22 783 widely adopted when creating local or regional datasets, future efforts to integrate these into larger  
23 784 databases will have to rely on close collaborations among domain experts and ecoinformatics  
24 785 professionals, extensive manual interpretation of individual datasets, and funds sufficient to implement  
25 786 these labor-intensive approaches [16]. Nevertheless, it is worth the time and money invested in database  
26 787 integration if the resulting databases support new research, management, policy, public outreach, and  
27 788 education at all levels. We anticipate that LAGOS-NE will serve as a foundation for new data modules  
28 789 that can be used beyond the original intent of LAGOS-NE.  
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### 31 791 The economic value of water quality data in an integrated database

32 792 This extensive effort was supported by a U.S. National Science Foundation grant that totaled \$2.4  
33 793 million, along with resources from other projects. Our team ranged in size from 14-20 individuals across  
34 794 the six years of the project, with many members compiling and integrating data, authoring metadata,  
35 795 creating new data products, and implementing quality control procedures, resulting in a tremendous  
36 796 number of person-hours. However, when one puts the cost of the data collection for the water quality data  
37 797 in the first place, the expense of this post-processing integration work is not as large as it sounds. Sprague  
38 798 et al. [16] suggest that a single sample (estimated for collecting nutrient or chemistry data from streams)  
39 799 ranged in cost from \$2000-\$6000 per sample. If we assume similar rates for lake sampling and multiply  
40 800 this cost by the total number of records of nutrient or chemical samples in LAGOS-NE (n=589,909), then  
41 801 the combined estimate to collect the water quality data found in LAGOS-NE is in the range of \$1.2 - \$3.5  
42 802 billion. It cost us between 0.07 - 0.20 % of the cost to sample the data in the first place to harmonize these  
43 803 half a million records, and to build an ecological-context database for them. This relatively small  
44 804 investment in preserving, documenting, and harmonizing these valuable datasets creates the needed  
45 805 infrastructure for new broad-scaled research, management, education, and outreach uses.  
46 806

### 49 807 Strategies for broad-scale data-integration efforts:

50 808 One challenge is to prioritize research areas which datasets that may benefit from a similar type  
51 809 of integration. State water quality datasets were an excellent source of quality data for integration and  
52 810 conducting broad-scaled research on aquatic systems. There are likely other such data sources that would  
53 811 benefit from being integrated as we have done here. We recommend the following strategies to make the  
54 812 best use of future data integration efforts.  
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57 814 (1) The database integration effort should be driven by key underlying research questions or goals, and  
58 815 grounded in a strong conceptual foundation of the important features to include. In our case, the principles  
59 816 of landscape limnology [18,19,20,12] guided the development of LAGOS-NE which helped us to  
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4 817 prioritize geospatial and lake features for inclusion in the database because the addition of any data type  
5 818 or dataset cost time and money.

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7 820 (2) For databases with more than one major data type, it is very helpful to build the database in modular  
8 821 form, each with its own versioning system, specific data integration methods, and quality control  
9 822 procedures. This strategy was not a primary goal at the outset of our project, but, it emerged somewhat  
10 823 organically through the life of the project. We now recognize the many benefits that the modularity brings  
11 824 to the database, including making it much easier to be dynamic rather than static by providing a platform  
12 825 for the addition of new data, new types of data, and new modules in the future (such as for biological  
13 826 data, or data from high-frequency sensors).

14 827  
15 828 (3) The entire process should be grounded in an open-science framework. Knowing that the database,  
16 829 design, and methods were to be shared and made usable by future users influenced our decisions  
17 830 throughout the process, and made documentation a high priority throughout.

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19 832 (4) Creation of LAGOS-NE required a strong focus on team science, and in particular the roles of and  
20 833 incentives for early-career researchers in such efforts. This type of research cannot be conducted in a  
21 834 single-investigator mode, but requires a highly collaborative and effective team-based model (e.g., [49,  
22 835 50, 51]). We explicitly considered strategies for ensuring that early-career team members get credit for  
23 836 their contributions [52]. We recommend providing these essential team members with opportunities for  
24 837 leadership, project management, personnel management, and intellectual growth. For example, they can  
25 838 be part of major decisions and can lead smaller efforts throughout the project, as well as be given power  
26 839 to shape team policies and practices. This integration of early-career researchers into the entire research  
27 840 team and effort will give early-career professionals deep knowledge of the database, the procedures, as  
28 841 well as the skills to conduct such work in the future.

29 842  
30 843 (5) The decision how to disseminate the database documentation needs to be considered early in the  
31 844 project. For example, database documentation papers are rare, especially in ecology, but are very  
32 845 important. The dissemination of the documentation and procedural approaches for making this large,  
33 846 integrated, and heterogeneous database had to be published prior to making the database available [17]  
34 847 and prior to publication of research results stemming from LAGOS-NE because methods sections in  
35 848 journal articles are too short to include all the necessary documentation of such methods. Other  
36 849 researchers may be discouraged by the very real consequence that publishing such products take time and  
37 850 energy investments that may slow down production of research publications. However, such a paper was  
38 851 instrumental in supporting later research articles that used LAGOS-NE. Before making all of LAGOS-NE  
39 852 available to researchers, we supported open science by publishing subsets of LAGOS-NE data that were  
40 853 used in individual publications (e.g., [53, 54]). Therefore, we recommend that this (and other) database  
41 854 documentation papers become a more standard type of paper to describe the extensive methods involved  
42 855 and to supplement data papers. Such papers will facilitate the use, extension, and translation of these  
43 856 databases well into the future, as well as foster future research on broad-scale, complex, and societally-  
44 857 relevant environmental questions.

#### 45 858 46 859 **AVAILABILITY OF SUPPORTING DATA**

47 860 The data sets supporting the results of this article are available in the Ecological Data Initiative repository,  
48 861 including the following specific components:

- 49 862 • LAGOS-NE-LOCUS v1.01:  
50 863 <https://portals.edirepository.org/nis/mapbrowse?scope=edi&identifier=100>
- 51 864 • LAGOS-NE-LIMNO v1.087.1:  
52 865 <https://portals.edirepository.org/nis/mapbrowse?scope=edi&identifier=101>
- 53 866 • LAGOS-NE-GEO v1.05  
54 867 <https://portals.edirepository.org/nis/mapbrowse?scope=edi&identifier=99>

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- An R package to access the data in this paper: <https://github.com/cont-limno/LAGOS>
- GIS coverages of the freshwater features that are linked to the data tables: <https://portals.edirepository.org/nis/mapbrowse?scope=edi&identifier=98>
- Individual water quality datasets and associated metadata for LAGOS-NE<sub>LIMNO</sub>: url

## DECLARATIONS

### List of abbreviations

LAGOS-NE – LAke multi-scaled GeOSpatial and temporal database for the 17 Northeastern and Midwest U.S. states  
GIS – Geographic Information System  
US-EPA – United States Environmental Protection Agency  
EML – Ecological Metadata Language  
USGS – United States Geological Survey  
NHD – National Hydrography Dataset  
WBD – Watershed Boundary Dataset  
IWS – Interlake Watershed  
SRP – Soluble Reactive Phosphorus  
TP – Total Phosphorus  
TN – Total Nitrogen  
DOC – Dissolved Organic Carbon  
MAV – Maximum Allowable Value  
TDN – Total Dissolved Nitrogen  
IQR – Interquartile Range  
LULC – Land Use Land Cover  
CONN – Connectivity and abundance (lake, stream, and wetland)  
CHAG – Climate, Hydrology, Atmospheric deposition of nitrogen and sulfur, and surficial Geology  
HUC – Hydrologic Unit Code  
CSI – Cross Scale Interactions

### Competing interesting

The authors declare they have no competing interests

### Funding

The creation of LAGOS-NE was supported by:

The National Science Foundation MacroSystems Biology Program in the Emerging Frontiers Division of the Biological Sciences Directorate (EF-1065786, EF-1638679, EF-1065649, EF-1065818, EF-1638554) and the USDA National Institute of Food and Agriculture, Hatch project 176820 to PAS. KEW thanks the STRIVE Programme (2011-W-FS-7) from the Environmental Protection Agency, Ireland. SMC thanks the NSF Division of Biological Infrastructure (1401954).

The water quality data that are incorporated into LAGOS-NE were originally funded by the following sources:

State of Maine; Michigan Agricultural Experiment Station; Fisheries Division, Michigan Department of Natural Resources; New York State Division of Water Quality; Wisconsin Department of Natural Resources; University of Wisconsin-Madison; State/Trust; Michigan State University Agriculture Experimental Station Disciplinary Research Grant Program; US EPA; US EPA Section 106/319 Grants; Tribal General Fund; U.S. Army Corps of Engineers Federal Lakes Operation & Maintenance Funds; Aquatic Plant Management Society; Aquatic Ecosystem Restoration Foundation; Michigan State

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4 919 University; Michigan State University Department of Fisheries and Wildlife; EPA Star Fellowship to  
5 920 K.S.C. (U-915342-01-0); Andrew W. Mellon Foundation; Federal Aid in Sport Fish Restoration Program  
6 921 (Grant F-69-P, Fish Management in Ohio) administered jointly by the U.S. Fish and Wildlife Service and  
7 922 the Ohio Department of Natural Resources, Division of Wildlife; Iowa Department of Natural Resources  
8 923 (Contract #ESD04HALFasch110155); Minnesota Pollution Control Agency; NSF-Division of  
9 924 Environmental Biology; Ohio DNR Division of Wildlife; University of Rhode Island Watershed Watch;  
10 925 NSF Kellogg Biological Station Long Term Ecological Research (LTER) Program, DEB 1027253; NSF  
11 926 North Temperate Lakes LTER Program, DEB 1440297; Lac du Flambeau Band and Bureau of Indian  
12 927 Affairs; Indiana Department of Environmental Management; Missouri Department of Natural Resources;  
13 928 Clean Water Act Section 16; Michigan Department of Environmental Quality; Massachusetts Water  
14 929 Supply Protection Trust; US EPA Clean Air Markets Division (LTM Network); US EPA Office of  
15 930 Research and Development; New York City Department of Environmental Protection (NYSDEP); City of  
16 931 New York; USGS Water Availability and Use Science Program (WAUSP); U.S. Geological Society;  
17 932 New York State Energy Research and Development Authority; National Institute of Food and  
18 933 Agriculture, U.S. Department of Agriculture, Hatch Grant 1003732; the New York State Department of  
19 934 Environmental Conservation; Lake Sunapee Protective Association; National Oceanic and Atmospheric  
20 935 Administration; Gull Lake Quality Organization; Clean Michigan Initiative; NSF grant DEB-1455461.  
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#### 26 938 **Authors' contributions**

27 939 Data for the database were contributed by: LCB, MB, KEB, MGB, MTB, SRC, JWC, KSC, MC, JDC,  
28 940 JAD, JD, CTF, CSF, MJG, LTG, JDF, SKH, PCH, EH, CH, JRJ, KJH, LLJ, WWJ, JRJ, CMK, SAK, BL,  
29 941 JAL, YL, NRL, JAL, LJM, WHM, KEBM, PBN, SJN, MLP, DCP, AIP, DMP, POR, DOR, KMR, LGR,  
30 942 OS, NJS, PAS, NRS, EHS, JLS, JMT, TPT, MV, GW, KCW, KEW, JDW, and MKW. The idea to create  
31 943 the database was conceived by PAS and KSC. PAS coordinated the different activities across team-  
32 944 members to build LAGOS-NE. The database was designed by EGB, PNT, CG, and PAS; and, created and  
33 945 managed by EGB. The following authored metadata for the individual water quality data sets using  
34 946 information provided by the data providers: MTB, CKB, KSC, SMC, CEF, CTF, ENH, NRL, SKO, NKS,  
35 947 PAS, EHS, and KEW. CEF prepared the integrated LAGOS-NE metadata, and developed the protocols  
36 948 for authoring the EML metadata; and, CEF and CKB created EML metadata for the 87 water quality data  
37 949 sets. SKO wrote the final variables definitions for the integrated metadata. CG helped to prepare the  
38 950 needed metadata and documentation for loading the data in the data repository. Code for importing the  
39 951 datasets into the database was written by EGB, STC, NRL, and SY. JS and SBS performed geospatial  
40 952 analyses and created the LAGOS-GIS Toolbox. The conceptual foundation for measuring freshwater  
41 953 connectivity was led by CEF. SBS developed the methods to delineate lake watersheds. The quality  
42 954 control methods development and analysis on LAGOS-NE<sub>LIMNO</sub> were conducted by NRL; the quality  
43 955 control of LAGOS-NE<sub>GIS</sub> was led by CES and SMC, and conducted by CES, SMC, CEF, NKS, and  
44 956 KEW. The quality control of LAGOS-NE<sub>LOCUS</sub> was conducted by EGB. Many authors who were part of  
45 957 the database integration team wrote the technical documentation; JFL served as editor of these technical  
46 958 documents. Tables and figures were prepared by SMC, KBSK, JFL, NRL, ACP, NKS and PAS and  
47 959 edited by many of the contributing authors. SKO and JJS wrote the LAGOS-NE R package. NJS prepared  
48 960 the GIS data and its corresponding metadata. PAS coordinated the writing of the manuscript, and major  
49 961 parts of the manuscript were written by: PAS, KSC, SMC, JFL, NRL, SKO, JJS, EHS, PNT, TW, and  
50 962 SY. After the lead author, authors are listed alphabetically.  
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#### 54 964 **Competing Interests**

55 965 The authors declare that they have no competing interests  
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#### 57 967 **Acknowledgments**

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968 We thank the contributions over the past several decades of many hundreds to thousands of governmental,  
969 tribal and citizen scientists whose efforts from lake sampling to water quality analysis to dataset  
970 compilation enabled LAGOS-NE to become a reality and a resource for the future. Specifically, we  
971 dedicate this paper to the memory of Jody Connor, whose three decades of innovative and science-driven  
972 lake management while working for the New Hampshire Department of Environmental Services  
973 generated meaningful contributions to the protection and restoration of lake quality and to lasting data  
974 legacies such as volunteer monitoring in the state. This is Great Lakes Environmental Research  
975 Laboratory contribution number xxxx. Any use of trade, firm, or product names is for descriptive  
976 purposes only and does not imply endorsement by the US Government.

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**Figure 1. Map of the study extent of LAGOS-NE.** Map includes 17 states in the upper midwest and northeastern U.S. outlined in white and 51,101 lakes  $\geq 4$  ha shown as blue polygons. Some lakes extend beyond state borders and are included in the database if it was possible to delineate their watersheds. Watershed boundaries rather than state boundaries were used for all analyses of lakes, streams and wetlands. The map is modified from [17].

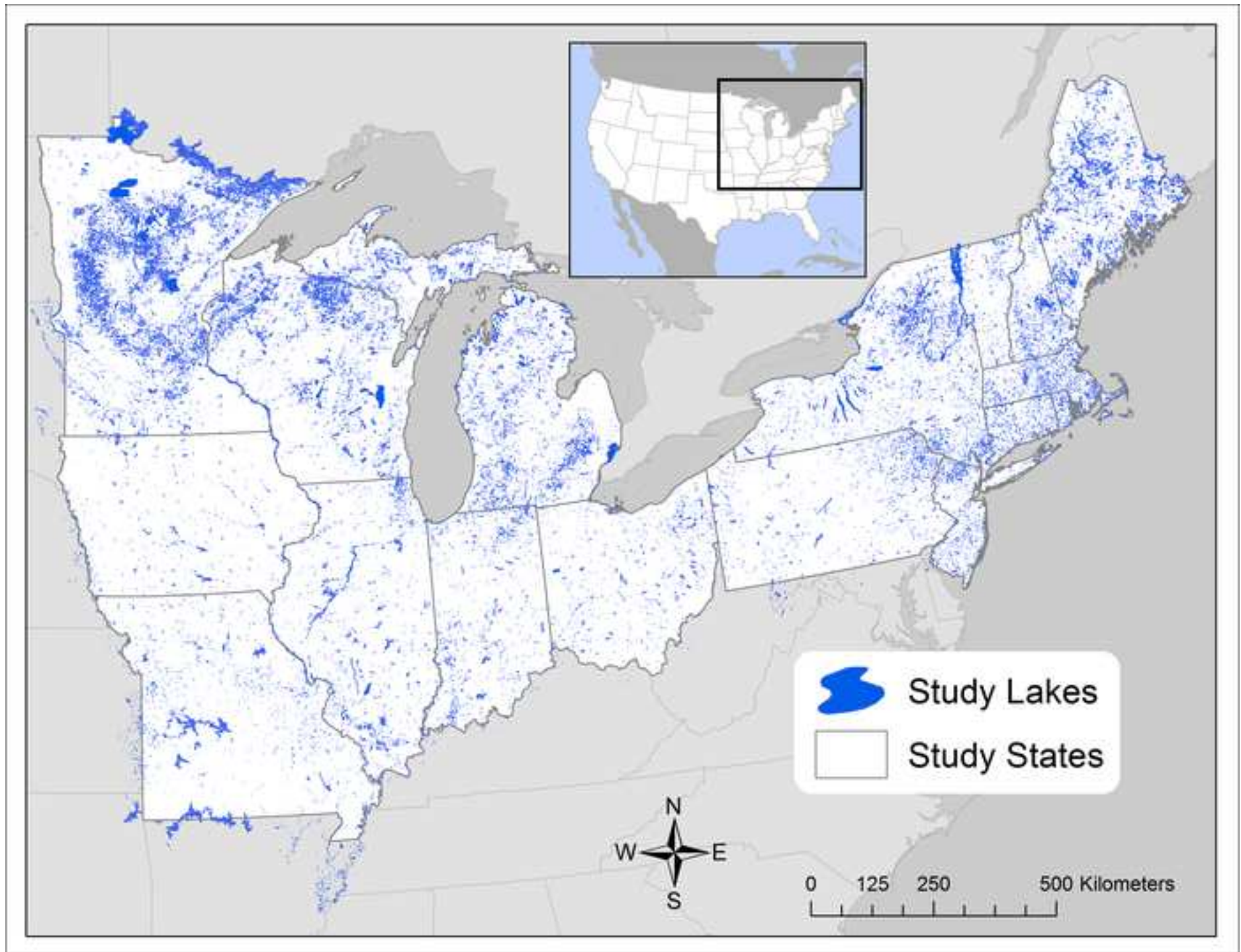
**Figure 2. LAGOS-NE data modules and version numbers.** The data modules and versions that are included in LAGOS-NE and are available with this paper include: LAGOS-NE<sub>GEO</sub> v.1.05, LAGOS-NE<sub>LOCUS</sub> v.1.01 (note, that in Soranno et al. [17], this module was called LAGOS-lakes), and LAGOS-NE<sub>LIMNOV</sub>.1.087.1. We include descriptions of the type of data that are included in each module; with the major categories of variables the same as those describing the data tables in Additional File 1. The black connectors among the modules show that the modules are connected to each other through common unique identifiers through the LAGOS-NE<sub>LOCUS</sub> module (either the unique lake ID or the zone ID). P is phosphorus, N is nitrogen, C is carbon, S is sulfur, atm is atmospheric, NHD is the National Hydrography Dataset, IWS is the interlake watershed, WBD is the Watershed Boundary Dataset, EDU is Ecological Drainage Unit. Figure is modified from Figure 1 in Soranno et al. [17].

**Figure 3. Examples lake watersheds (IWS) in LAGOS-NE.** The watersheds are coded by hydrologic class to which its lake belongs. Data are from the LAGOS-NE<sub>GEO</sub> v.1.01 data module and the GIS data coverages.

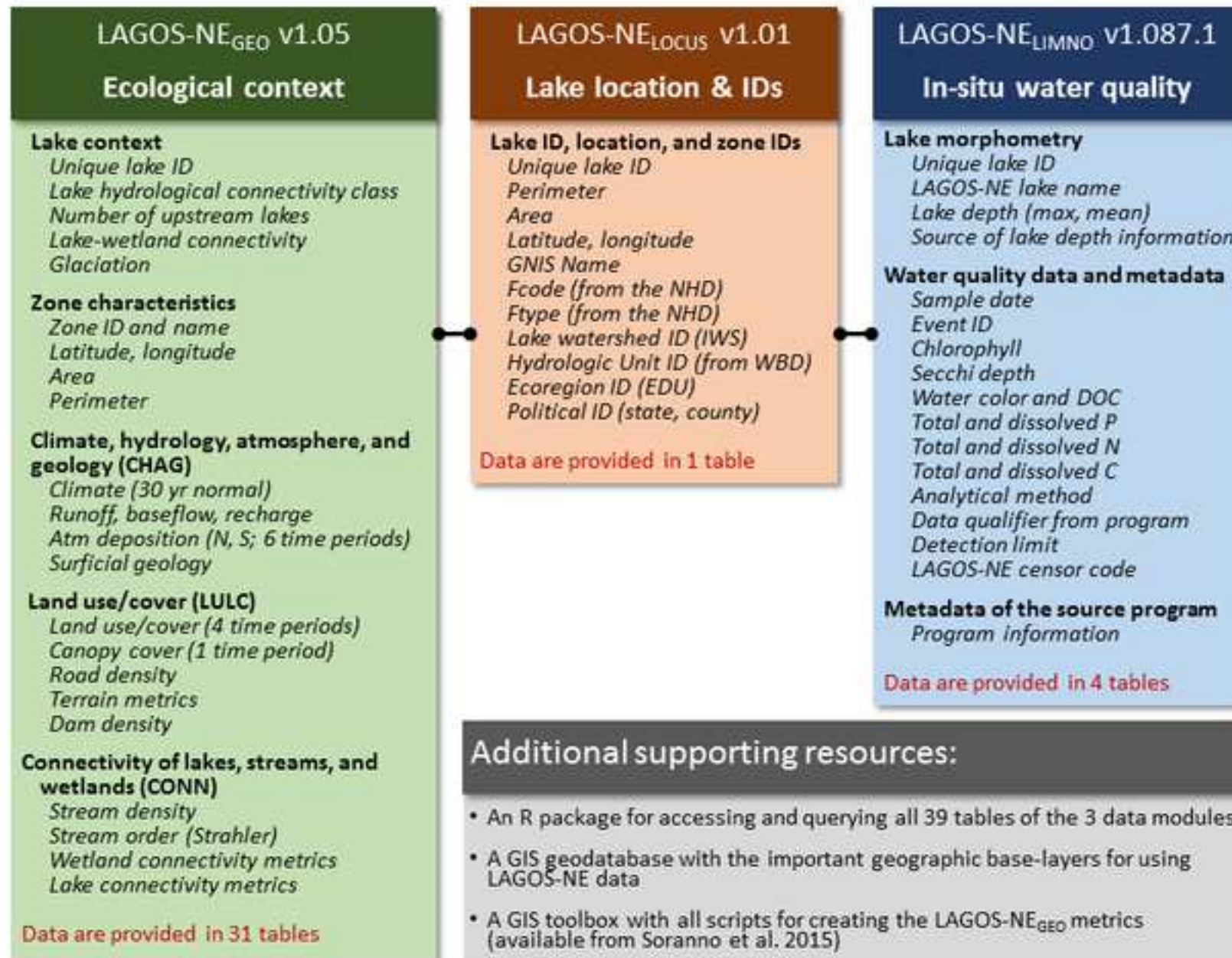
**Figure 4. Percentage of lakes by lake area with water quality data.** Percentage of census lakes in each lake area bin (top panel) compared to the percentage of census lakes for which there are limnological data for Secchi (second panel), chlorophyll *a* (third panel), and total phosphorus (TP; bottom panel)

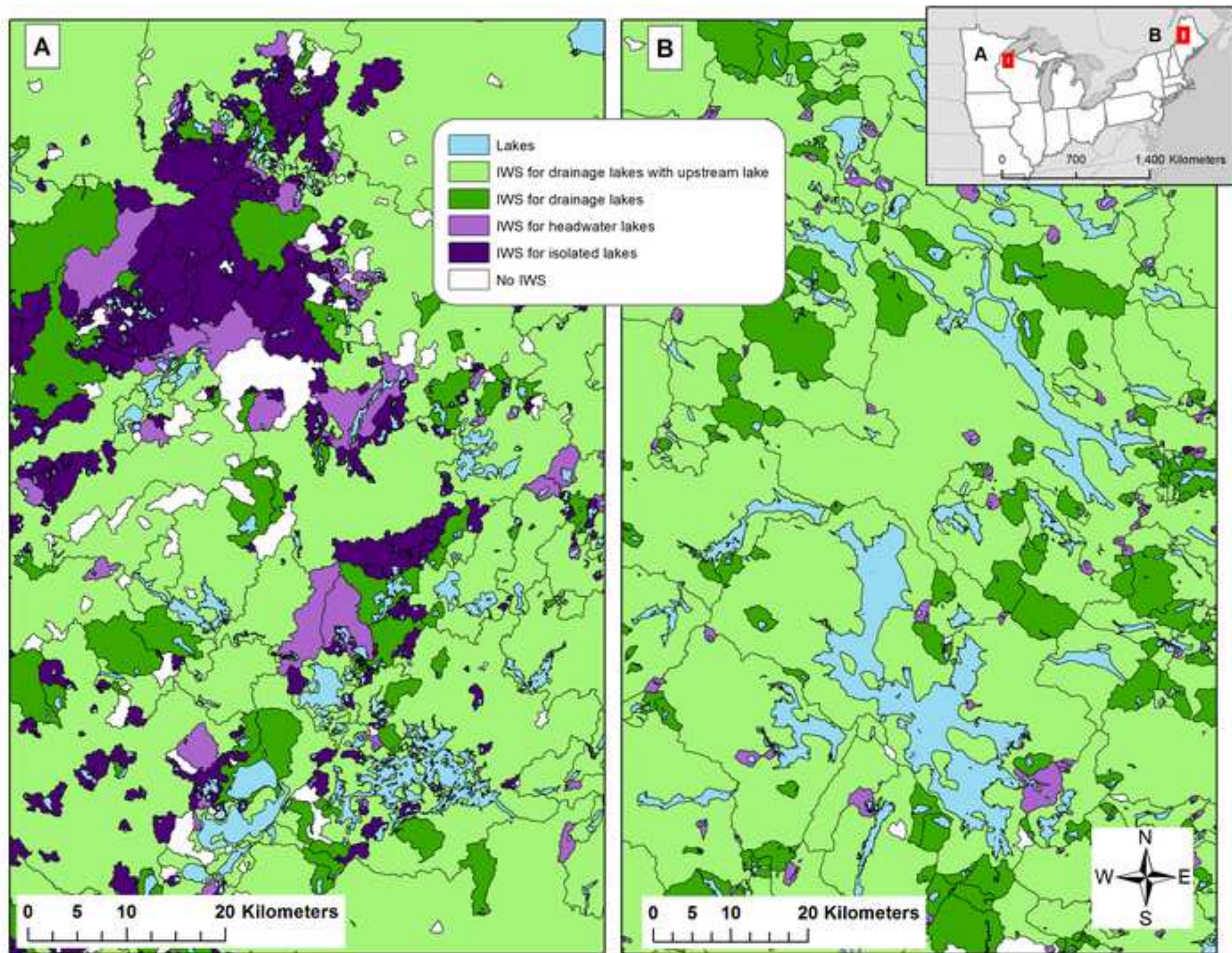
**Figure 5. The number of years of water quality data by lake.** The number of years for which at least one sample is taken during the summer stratified season (15 June to 15 September) for: Secchi depth in meters, total phosphorus in ug/L, total nitrogen in ug/L (includes both measured and calculated values), and chlorophyll *a* in ug/L.

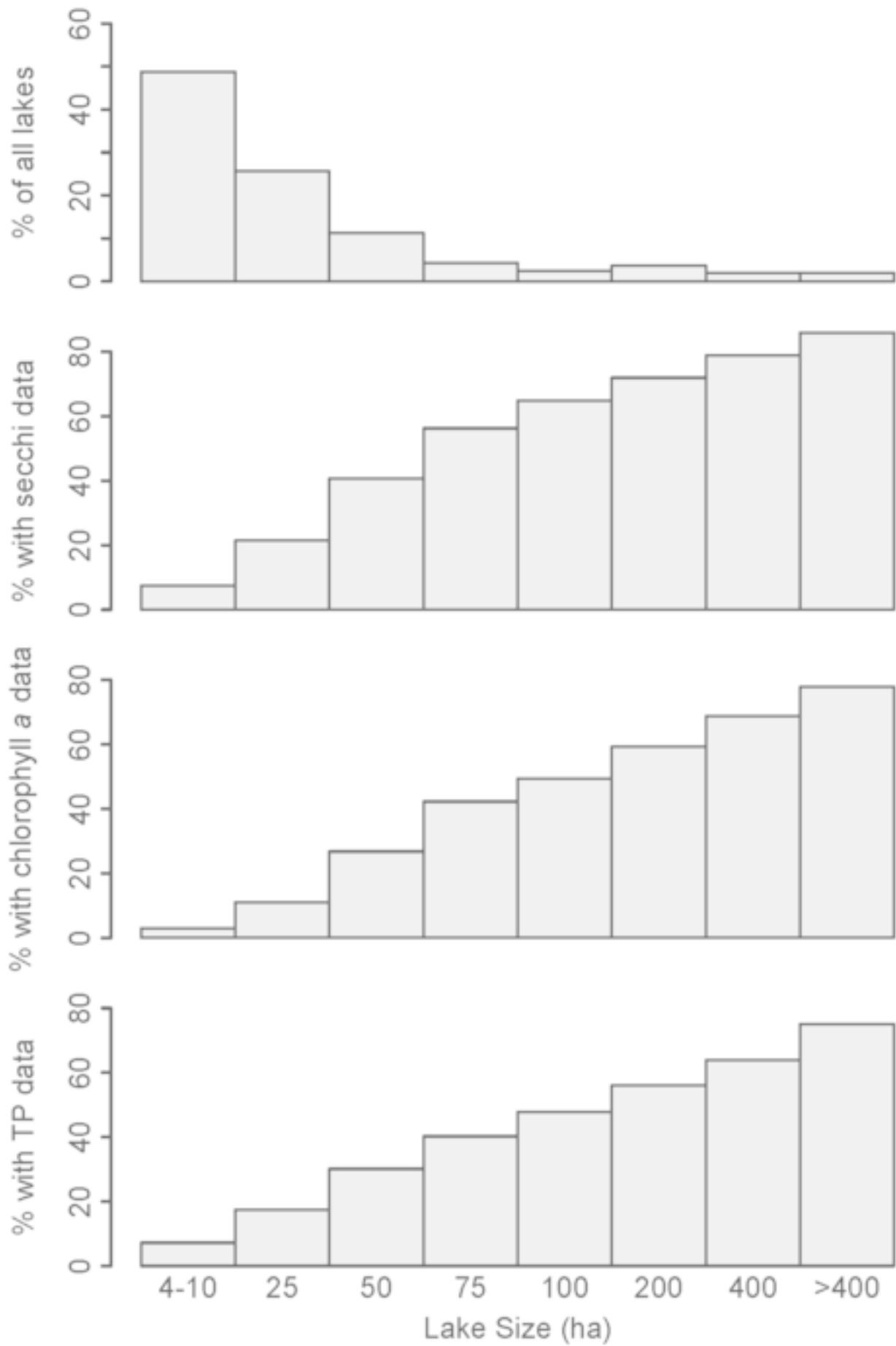
**Figure 6. Example ecological context variables by spatial classification in LAGOS-NE.** The top four panels are zoomed in to selected regions of Minnesota and Wisconsin so that the zone boundaries can be seen. The upper left panel shows stream density in each lake IWS, and the upper right panel shows the percent of connected wetlands in each lake IWS. The middle left panel shows the 2011 percent urban land use/cover in each hydrologic unit code 12 (HUC12), and the middle right panel shows the 2011 percent agricultural land use/cover in each hydrologic unit code 12 (HUC12). The lower left panel shows the 2010 nitrogen deposition in each HUC8, and the lower right panel shows the average percent of streamflow that is baseflow in each HUC8.

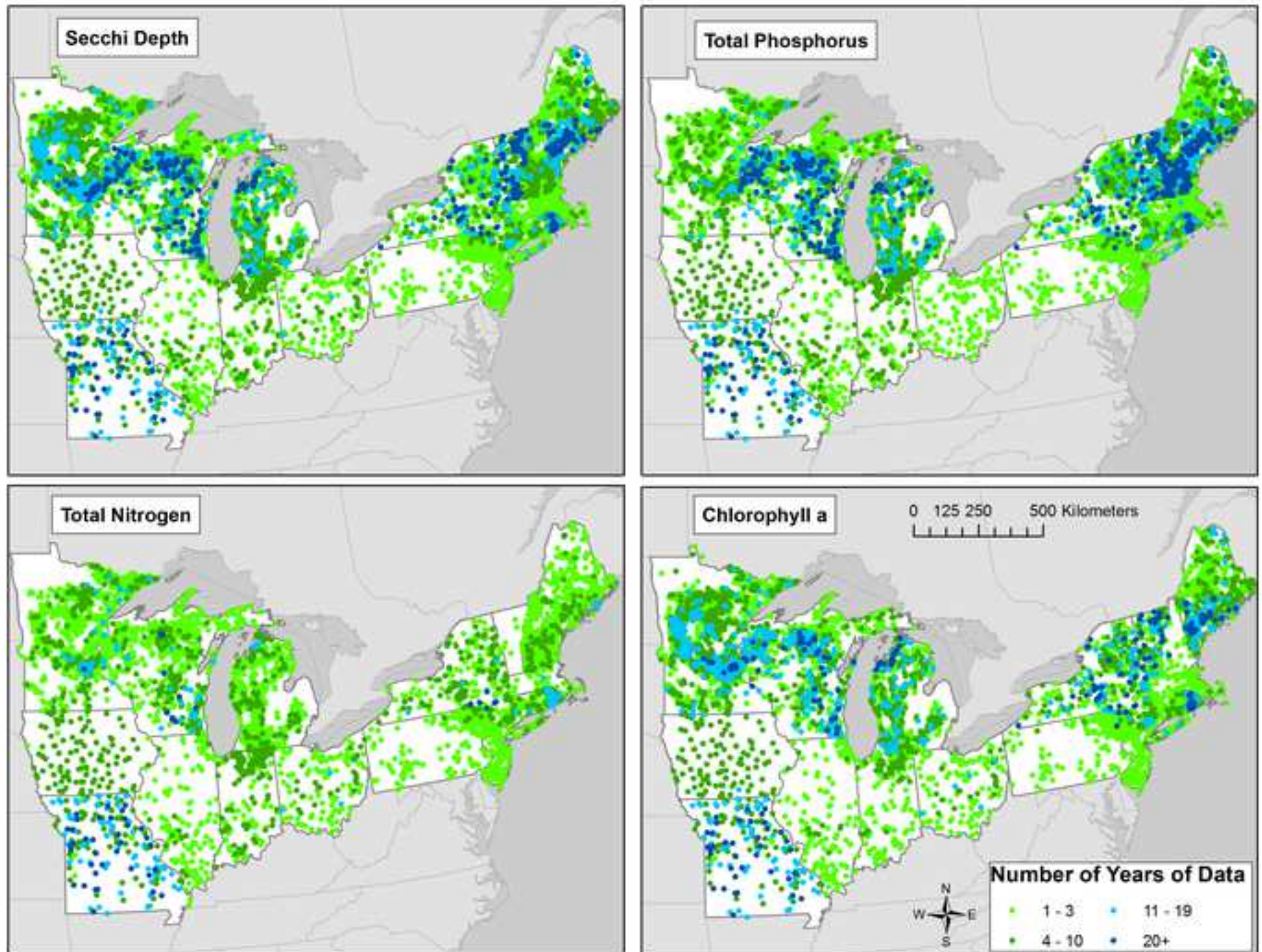


## LAGOS-NE Modules

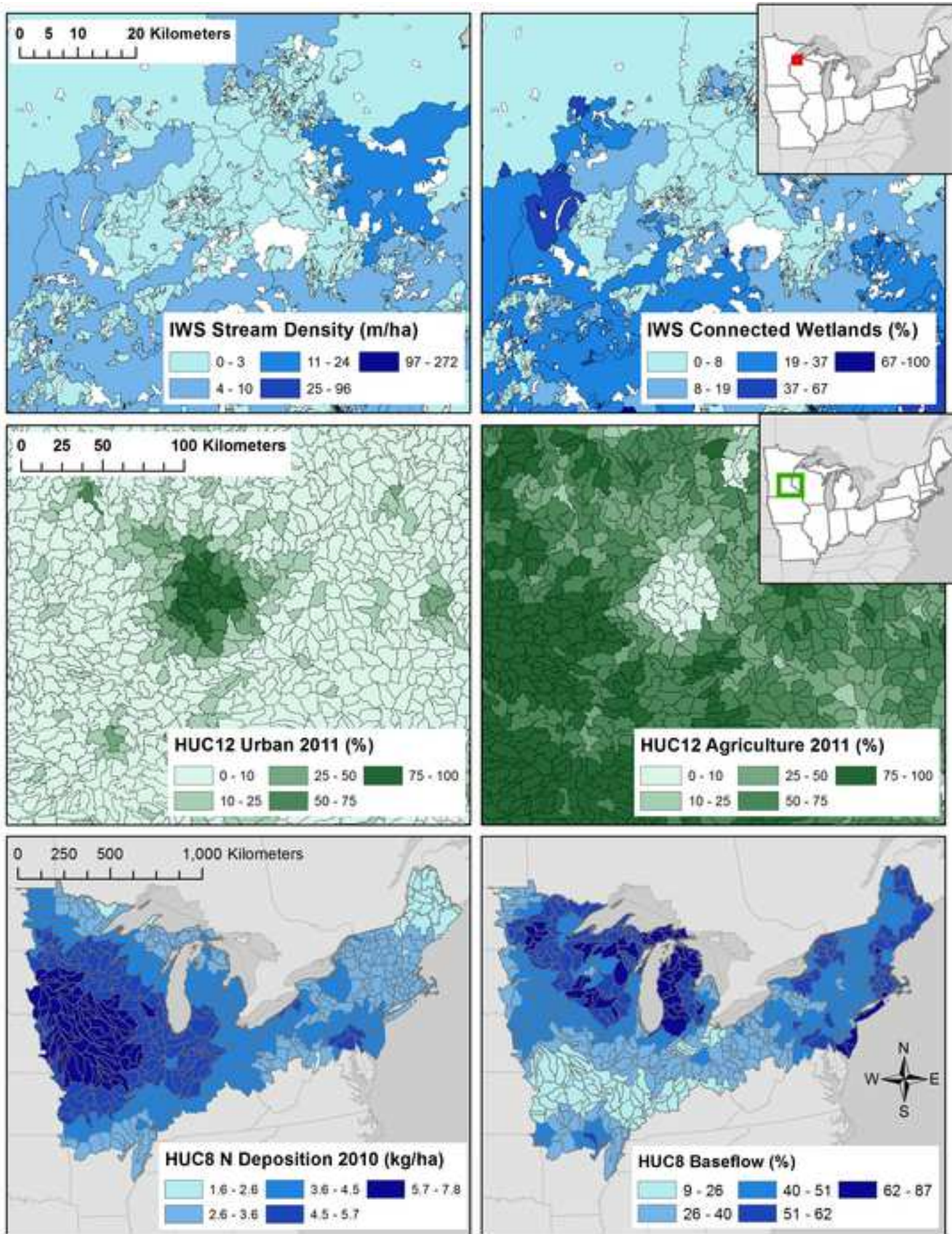















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**Supplementary Material**

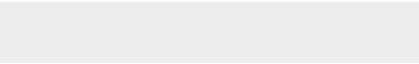

Soranno\_etal\_2017\_Additional file 1\_list of data  
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**Supplementary Material**

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Dr. Goodman, Editor-in-chief  
GigaScience

May 16, 2017

Dear Dr. Goodman,

Please find enclosed our manuscript, *LAGOS-NE: A multi-scaled geospatial temporal database of lake ecological context and water quality for thousands of U.S. lakes* by Soranno et al., which we would like to submit for publication as a *Data Note* in GigaScience. We describe and make available a very large integrated, geospatial database for water quality. Given the size and scope of the database, the Data Note is likely longer than many such articles published in this journal. However, we wanted to include sufficient detail to correctly describe the database for future use of scientists. This is the database for which we described previously in a Review article published in GigaScience in 2015 (<https://gigascience.biomedcentral.com/articles/10.1186/s13742-015-0067-4>). For this Data Note, we are making the data available, and describing the data itself. Given the reception that the previous article received, we think the research community will find our database useful. Also, we appreciated the flexibility that GigaScience provided us in drafting our previous paper that describe the methods in detail, and having the data paper published in the same journal seems to make sense so that future data users can find both papers easily. We have decided to place the data in the Environmental Data Initiative data repository as described in our paper.

We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. All authors have approved the manuscript, agree with its submission to GigaScience, and have no competing interests.

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We look forward to hearing from you.

Sincerely,



Dr. Patricia A. Soranno, corresponding author  
Professor  
Michigan State University