DATA NOTE

LAGOS-NE: a multi-scaled geospatial and temporal database of lake ecological context and water quality for thousands of US lakes

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Abstract
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 data sets across broad regions and across time into an integrated database. LAGOS-NE accomplishes this goal for lakes in the northeastern-most 17 US states. LAGOS-NE contains data for 51,101 lakes and reservoirs larger than 4 ha in 17 lake-rich US states. The database includes 3 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 3 decades for approximately 2600–12,000 lakes depending on the variable. The database contains approximately 150,000 measures of total phosphorus, 200,000 measures of chlorophyll, and 900,000 measures of Secchi depth. The water quality data were compiled from 87 lake water quality data sets from federal, state, tribal, and non-profit agencies, university researchers, and citizen scientists. 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

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 [2–4], although there is also recognition that eutrophication or its response to management actions does not progress in the same way in all lakes (e.g., [5–7]). 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., [10–12]). 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., [13–15]).

In practice, measures of water quality are often collected from a relatively small number of lakes within individual regions. In the United States, large investments have been made in water quality monitoring by federal, state, local, and tribal governments; and many, but not all, of the data sets 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 stream nutrient data obtained from NWIS, STORET, and more than 400 other organizations determined that more than 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 a database called LAGOS-NE, the “lake multi-scaled geospatial and temporal database” for thousands of inland lakes in 17 of the most lake-rich states in the upper Midwest.
and Northeastern United States (Fig. 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 ≥ 4 ha in the study area (1,800,000 km²).

We had 3 related motivations for developing this database: (i) 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); (ii) to build the capacity to apply this scientific understanding to environmental management and policy of inland waters; and (iii) 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.

LAGOS-NE comprises 3 data modules that, although integrated in the same database, were derived using different data sources and data integration methods, and thus must be version-controlled separately. LAGOS-NE LOCUS v1.01 includes lake location and physical characteristics based on an existing national-scale database of lake and streams in the United States for all lakes. LAGOS-NE GEO v1.05 includes measures of land, water, and air (ecological context) obtained from existing national-scale GIS (geographic information system) data sets and measured in multiple zones (delineated by different spatial classifications) around all lakes. This module also contains some temporal data for climate, land use/cover, and atmospheric deposition variables. LAGOS-NE LIMNO v1.087.1 includes in situ measurements of lake water quality for a subset of the above lakes. These 87 data sets of lake water quality were obtained from a combination of sources including government, tribal agencies, university researchers, citizen scientists, and non-profit agencies. Samples were taken during any season of the year from the most recent decades, mostly from the late 1980s to 2012.

The largest challenge in building LAGOS-NE was the heterogeneity of the data set formats, variable conventions and units, and metadata, none of which were standardized. Many steps of data integration required manual input from experts in diverse fields and close collaboration among specialists in ecoinformatics, database design, freshwater ecology, and geography; all combined, the effort took 6 years and involved ~15 individuals, spread across numerous institutions.

We designed the database using principles of open science so future users could ask new research questions by using the existing database or adding new data modules to the database. To ensure that users could do this, we documented the major steps of data set integration and carefully integrated metadata directly into the database itself, we emphasized data provenance, and we used a database versioning system. In this data paper, we make the following research products available: (i) data tables with the data that make up LAGOS-NE and an R package for accessing the data and integrating the tables; (ii) for each of the 87 water quality data sets, we provide the ecological metadata language (EML) metadata files that we authored after receiving the data, the data files that we processed to import into LAGOS-NE and the R-script that we wrote.
to process the data; and (iii) GIS coverages of the underlying freshwater geographic features (lakes, streams, and wetlands) that are linked to the data tables for GIS processing by researchers.

**Study Site: Midwest and Northeast US Lakes**

We selected an area of the United States known to have large numbers of lakes, well-developed lake water quality sampling programs, and that spans diverse geographic conditions and thus gradients of ecological context (Table 1). Our study area of 17 US states includes 51,101 lakes ≥ 4 ha (Fig. 1). These states are in the north temperate climatic zone, which experiences cold winters and warm, humid summers. The study area includes part of the Interior Plains, Laurentian Uplands, Appalachian Highlands, and Atlantic Plain geological provinces, and thus encapsulates a range of geological ages, glacial histories, and topography. Land use/cover is highly variable, ranging from regions of intense agriculture in the corn belt that span portions of Minnesota, Wisconsin, Iowa, Missouri, Indiana, and Ohio, to predominantly forested or urban regions of the northeastern United States, including the states of Maine, New Hampshire, New Jersey, and parts of New York, and primarily forested regions of northern Minnesota, Wisconsin, and Michigan.

Although the majority of the data that we provide are for lakes ≥ 4 ha (see below for reasons for using this threshold), we do include some data on lakes ≥ 1 ha and < 4 ha if data were available. Although there may be water quality data for some lakes in this smaller size range, ecological context variables are not available for these lakes.

**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 3 main categories of variables: (i) variables that describe the physical characteristics and location of lakes themselves; (ii) variables that describe in situ water quality; and (iii) 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 [12, 18–20]. 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, and 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 was 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 3 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 (Fig. 2). The module structure also facilitates data reuse and extension by accommodating future data modules related to any other lake or ecological context feature.

The design of LAGOS-NE and the workflow for its construction have been described previously in detail [17]. In particular, the database design is based on the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI),

**Table 1: Summary statistics for LAGOS-NE study area**

<table>
<thead>
<tr>
<th>State</th>
<th>Area (km²)</th>
<th>Number of lakes (≥ 4 ha)</th>
<th>Mean annual temperature (°C)</th>
<th>Mean annual precipitation (mm)</th>
<th>% agricultural land</th>
<th>% urban land</th>
<th>% forested land</th>
<th>% wetland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connecticut</td>
<td>12,878</td>
<td>763</td>
<td>9.7</td>
<td>1253</td>
<td>7.2</td>
<td>24.4</td>
<td>54.5</td>
<td>9.0</td>
</tr>
<tr>
<td>Illinois</td>
<td>145,920</td>
<td>2819</td>
<td>11.3</td>
<td>1005</td>
<td>68.9</td>
<td>11.9</td>
<td>15.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Indiana</td>
<td>93,717</td>
<td>1874</td>
<td>11.2</td>
<td>1072</td>
<td>62.0</td>
<td>10.8</td>
<td>22.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Iowa</td>
<td>145,736</td>
<td>903</td>
<td>9.1</td>
<td>881</td>
<td>78.0</td>
<td>7.5</td>
<td>6.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Maine</td>
<td>84,123</td>
<td>2645</td>
<td>5.1</td>
<td>1149</td>
<td>3.7</td>
<td>3.5</td>
<td>66.9</td>
<td>12.1</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>21,013</td>
<td>1698</td>
<td>8.9</td>
<td>1235</td>
<td>5.8</td>
<td>25.2</td>
<td>50.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Michigan</td>
<td>150,489</td>
<td>6511</td>
<td>7.2</td>
<td>841</td>
<td>26.2</td>
<td>10.6</td>
<td>35.5</td>
<td>19.2</td>
</tr>
<tr>
<td>Minnesota</td>
<td>218,543</td>
<td>13,984</td>
<td>5.3</td>
<td>709</td>
<td>44.7</td>
<td>5.7</td>
<td>19.7</td>
<td>19.0</td>
</tr>
<tr>
<td>Missouri</td>
<td>180,537</td>
<td>1858</td>
<td>12.7</td>
<td>1100</td>
<td>50.7</td>
<td>7.0</td>
<td>36.6</td>
<td>2.1</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>23,980</td>
<td>1109</td>
<td>6.5</td>
<td>1209</td>
<td>3.8</td>
<td>7.9</td>
<td>74.5</td>
<td>6.4</td>
</tr>
<tr>
<td>New Jersey</td>
<td>19,599</td>
<td>1143</td>
<td>11.8</td>
<td>1188</td>
<td>13.8</td>
<td>31.1</td>
<td>27.9</td>
<td>21.4</td>
</tr>
<tr>
<td>New York</td>
<td>126,070</td>
<td>4461</td>
<td>7.6</td>
<td>1094</td>
<td>21.9</td>
<td>9.3</td>
<td>54.1</td>
<td>7.2</td>
</tr>
<tr>
<td>Ohio</td>
<td>106,917</td>
<td>1279</td>
<td>10.6</td>
<td>1003</td>
<td>50.0</td>
<td>14.7</td>
<td>30.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>117,293</td>
<td>1755</td>
<td>9.3</td>
<td>1109</td>
<td>22.7</td>
<td>12.3</td>
<td>59.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>2809</td>
<td>253</td>
<td>10.0</td>
<td>1246</td>
<td>4.9</td>
<td>29.5</td>
<td>44.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Vermont</td>
<td>24,913</td>
<td>528</td>
<td>5.9</td>
<td>1176</td>
<td>13.3</td>
<td>5.5</td>
<td>70.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>145,295</td>
<td>6009</td>
<td>6.6</td>
<td>831</td>
<td>36.7</td>
<td>7.5</td>
<td>35.5</td>
<td>13.7</td>
</tr>
</tbody>
</table>

This table includes the numbers of lakes and geophysical setting of each state and state averages for climate and the 4 major land use/cover types, which do not add up to 100% because we do not include all cover types. Temperature and precipitation data are 30-year climate norms (1981–2010; PRISM, http://www.prism.oregonstate.edu/normals/); land use/cover data are from the 2011 National Land Cover Database (NLCD; USGS, http://www.mrlc.gov). Note, border lakes are only counted in 1 state.
LAGOS-NE Modules

**LAGOS-NE GEO v1.05**
- **Ecological context**
  - Lake context
    - Unique lake ID
    - Lake hydrological connectivity class
    - Number of upstream lakes
    - Lake-wetland connectivity
  - Glaciation

**LAGOS-NE LOCUS v1.01**
- **Lake location & IDs**
  - Lake ID, location, and zone IDs
    - Unique lake ID
    - Perimeter
    - Area
    - Latitude, longitude
    - Elevation
    - GNIS Name
    - Fcode (from the NHD)
    - subtype (from the NHD)
    - Unique lake ID:
      - Lake watershed ID (IWS)
      - -Lake ID (from the NHD)
    - Ecoregion ID (EDU)
    - -Political ID (state, county)

**LAGOS-NE LIMNO v1.087.1**
- **In situ water quality**
  - Lake morphometry
    - Unique lake ID
    - LAGOS-NE lake name
    - Lake depth (max, mean)
    - Source of lake depth information

**Water quality data**
- Sample date
- Event ID
- Chlorophyll a
- Secchi depth
- Water color and DOC
- Total and dissolved P
- Total and dissolved N
- Total and dissolved C

**Metadata for each data value**
- Analytical method
- Data qualifier from program
- Detection limit
- LAGOS-NE censor code

**Metadata of the source program**
- Program information

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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 GEO v1.05, LAGOS-NE LOCUS v1.01 (note that in Soranno et al. [17], this module was called LAGOS-lakes), and LAGOS-NE LIMNO v1.087.1. We include descriptions of the types 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 LOCUS module (through the unique lake ID). P is phosphorus, N is nitrogen, C is carbon, S is sulfur, and atm is atmospheric. This figure is modified from Fig. 1 in Soranno et al. [17].

Community Observations Data Model (ODM; CUAHSI ODM) as described in Soranno et al. [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 ODM because it is a flexible data model (i.e., allows the incorporation of a 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 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 data sets available to facilitate geospatial analyses of lakes, streams, and wetlands used to create some of the major components of LAGOS-NE.

**Description of the LAGOS-NE LOCUS v1.01 data module**

The LAGOS-NE LOCUS 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 141378 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 LIMNO 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 (which are typically the centroid of the lake or a central point that is within the lake boundary), GNIS name, and the zone IDs that the lake is located within (e.g., state, county, or hydrologic units). The GIS data sets that we also make available provide the...
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Figure 3: Examples of lake watersheds in LAGOS-NE. The watersheds are coded by the hydrologic class to which each lake belongs. Data are from the LAGOS-NEgeo v1.01 data module and the GIS data coverages.

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 5 Laurentian Great Lakes in our database. This definition of “lake” for LAGOS-NE has been developed only for the purpose of this database and its applications (e.g., to answer questions about lake water quality). The intent of LAGOS-NE is not to document and measure the total number of water bodies in our study area, although we are able to perform this calculation for lakes ≥4 ha with an acceptable level of uncertainty (see below).

Definition of lake watersheds

We calculated lake watersheds as “inter-lake watersheds” (IWS), defined as the area of land draining directly into the lake as well as the area that drains into upstream-connected streams and lakes <10 ha (Fig. 3). We defined lake watersheds this way to define the drainage basin of lakes that includes connected streams and their drainage basins. However, because research has shown that large upstream lakes can trap nutrients flowing into them, these large lakes can block the transport of nutrients that originate upstream from them to downstream lakes in a connected lake chain (e.g., [22]). Therefore, to calculate a drainage basin for a lake with large upstream connected lakes, we did not include the drainage basins of upstream lakes >10 ha. See Soranno et al. [17] for full details on how lake IWSs were calculated and the section on LAGOS-NEgeo for further details.

Lakes near and beyond the state borders

For some of our analyses, we delineated boundaries in other ways than political boundaries that were more ecologically relevant, which resulted in the inclusion of some lakes outside of the exact 17-state border. This fact allowed us to include more in situ data collected by state and citizen sampling programs that
do not always follow strict state borders and may include lakes that are outside of state lines. Although most of these border lakes have hydrologic (i.e., lake connectivity measures) and topographic (i.e., lake watershed delineations) calculations or water quality data, some measures of ecological context may be missing. For example, for lakes in Canada, we were not able to estimate any data that relied on national data sets that stopped at the Canadian border; one exception is the NHD, which extends into Canada to retain hydrologic boundaries.

Data sources of the LAGOS-NELOCUS module

Detailed information on data sources are found in Additional file 5 in Soranno et al. [17]. Briefly, the data source for lakes and streams in the 17-state area was the NHD [21]. The hydrologic boundaries (i.e., for 3 of the spatial classifications, HUC12, HUC8, HUC4) came from the Watershed Boundary Dataset (WBD) [23]. In addition, we used the digital raster data set of elevation for watershed delineation from the National Elevation Dataset [24]. All download dates for these data sources are provided in Additional file 5 in the above citation.

Data-integration methods of the LAGOS-NELOCUS module

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

Quality Control of the LAGOS-NELOCUS module

The full description of error analysis for this module is described in Soranno et al. [17]. However, here we briefly describe our efforts to determine the minimum area of a lake that we could confidently represent using the NHD (further details located in Additional file 9 in Soranno et al. [17]). Although the NHD is a national data set, 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, and 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 4 states (WI, MI, IA, ME) in which to evaluate error rates of water body identification for lakes ≥ 1 ha and 7 states (WI, MI, IA, ME, MO, NH, OH) in which to evaluate error rates for lakes ≥ 4 ha. We randomly selected three 100-km² rectangles from each state then compared the number of lakes occurring in the NHD GIS coverage with 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 ≥ 1 ha 4-state test and 13% for the ≥ 4 ha 7-state test. Because an average of 87% of lakes ≥ 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-NELOCUS module

Figure 1 shows the census population of all lakes ≥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 (9808 lakes with maximum depth values, and 4090 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 (Fig. 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).

Description of the LAGOS-NE_LIMNO v1.087.1 Data Module

The LAGOS-NE_LIMNO 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 (water quality data and metadata, including chlorophyll a, Secchi depth, water color, DOC, total and dissolved phosphorus [P], nitrogen [N], and carbon [C]) (Fig. 2). For each water quality data value, we also include metadata as additional columns in the exported data table (metadata including analytical method, data qualifier from the program, detection limit [when available], and the LAGOS-NE censor code) (Fig. 2), including 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). Finally, we include documentation about each source program that is linked to each data value.

Data sources of the LAGOS-NE_LIMNO module

We acquired individual water quality data sets for LAGOS-NE_LIMNO by contacting individuals at each of the 17 state and 5 tribal agencies. These contacts helped us to identify the state agency–collected data set required by the Clean Water Act that was most likely to be in the public domain. In this way, we were able to acquire at least 1 (and typically more) data set 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 data sets with other known sources of water quality data, including university researchers, federal agencies, and non-profit groups, to integrate into the LAGOS-NE_LIMNO module. The full list of data sources acquired is in Soranno
et al. [17] in Additional file 17; however, we incorporated a sub-set of these data sets in LAGOS-NE\_ELIMNO 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\_ELIMNO module**

All methods to create this module are described in Soranno et al. [17]. Briefly, for each data set 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 data set was unique in structure, file format, and naming conventions, we manually processed each data set 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 data set separately (included in this data paper).

**Quality control of the LAGOS-NE\_ELIMNO module**

The full description of our quality assurance/quality control (QAQC) procedures for this module is 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 3 major phases in the QAQC procedure for LAGOS-NE\_ELIMNO. Phases I and II were designed to identify the egregious values that we defined as those that (i) did not make ecological sense, (ii) were far beyond what has been detected in previous studies, (iii) were not technically feasible (e.g., SRP > TP), or (iv) were a result of a data 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\_ELIMNO data export provided in this data paper because we had 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 seemed to be lower than analytically possible (i.e., below detection limits) when there were 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 when those data could be valid.

For all versions of LAGOS-NE\_ELIMNO, phases I and II are conducted on the entire cumulative data set to leverage as large of a sample size as possible to detect problem values. In other words, because many of the QAQC analyses outlined here make use of all information from an individual lake or variable, incorporating new data may result in a better assessment of the data than when there are fewer data. Thus, for each new version of LAGOS-NE\_ELIMNO, new decisions are made about egregious values. In this data paper, we describe the procedures for assessing all major versions of LAGOS-NE\_ELIMNO, but we present the results only for this version of LAGOS-NE\_ELIMNO (v1.087.1).

Because there are few accepted practices for conducting such quality control on a large, integrated database, we created our own procedures for phases I and II by creating tests to identify egregious values that leverage a large, integrated database with multiple measures of water quality and well-established expected relationships among variables. The database that we used to identify egregious values was based on data in the full LAGOS-NE\_ELIMNO database for samples taken from all lake depths provided by the source data sets (note, our data exports in this data paper are only for epilimnetic or surface samples). While the quality control procedures that we implemented here were designed to help resolve the large and egregious errors in a combined data set such as this, there are likely additional extreme values in the database due to the size and heterogeneity of the data. Users may want to check for additional issues in the data values specific to their intended analyses.

### Table 2: Numbers of lakes in each state by lake hydrologic class

<table>
<thead>
<tr>
<th>State</th>
<th>Lakes ≥4 ha (#)</th>
<th>Isolated Lakes (#)</th>
<th>Headwater lakes (#)</th>
<th>Drainage lakes (#)</th>
<th>Drainage lakes with upstream lakes (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connecticut</td>
<td>770</td>
<td>40</td>
<td>119</td>
<td>424</td>
<td>187</td>
</tr>
<tr>
<td>Illinois</td>
<td>2831</td>
<td>1417</td>
<td>279</td>
<td>952</td>
<td>183</td>
</tr>
<tr>
<td>Indiana</td>
<td>1883</td>
<td>760</td>
<td>244</td>
<td>697</td>
<td>182</td>
</tr>
<tr>
<td>Iowa</td>
<td>915</td>
<td>339</td>
<td>87</td>
<td>402</td>
<td>87</td>
</tr>
<tr>
<td>Maine</td>
<td>2661</td>
<td>94</td>
<td>619</td>
<td>1211</td>
<td>737</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>1716</td>
<td>210</td>
<td>269</td>
<td>751</td>
<td>486</td>
</tr>
<tr>
<td>Michigan</td>
<td>6531</td>
<td>2649</td>
<td>1087</td>
<td>1672</td>
<td>1123</td>
</tr>
<tr>
<td>Minnesota</td>
<td>14 031</td>
<td>6609</td>
<td>1894</td>
<td>2673</td>
<td>2855</td>
</tr>
<tr>
<td>Missouri</td>
<td>1865</td>
<td>435</td>
<td>179</td>
<td>1113</td>
<td>138</td>
</tr>
<tr>
<td>New Hampshire</td>
<td>1118</td>
<td>70</td>
<td>224</td>
<td>581</td>
<td>243</td>
</tr>
<tr>
<td>New Jersey</td>
<td>1148</td>
<td>219</td>
<td>129</td>
<td>521</td>
<td>279</td>
</tr>
<tr>
<td>New York</td>
<td>4477</td>
<td>629</td>
<td>1210</td>
<td>1915</td>
<td>723</td>
</tr>
<tr>
<td>Ohio</td>
<td>1282</td>
<td>543</td>
<td>105</td>
<td>520</td>
<td>114</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>1757</td>
<td>316</td>
<td>397</td>
<td>840</td>
<td>204</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>266</td>
<td>35</td>
<td>40</td>
<td>115</td>
<td>76</td>
</tr>
<tr>
<td>Vermont</td>
<td>531</td>
<td>14</td>
<td>74</td>
<td>364</td>
<td>79</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>6026</td>
<td>2982</td>
<td>823</td>
<td>1236</td>
<td>985</td>
</tr>
<tr>
<td>Total</td>
<td>49 808</td>
<td>17 361</td>
<td>7779</td>
<td>15 987</td>
<td>8681</td>
</tr>
</tbody>
</table>

The number of lakes ≥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 2 states are counted in both states).
northeastern United States in the 1980s-present has resulted in long-term monitoring programs are localized to a few lakes, whereas others are short-term initiatives. Typically, data.

Across all states, almost 80% of lakes >400 hectares have water quality data.

Lakes are not sampled the same way by all individuals, groups, or agencies; there are differences in the variables measured, the frequency and timing of sampling, and the proportion of lakes sampled. For example, for total phosphorus, the 4 states with the largest number of unique lakes with at least 1 value for total phosphorus per state include Wisconsin (1920 lakes), Minnesota (1588), New York (1289), and Michigan (1109) (Table 3). However, the states with the highest proportion of their lakes with total phosphorus samples are the smaller states with fewer lakes, such as New Hampshire (64%), Vermont (58%), and Rhode Island (42%). Notably, there are some states with intermediate numbers of lakes that still have quite large percentages of their lakes with total phosphorus values, including Maine (35% of 2645 lakes), Wisconsin (32% of 6009 lakes), and New York (29% of the 4461 lakes).

The most commonly measured variable in LAGOS-NELimn is water clarity, measured as Secchi depth (a relatively easy and cost-effective measure of water quality), with 897,724 measurements taken from 12,034 unique lakes in the 17 states from mostly the mid 1980s to 2011 (Table 3). The second and third most sampled measures of water quality are chlorophyll a and total phosphorus, respectively. Although it appears that total nitrogen is sampled far less frequently than total phosphorus, some labs measure total nitrogen directly and report that single value, whereas other labs measure the constituents that make up total nitrogen (total Kjeldahl nitrogen and nitrate+nitrite) and sum them together to calculate total nitrogen. All of our analyses conducted on total nitrogen have used such calculated and measured values of nitrogen together, which increase the sample sizes for total nitrogen markedly.

Most of our data came from state agencies, either alone or as part of joint programs with citizen scientists or university researchers (Table 4), which highlights the importance of citizen science programs for monitoring lake water quality in this lake-rich area of the United States. Using the 3 most sampled variables in the data set (Secchi depth, chlorophyll concentration, and total phosphorus), we found that larger lakes were more likely to be sampled for water quality than smaller lakes (Fig. 4). This result was expected given the economic and recreational interest in larger lakes, including easier public access. Previous research has already documented this basic pattern in 6 of the states included in LAGOS-NE [30]. Across all states, almost 80% of lakes >400 ha have water quality data.

Lakes are also unevenly sampled through time, depending on the variable (Fig. 5). Some programs’ focus is on long-term monitoring, whereas others are short-term initiatives. Typically, long-term monitoring programs are localized to a few lakes, although there are exceptions (e.g., monitoring for acid rain in the northeastern United States in the 1980s-present has resulted in good temporal and spatial coverage for some variables through time and space) [31].

Description of the LAGOS-NEGEO v1.05 Data Module

The LAGOS-NEGEO module includes information on the ecological context of the census lakes, their watersheds, and their regions. The information provided in the data tables for this module is organized into 3 main themes in which data are exported into individual tables: CHAG—climate, hydrology, atmospheric deposition of nitrogen and sulfur, and surficial geology; LULC—land use/cover, canopy cover, terrain metrics, and dam density; and CONN—lake, stream, and wetland abundance and connectivity measures (Fig. 2). We also provide the GIS coverages that include some of the underlying data for this module, including lake polygons and their hydrologic classifications, defined in Soranno et al. [17]; wetland polygons and their classification; streams as a line coverage and their classification by stream order; the zones used for this study (state and county, hydrologic units, and 100-meter buffers) [32]; and lake watersheds (IWS). We also include boundaries of US states and Canadian provinces for mapping.

Data sources of the LAGOS-NEGEO module

Detailed information on data sources are found in Additional file 5 in Soranno et al. [17]. Almost all data sources for this module are from national-scale data sets and thus use standardized methods throughout the study extent.

Data integration methods of the LAGOS-NEGEO module

All methods to create this module are described in Additional files 5, 7, 8, 13, and 14 in Soranno et al. [17]. Briefly, we calculated the metrics for this module that describe the ecological context surrounding lakes by developing project-specific GIS tools in the ArcGIS environment, which are referred to as the LAGOS GIS Toolbox [33]. The toolbox outputs multiple individual data tables of calculated values organized by the above 3 data themes that are then imported into LAGOS-NEGEO for different spatial classifications, including values calculated at the level of the individual lake, 100-meter and 500-meter buffers around each lake, the lake IWS, states and counties, hydrologic units, and ecological drainage units (an ecoregion spatial classification). The unique identifiers for this data module are the zone IDs for each spatial classification for which we calculate these metrics. In other words, we calculate land use around a lake in each of the zones of the many spatial classifications in LAGOS-NE. However, the data are exported into individual tables by spatial classification. Therefore, there are different numbers of rows in each table; for example, there are 51,101 rows for the land use metrics calculated for the 100-meter lake buffer because there are 51,101 lakes that have a 100-meter buffer area, but only 17 rows for the land use metrics calculated for the state spatial classification.

Quality control of the LAGOS-NEGEO module

The full description of error analysis for this module is described in Additional file 14 in Soranno et al. [17]. The quality control procedures for this module included procedures to identify possible errors or improbable values as a result of the extensive automated GIS data processing that creates the LAGOS-NEGEO data tables and to correct those problems. We assumed that the
Table 3: Summary of the water quality variables and the number of values per variable by state

<table>
<thead>
<tr>
<th>State</th>
<th>Number of lakes (≥ 4 ha)</th>
<th>Variable</th>
<th>Total phosphorus</th>
<th>Secchi depth</th>
<th>Chlorophyll a</th>
<th>True color</th>
<th>Apparent color</th>
<th>Dissolved organic carbon</th>
<th>Total nitrogen</th>
<th>Total Kjeldahl nitrogen</th>
<th>Nitrate + nitrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connecticut</td>
<td>763</td>
<td># of samples</td>
<td>1294</td>
<td>1943</td>
<td>1160</td>
<td>53</td>
<td>0</td>
<td>74</td>
<td>853</td>
<td>55</td>
<td>397</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled Lakes</td>
<td>143</td>
<td>168</td>
<td>149</td>
<td>37</td>
<td>0</td>
<td>49</td>
<td>99</td>
<td>26</td>
<td>81</td>
</tr>
<tr>
<td>Illinois</td>
<td>2819</td>
<td># of samples</td>
<td>2816</td>
<td>2317</td>
<td>1438</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>43</td>
<td>1526</td>
<td>2351</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled lakes</td>
<td>191</td>
<td>185</td>
<td>167</td>
<td>17</td>
<td>0</td>
<td>17</td>
<td>18</td>
<td>155</td>
<td>188</td>
</tr>
<tr>
<td>Indiana</td>
<td>1874</td>
<td># of samples</td>
<td>1232</td>
<td>1303</td>
<td>909</td>
<td>57</td>
<td>0</td>
<td>57</td>
<td>57</td>
<td>1183</td>
<td>1237</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled lakes</td>
<td>341</td>
<td>340</td>
<td>320</td>
<td>51</td>
<td>0</td>
<td>51</td>
<td>51</td>
<td>322</td>
<td>341</td>
</tr>
<tr>
<td>Iowa</td>
<td>903</td>
<td># of samples</td>
<td>2873</td>
<td>2836</td>
<td>2711</td>
<td>18</td>
<td>0</td>
<td>18</td>
<td>2244</td>
<td>6</td>
<td>2229</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled lakes</td>
<td>111</td>
<td>111</td>
<td>103</td>
<td>12</td>
<td>0</td>
<td>16</td>
<td>111</td>
<td>1</td>
<td>111</td>
</tr>
<tr>
<td>Maine</td>
<td>2645</td>
<td># of samples</td>
<td>17314</td>
<td>83472</td>
<td>12480</td>
<td>1927</td>
<td>1676</td>
<td>3321</td>
<td>1260</td>
<td>8</td>
<td>1577</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled lakes</td>
<td>933</td>
<td>1047</td>
<td>793</td>
<td>601</td>
<td>466</td>
<td>848</td>
<td>461</td>
<td>3</td>
<td>347</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>1698</td>
<td># of samples</td>
<td>570</td>
<td>760</td>
<td>326</td>
<td>277</td>
<td>228</td>
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<td>89</td>
<td>140</td>
<td>37</td>
<td>4</td>
<td>132</td>
</tr>
<tr>
<td>Michigan</td>
<td>6511</td>
<td># of samples</td>
<td>10 143</td>
<td>95823</td>
<td>12243</td>
<td>1811</td>
<td>69</td>
<td>987</td>
<td>749</td>
<td>2651</td>
<td>4850</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled lakes</td>
<td>1109</td>
<td>1233</td>
<td>862</td>
<td>836</td>
<td>69</td>
<td>353</td>
<td>200</td>
<td>713</td>
<td>948</td>
</tr>
<tr>
<td>Minnesota</td>
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<td># of samples</td>
<td>10 974</td>
<td>49764</td>
<td>81925</td>
<td>406</td>
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<td>7717</td>
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<td># of sampled lakes</td>
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<td>4118</td>
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<td>253</td>
<td>1368</td>
<td>811</td>
<td>619</td>
<td>2018</td>
<td>1522</td>
</tr>
<tr>
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<td>1858</td>
<td># of samples</td>
<td>11 619</td>
<td>11794</td>
<td>11578</td>
<td>27</td>
<td>0</td>
<td>27</td>
<td>11 340</td>
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<td># of sampled lakes</td>
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<td>207</td>
<td>201</td>
<td>23</td>
<td>0</td>
<td>23</td>
<td>207</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
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<td># of samples</td>
<td>9289</td>
<td>2958</td>
<td>154</td>
<td>237</td>
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<td>22</td>
<td>1209</td>
<td>2445</td>
</tr>
<tr>
<td></td>
<td></td>
<td># of sampled lakes</td>
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<td>618</td>
<td>21</td>
<td>111</td>
<td>603</td>
<td>143</td>
<td>17</td>
<td>535</td>
<td>704</td>
</tr>
<tr>
<td>New Jersey</td>
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<td># of samples</td>
<td>421</td>
<td>461</td>
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<td>27</td>
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<td></td>
<td># of sampled lakes</td>
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<td>174</td>
<td>157</td>
<td>25</td>
<td>0</td>
<td>36</td>
<td>8</td>
<td>157</td>
<td>175</td>
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</table>
### Table 3: Continued

<table>
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<th>Variable</th>
<th>Total phosphorus</th>
<th>Secchi depth</th>
<th>Chlorophyll a</th>
<th>True color</th>
<th>Apparent color</th>
<th>Dissolved organic carbon</th>
<th>Total nitrogen</th>
<th>Total Kjeldahl nitrogen</th>
<th>Nitrate + nitrite</th>
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<td>545</td>
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<td>897 724</td>
<td>202 789</td>
<td>38 764</td>
<td>15 709</td>
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We include the number of individual values (representing an individual sampling event), the number of unique lakes for which there is at least 1 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-NR\text\_ENO 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.
Table 4: The number of data sets, data values, and lakes from the different types of sampling programs in LAGOS-NE v1.087.1

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<th>Program Type</th>
<th>Number of data sets</th>
<th>Number of lakes (≥4 ha)</th>
<th>Total phosphorus</th>
<th>Secchi depth</th>
<th>Chl. a</th>
<th>True color</th>
<th>Apparent color</th>
<th>Dissolved organic carbon</th>
<th>Total nitrogen</th>
<th>Total Kjeldahl nitrogen</th>
<th>Nitrate + nitrite</th>
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<td>69</td>
<td>318</td>
<td>396</td>
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</table>
original data layers had already gone through extensive quality control by the originators of the data sets. We defined errors and improbable values to be: (i) values that did not make ecological sense; (ii) values that were well beyond what has been observed in previous studies; (iii) values that are not technically feasible; or (iv) null values that indicate an absence of data, when in fact data exist based on the input data coverages. Note, it was not our intention to remove statistical outliers that may or may not be real/true values. Rather, we conducted procedures on each exported table that included verifying column headers and units, mapping the exported data to evaluate mapping extent and boundary issues using visual inspection, mapping the data distributions of each value, identifying values that were missing or zero, plotting distributions of the data, ensuring that proportions summed to 100 where relevant, and inspecting univariate plots of metrics that are known to be related (e.g., % urban land use vs % impervious surface).

Data in the LAGOS-NEGEO module

This module contains the largest amount of data of any of the modules. For example, Fig. 6 shows the wide range of ecological context for the LAGOS-NE study area calculated for 3 different spatial classifications. For those variables that are measured coarsely (e.g., baseflow, runoff, atmospheric deposition, geology), we calculated variables for only the broader spatial classifications. For example, we did not calculate baseflow for spatial classifications finer than HUC12 because the underlying data for baseflow are estimated on a zone generally coarser than the area of a lake watershed.

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 number of lakes with in situ water-quality measurements and their wide gradients of ecological context. The lake census data set also makes it possible to quantify the types of biases present in the data set 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 3 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 2 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 2 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 (i) a lack of lake depth information (lake depth drives many in-lake processes), (ii) the need to develop a flexible method for creating ecological regions from multi-themied mapped data, which are often used in macroscale research to account for broad-scale patterns and processes, and (iii) 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. Cheruvelil et al. [35] have 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...
A water quality database for US lakes

Figure 5: The number of years of water quality data by lake. The number of years for which at least 1 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.

Lake water quality is affected by many ecological context features, such as lake physical characteristics, land cover, land use, and climate. The relationship between these features and the water quality measurements is not always linear. In addition, the data tend to be noisy and often contain missing values, which makes it challenging to fit effective statistical models. To overcome these challenges, Yuan et al. [37] developed a novel algorithm for learning non-linear features to predict lake water quality. The algorithm also enables the missing values to be imputed in a way that preserves the relationship between the predictors and response variables. Furthermore, because many of the lake water quality variables are strongly correlated with each other, their models are expected to be similar. This similarity information can thus be exploited to build better models, especially for the lake water quality variables that have very few observations because they are not sampled frequently. Members of our research team are developing a machine learning approach known as multi-task learning that can simultaneously build regression models of multiple lake water quality variables for a large number of lakes, taking into account both the correlation between the variables and the spatial autocorrelation among the lakes. Because we expect many ecological data sets across broad geographic scales to have similar data gaps and challenges as LAGOS-NE, we think these methods will be extremely valuable for other researchers studying different macroscale questions.
Figure 6: Example ecological context variables by spatial classification in LAGOS-NE. The top 4 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 percentage 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 percentage of streamflow that is baseflow in each HUC8.
Understanding spatial variation in lake nutrients and eutrophication at sub-continental scales

LAGOS-NE allows investigation of spatial variation in lake nutrients and eutrophication at macroscales. For example, members of our team have identified general spatial principles that constrain relationships between ecosystem variables with different spatial structures. In other cases, specific questions regarding spatial patterns have focused on identifying important landscape controls on nutrients and their ratios [38], potential stress induced on phytoplankton communities by high nitrogen levels, and spatial autocorrelation in lake-specific relationships between chlorophyll and nutrients and carbon [39]. In addition, LAGOS-NE contains a wealth of information on a variety of lake ecosystem types. Shallow lakes, in particular, are very abundant across the study area and represent systems that can exhibit hysteresis in response to lake eutrophication. Our team is also investigating the spatial distribution and temporal dynamics of water clarity in shallow lakes of the LAGOS-NE study area.

An important area of research, and one that was a motivating factor for the creation of LAGOS-NE, is understanding the importance of cross-scale interactions (CSIs)—where ecological processes operating at one spatial or temporal scale interact with processes operating at another scale—in lake ecosystems. Because of their importance ecologically and the challenge of quantifying them over large spatial extents, Wagner et al. [40] evaluated the statistical power of large multi-thematic, multi-scaled data sets, such as LAGOS-NE, to detect CSIs. This work not only helped inform the design of large-scale studies aimed at detecting CSIs, but also focused attention on the importance of considering CSI effect sizes and their ecological relevance. To extend this work, members of our team are investigating the importance of both within- and cross-scale interactions in landscape models predicting lake nutrients, and the role that connectivity among freshwaters plays in these interactions. Understanding and predicting nutrients in lakes at macroscales is important to inform estimates of lake contributions to continental and global nutrient cycles. To date, much of this work has been performed on a nutrient-by-nutrient basis, despite knowing that cycles of nitrogen and phosphorus and other key elements are best understood by considering multiple elements in tandem, e.g., in a stoichiometric framework [41] or through analysis of coupled biogeochemical cycles (e.g., [42–44]). Currently, efforts are underway to develop spatial joint nutrient distribution models to evaluate how our understanding of landscape-scale drivers of lake nutrients and predictive performance are improved by considering multiple nutrients simultaneously (multivariate models) compared with traditional univariate approaches that ignore that nutrient cycles can be tightly coupled in freshwaters.

Understanding temporal and spatial variation in lake eutrophication at sub-continental scales

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

For example, nearly 3000 lakes were examined for trends in nutrients and chlorophyll from 1990 to 2013 using LAGOS-NE [45]. Across all lakes, nitrogen has declined, and phosphorus and chlorophyll have not changed. Nitrogen and stoichiometric changes in lakes were related to atmospheric deposition of nitrogen, providing key insight into large-scale nutrient transport and policies such as the Clean Air Act. Using only citizen science data in a subset of the LAGOS-NE database, Lottig et al. [46] showed results that suggested little evidence for major declines or improvements in water quality. In addition, members of our team are examining the relationships between a wide range of climate metrics and water quality in ~11 000 lakes in LAGOS-NE to determine (i) which climate metrics are most related to water quality; (ii) whether physical, chemical, and biological aspects of lakes respond to climate in the same way; and (iii) how the climate–water quality relationship varies across space and regions with different ecological contexts. However, the temporal dynamics of lake ecosystem properties can sometimes be non-linear and exhibit variability across the landscape—largely because of climate and within-lake processes. Our team has developed models for understanding and predicting the often complex temporal patterns observed in water clarity. These studies point to the importance of considering both space and time when trying to understand broad-scale environmental issues in surface waters.

Using LAGOS-NE for Future Research, Management, and Policy

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

Key motives for constructing this database included interest in examining lake nutrients and productivity at multiple spatial and temporal scales, fostering broad-scale aquatic ecology and macrosystems research in an open-science platform, and providing new understanding and resources for management and policy-makers. To this end, several team members have made presentations at scientific meetings about the structure and use of LAGOS-NE, and subsets of LAGOS-NE data have been shared with other researchers and stakeholders and agency personnel in advance of this publication. These early uses of LAGOS-NE data by other researchers outside of our team include an investigation of patterns and causes of shifting distribution of a sentinel fish species, developing models to simulate lake temperatures and fish species distributions, and developing a recruitment model for a popular game fish. Results from the latter...
2 efforts will inform state-level fisheries management as well as aid in prioritization of lakes for habitat conservation action across a tri-state region.

Much of the research that we and others are conducting with LAGOS-NE has implications for ecosystem management or environmental decision-making. In addition, we have collaborated with boundary organizations and decision-makers. For example, under development is a dashboard of the ecosystem services provided by lakes for use by land managers. In addition, we have helped the state of Michigan determine lake-specific nutrient standards. Our hope is that this database and the associated support tools and documentation serve as a powerful resource and a foundation for future research and decision-making by a broad community of scientists, policy-makers, and natural resource managers. Indeed, our success and experience with database construction and research have inspired us to expand the spatial extent for LAGOS-NE. We have begun to build LAGOS-US, which will include similar data as LAGOS-NE but will be for the continental United States.

**Challenges and Recommendations for Creating Large, Integrated, and Heterogeneous Databases**

We found that the largest challenge when creating this database was integrating many small heterogeneous data sets that had few common standards. Although creating such large, integrated data sets using fully automated procedures may happen someday, it appears that we are nowhere near such automation today. Until standards in metadata documentation and robust ontologies are created and widely adopted when creating local or regional data sets, future efforts to integrate these into larger databases will have to rely on close collaborations among domain experts and ecoinformatics professionals, extensive manual interpretation of individual data sets, and funds sufficient to implement these labor-intensive approaches [16]. Nevertheless, it is worth the time and money invested in database integration if the resulting databases support new research, management, policy, public outreach, and education at all levels. We anticipate that LAGOS-NE will serve as a foundation for new data modules that can be used beyond the original intent of LAGOS-NE.

The economic value of water quality data in an integrated database

This extensive effort was supported by a US National Science Foundation grant that totaled $2.4 million, along with resources from other projects. Our team ranged in size from 14–20 individuals across the 6 years of the project, with many members compiling and integrating data, authoring metadata, creating new data products, and implementing quality control procedures, resulting in a tremendous number of person-hours. However, when one considers the cost of the data collection for the water quality data in the first place, the expense of this post-processing integration work is not as large as it sounds. Sprague et al. [16] suggest that a single sample (estimated for collecting nutrient or chemistry data from streams) ranged in cost from $2000 to $6000 per sample. If we assume similar rates for lake sampling, but lower the cost as some aspects of lake sampling may be cheaper than stream sampling and multiply that cost (estimated as $1000–$4000 US) by the total number of records of nutrient or chemical samples in LAGOS-NE \( (n = 589,909) \), then the combined estimate to collect the water quality data found in LAGOS-NE is in the range of $0.5–2.4 billion US. It cost us between 0.10% and 0.40% of the cost to sample the data in the first place to harmonize these half a million records and to build an ecological context database for them. This relatively small investment in preserving, documenting, and harmonizing these valuable data sets creates the needed infrastructure for new broad-scale research, management, education, and outreach uses.

**Strategies for broad-scale data integration efforts**

One challenge is to prioritize research areas and to identify the types of data sets that may benefit from a similar type of integration. State, federal, tribal, and citizen science water quality data sets were an excellent source of quality data for integration and conducting broad-scale research on aquatic systems. There are likely other such data sources that would benefit from being integrated as we have done here. We recommend the following strategies to make the best use of future data integration efforts.

1. The database integration effort should be driven by key underlying research questions or goals and grounded in a strong conceptual foundation of the important features to include. In our case, the principles of landscape limnology [12, 18–20] guided the development of LAGOS-NE, which helped us to prioritize geospatial and lake features for inclusion in the database because the addition of any data type or data set cost time and money.

2. For databases with more than 1 major data type, it is very helpful to build the database in modular form, each with its own versioning system, specific data integration methods, and quality control procedures. This strategy was not a primary goal at the outset of our project, but it emerged somewhat organically through the life of the project. We now recognize the many benefits that the modularity brings to the database, including making it much easier to be dynamic rather than static by providing a platform for the addition of new data, new types of data, and new modules in the future (such as for biological data or data from high-frequency sensors).

3. The entire process should be grounded in an open-science framework. Knowing that the database, design, and methods were to be shared and made usable by future users influenced our decisions throughout the process and made documentation a high priority throughout. Although we are making the full database available now, before this point, we supported open science by publishing subsets of LAGOS-NE data that were used in individual publications (e.g., [48, 49]).

4. Creation of LAGOS-NE required a strong focus on team science, and in particular the roles of and incentives for early-career researchers in such efforts. This type of research cannot be conducted in a single-investigator mode, but requires a highly collaborative and effective team-based model (e.g., [50–52]). We explicitly considered strategies for ensuring that early-career team members get credit for their contributions [53], and we recommend providing team members with opportunities for leadership, project management, personnel management, and intellectual growth. For example, they can be part of major decisions and can lead smaller efforts throughout the project, as well as be given power to shape team policies and practices. This integration of early-career researchers into the entire research team and effort will give early-career professionals deep knowledge of the database and procedures, as well as the skills to conduct such work in the future.
(5) The decision of how to disseminate the database documentation needs to be considered early in the project. For example, database documentation papers are rare, especially in ecology, but are very important. The documentation and procedural approaches for developing this large, integrated, and heterogeneous database had to be disseminated through publication prior to making the database available [17] and prior to publication of research results stemming from LAGOS-NE because methods sections in journal articles are too short to include all the necessary documentation of such methods. Other researchers may be discouraged by the very real consequence that publishing such products takes time and energy investments that may slow down production of research publications. However, such a paper was instrumental in supporting later research articles that used LAGOS-NE. Therefore, we recommend that this (and other) database documentation papers become a more standard type of paper to describe the extensive methods involved and to supplement data papers. Such papers will facilitate the use, extension, and translation of these databases well into the future, as well as foster future research on broad-scale, complex, and societally relevant environmental questions.

Availability of supporting source code and requirements
Project name: LAGOS-NE
Project home page: https://github.com/cont-limno/LAGOS
Operating system(s): e.g., platform independent
Programming language: R
Other requirements: R packages required (with associated versions): dplyr (≥0.7.0), rappdirs (≥0.3.1), lazyeval (≥0.2), purrr (≥0.2.2.2), magrittr (≥1.5), sf, curl (≥2.7.0), stringr (≥1.2.0)
License: GPL

Availability of supporting data
The data sets supporting the results of this article are available in the Ecological Data Initiative repository, including the following specific components:
- LAGOS-NE-LOCUS v1.01 [54];
- LAGOS-NE-LIMNO v1.087.1 [55];
- LAGOS-NE- GEO v1.05 [56];
- LAGOS-NE-GIS v1.0 [57];
- Snapshots of the R package in the LAGOS GitHub page are also available in the GigaScience repository, GigaDB [58].

Additional files
Soranno etal_2017Additional file 1_8SEP17_final.docx
Soranno etal_2017Additional file 2_qaqc-limno_v2.docx

Abbreviations

Competing interests
The authors declare that they have no competing interests.

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Author contributions


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