Chapter

Jewels across the Landscape: Monitoring and Assessing the Quality of Lakes and Reservoirs in the United States

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Abstract

An early naturalist described lakes as "jewels" across the landscape and indeed they were…at the end of the nineteenth century. As we settled the country and began to utilize the lake resource for our needs, things changed. Additionally, our needs for water brought about the construction of impoundments from ice ponds to small stock ponds up to mainstem impoundments along our major rivers. The lake resource in the United States now includes natural lakes in our northern tier of states, unique physiographic regions such as Florida and the Sand Hills of Nebraska, and the mountainous regions, and impoundments scattered across the entire landscape. In this chapter, we will describe efforts by an unique partnership between the individual states and tribal nations of the USA and the US Environmental Protection Agency to monitor and assess these systems. These efforts go beyond single water quality (chemistry) issues and include assessments targeting the goal of the Clean Water Act, namely, restoring, maintaining, and protecting the chemical, physical, and biological integrity of the nation's lakes and reservoirs.

Keywords: lakes, reservoirs, monitoring, assessment, National Lakes Assessment, United States, ecological indicators, survey design, National Aquatic Resource Assessments, water quality, trophic state, biological integrity, lakeshore habitat, Clean Water Act

1. Introduction

The United States' love affair with lakes dates back a long way. In 1896, MacGonigle [1] described lakes in central Florida this way: "Dotting the landscape, like jewels of crystal in a field of green, are numberless lakes, varying in size from a gem-like lakelet to the broad expanse of Okeechobee". Many states, in particular Vermont, New York, Maine, Michigan, Wisconsin, and Minnesota, have extensive histories and ties with their lakes. In this chapter, we discuss why lake monitoring is important, and what are the essential characteristics of the U.S. National Lakes Assessment (NLA) that allow us to rigorously characterize the status of this precious lake resource and track how the status is changing over time.

2. Background

The US Clean Water Act (CWA) of 1972 [2] expresses the national desire to restore and maintain the physical, chemical, and biological integrity of USA waters and requires that information on status and trends be reported every 2 years by the states. Different States vary greatly in their monitoring focus and approaches. It has long been recognized that these reports cannot be combined to create a coherent picture of the degree to which lakes in the USA meet the goals of the CWA [3–9]. Looking back at the history of national lake assessments, it is clear that our focus in assessing lake condition has shifted over time as each new threat to lake quality emerged. In the 1960s–1970s, our focus was the "cultural eutrophication" of lakes, that is, the nutrient enrichment of lakes through human activities, via point or nonpoint sources of organic and inorganic nutrients. This enrichment led to everything from "unsightly" algal growth to health problems associated with recreational contact. When extreme, these algal blooms eventually led to low dissolved oxygen levels as the algae died and decayed. The low dissolved oxygen ultimately led to die-off of sensitive fish communities in many lakes. These concerns about eutrophication led to the first ever national lake survey in the USA, the National Eutrophication Survey (NES) [10]. The survey focused on lakes near population centers that were likely subjected to point-source release of nutrients or oxygen demanding compounds. Over 800 lakes suspected of having problems were sampled during this survey using a targeted approach. Ultimately, these concerns led to the funding of the Clean Lakes Program, a Congressionally funded program managed by the fledgling Environmental Protection Agency to provide states and communities with funding to solve specific problems with individual lakes.

The concern about eutrophication and desire to engage the public through citizen monitoring continued into the 1990s. In 1994, the National Secchi Dip-In program was implemented. The Dip-In is a volunteer effort in which citizens from various localities send in their Secchi Depth readings (a measure of lake water clarity) for lakes of interest during a particular week during the summer. This event continues under the sponsorship of the North American Lake Management Society [11].

The 1980s saw increasing concerns about releases of nitrogen and sulfur compounds into the atmosphere and the deposition of these acidic compounds onto lakes and stream watersheds in poorly buffered landscapes. When inquiring into the extent of the problem at the time, William Ruckelshaus, the EPA Administrator at the time, was rumored to have said something along the lines of "What do you mean you don't know how many acid lakes there are?" A definitive answer to this question was not possible at that time for several reasons, including the uncertainty in extrapolating results from site-specific studies to regional or national populations of lakes [12]. These concerns, in Europe and North America, particularly in highly visible regions like the Adirondacks, eventually led to the implementation of the National Acidic Precipitation Assessment Program (NAPAP). Key projects within NAPAP were the National Surface Water Surveys (NSWS), probability-based surveys of lakes (and streams) that set out to document how many acidic lakes and streams there were in the U.S. and how these systems might be changing in response to the 1990 Clean Air Act Amendments [12–14].

Following the completion of the initial NAPAP-sponsored surveys, EPA began to ask whether there might be a better, more consistent approach to directly address the CWA objectives for assessing the condition of lakes and other important ecological resources rather than mounting new surveys for each new problem that arose. The Environmental Monitoring and Assessment Program (EMAP) was a research program designed to develop this approach [6, 15] with a focus on CWA objectives. These research efforts culminated, for lakes, in the implementation and completion of the EMAP Northeastern Lakes Regional Demonstration Project conducted from 1991 to 1995 in the New England states, New Jersey, and New York [16–18].

As the EMAP research efforts on lake, stream, river, wetland, and estuary monitoring demonstrated their potential effectiveness, the US Office of Management and Budget (OMB) directed the EPA Office of Water to partner with the individual states of the USA to implement the EMAP concepts on a national scale for all waterbody types under the National Aquatic Resources Surveys (NARS). The first National Lake Assessment (NLA) was conducted in 2007 with recurrent surveys in 2012 and 2017 and planned surveys for every 5 years following. The description below outlines the conceptual and practical basis for the lakes monitoring efforts are taking place as part of the NLA.

3. Conceptual approach

Three aspects of the NLA make up the overall conceptual approach – the selection of indicators, the approach (survey design) for selecting sites to sample and making inferences to all lakes, and the strategy (response design) for acquiring data at each site for all indicators [6, 19]. This conceptual approach ensures that the NLA will address the main goal of the CWA as well as address the five big questions most frequently asked by the public:

1. Is there a problem with the condition of lakes?

2. How big is the problem?

3. Is the problem widespread or localized in hot spots?

4. Is the problem getting better or worse?

5. What is causing the problem?

Past surveys of lakes have pursued individual stressors or anthropogenic problems and measured them, for example, the National Eutrophication Survey focused on nutrients, phosphorus in particular, and the National Surface Water Surveys (NSWS) under NAPAP focused on acidification. The NLA, under NARS, is intended to have a broader perspective by using a variety of indicators to examine the overall health of lakes and ranking the importance of individual anthropogenic stressors.

This perspective drove the NLA to focus on indicators related to the attribute of "biological integrity" referenced in the CWA [2] to describe "condition" of lakes. In addition, indicators of "physical integrity" and "chemical integrity" describe the relative importance of human-mediated disturbances impacting lake condition.

The survey design plays a critical role in the overall approach within the NARS and the NLA. Frequently, surveys are developed with little attention to the final statements that are intended to be made from the data. The National Eutrophication Survey, for example, was based on a targeted judgment sample of 817 lakes potentially influenced by nutrient inputs from domestic wastewater treatment plants. Without statistically representative site selection, the only conclusions that could be reliably made from the data were about those 817 specific lakes. The Great Secchi Dip-In acquires data from thousands of lakes each year. The results provide important information about those lakes being monitored, but because the lakes selected for sampling are chosen by those submitting the data, the results are not necessarily representative of the total lake population (e.g., see [20]). The lake surveys conducted as part of the National Surface Water Surveys (NSWS) used a statistical design restricted to acid-sensitive regions (rather than the whole country) that allowed inference to be made from the sampled lakes to the greater population of lakes they represented in those defined areas. Because the focus was on acidification and acid deposition, the selection of lakes was understandably limited to lakes in regions of the country that had poor buffering capacity in the soils. Therefore, these lakes were potentially sensitive to acidification from acids in atmospheric deposition. By contrast, the NLA is the first national survey that focuses on all waterbodies in the conterminous U.S. meeting the definition of a lake (both natural and man-made) and employs a survey design that ensures that inferences can be made to that full "target" population of lakes [21]. More details of the NLA survey design are provided in following sections of this chapter.

The final aspect of the conceptual approach for indicators or measurements is the "response design," that is, when the crews get to specific lakes, where and how do they collect samples or measurements for the various indicators? This will be described in more detail below.

3.1 Indicators

Indicators used in the NLA are selected to assess status related to trophic state, water quality, the condition of biological assemblages, physical habitat condition, and human use (**Table 1**). The set of selected indicators are intended to be most appropriate for the assessment of lake condition at regional and national scales. Indicators range from direct measurements of specific variables to more complex indices representing biological or physical habitat condition.

3.2 Survey design

The target population (i.e., the set of lakes about which inferences are to be made) for the NLA includes all natural lakes and ponds, reservoirs, and man-made ponds within the conterminous USA (i.e., the "lower" 48 states) that are greater than 1 hectare (ha) in surface area, are permanent waterbodies, have an estimated maximum depth greater than 1 m, and have more than 1000 m^2 of open water on the day of sampling. An early decision was made to sample lakes as a finite resource and provide estimates of "lake number" and "proportion of lake number" rather than as "lake area" (although areal estimates can also be made with the NLA data). The NLA design requires some level of stratification or unequal sampling probability to accommodate regional variation in the abundance of lakes, and the preponderance of small lakes [22, 23]. A simple random sample will be dominated by small lakes (less than 4 ha), and the bulk of lakes sampled will be in the Upper Midwest where lakes are most abundant. Because of the desire to make both national and regional estimates, care is taken to spread the sample across the conterminous USA and across the size range of lakes available. For regional coverage, variable selection probabilities are set to ensure the ability to describe conditions in all 10 EPA Regions [24], 9 aggregated NARS ecoregions (**Figure 1**) [25] and roughly 15 hydrologic basins. Variable selection probabilities are also set to ensure that the NLA samples are spread across the size range of lakes so that small lakes do not dominate the sample. Samples are currently allocated among 5 lake surface area categories: 1–4, 4–10, 10–20, 20–50 ha, and greater than 50 ha. Each site sampled receives a "weight" inversely proportional to its probability of inclusion in the sample. The weights are then used to make the inferences from

Indicator and rationale	Sample location
Zooplankton assemblage: important element of the food web; responds to stressors such as nutrient enrichment and acidification	Collected from the upper portion of the water column at the open-water site. Organisms were usually identified to genus and an multimetric index was developed based on life history characteristics and tolerance to environmental conditions
Trophic state (chlorophyll *a*): responsive to nutrient enrichment and can be associated with risk of harmful algal blooms	A trophic state index was calculated based on measured chlorophyll *a* concentration
Benthic macroinvertebrate assemblage: responsive to a variety of stressors and can integrate exposure to current and recent past levels	Kicknet samples collected from the lake bottom at 10 shoreline locations and combined into a single composite sample for each lake. Organisms were usually identified to genus and a multimetric index was developed based on life history characteristics and tolerance to environmental conditions
Total phosphorus: important nutrient affecting trophic state and algal community structure	Collected from a vertically integrated sample of the upper water column at the open-water site. Measured concentrations were compared to benchmarks
Total nitrogen: important nutrient affecting trophic state and algal community structure	Collected from a vertically integrated sample of the upper water column at the open-water site. Measured concentrations were compared to benchmarks
Dissolved oxygen: low levels can result from nutrient enrichment and lead to loss of biota	In situ measurements were collected from the entire water column at the open-water site. The mean value of measurements from the top 2 m of the profile was calculated and compared to benchmarks
Acidification (acid neutralizing capacity—ANC): indicates potential exposure to episodic or chronic acidification, which can affect structure and composition of algal, zooplankton, and fish assemblages	ANC (corrected for DOC) measured from a vertically integrated sample of the upper water column at the open-water site. Measured concentrations were compared to benchmarks
Lake habitat complexity: indicates effects of human activities on the complexity of cover features in the riparian, shoreline, and littoral zones. Supports diversity of biotic assemblages such as fish, benthic invertebrates, and birds	Observations were recorded from 10 shoreline locations around each lake. Observed indicator values were compared with lake-specific expected values based on natural controlling factors within each region. Condition determinations were based on magnitude of deviations from expected values
Shallow water habitat: indicates effects of human activities on or near lakeshores on the complexity of littoral cover features that support biota	Same as for lake habitat complexity
Lakeshore disturbance: indicates types and potential severity of human activities in shoreline and littoral habitats	Observations were recorded from 10 shoreline locations around each lake. Uniform disturbance level criteria used nationwide
Riparian vegetation: reflects ability to buffer lake from influence of upland land use activities	Same as for lake habitat complexity
Lake drawdown exposure: reflects potential loss of littoral habitat and loss of connectivity between littoral and riparian zones due to hydrologic alteration and/or drought	Observations were recorded from 10 shoreline locations around each lake. Information was compared to distribution of drawdown exposure in regional reference sites
Atrazine: provides an indication of exposure to herbicides	Collected from a vertically integrated sample of the upper water column at the open-water site. We report on detection; measured concentrations were compared to an EPA plant-effects benchmark
Chlorophyll *a*: indirect measure of algal biomass, trophic state, and the potential for presence of algal toxins	Collected from a vertically integrated sample of the upper water column at the open-water site. Concentrations were compared to WHO algal toxin benchmark for recreation

Indicator and rationale	Sample location
Methyl mercury: toxic form of mercury that bioaccumulates in the lake food chain	Collected from the top 2 cm of sediment from a core taken from the bottom of the lake. Concentrations were compared to a benchmark
Total mercury: indicates potential exposure and availability of mercury to lake biota	Collected from the top 2 cm of sediment from a core taken from the bottom of the lake. Concentrations were compared to a benchmark
Microcystin: direct measure of algal toxin concentration present on day of sampling	Collected from a vertically integrated sample of the upper water column at the open-water site. We report on detection; measured concentrations were compared to the World Health Organization (WHO) algal toxin benchmark for recreation
Cyanobacteria: includes organisms responsible for release of algal toxins	Collected from a vertically integrated sample of the upper water column at the open-water site. Concentrations were compared to WHO algal toxin benchmark for recreation

Table 1.
Indicators and sampling locations for the national lakes assessment.

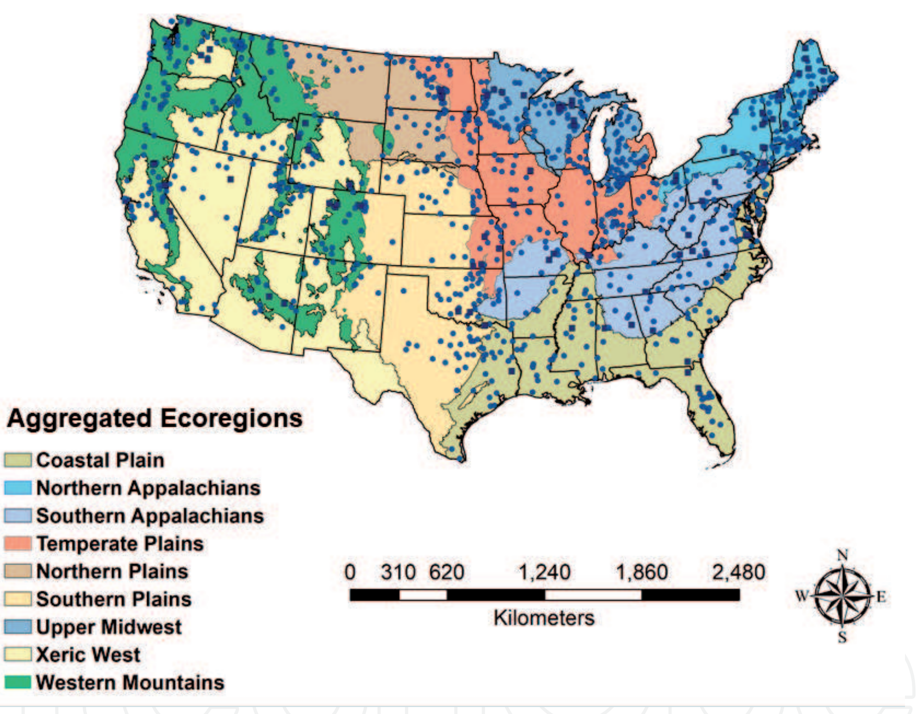

Figure 1.
Distribution of lakes sampled for the 2012 National Lakes Assessment. Circles represent sites selected as part of the probability-based survey design. Squares represent lakes hand selected as additional candidate "least-disturbed" reference sites for use in assigning lake condition categories. Aggregated ecoregions are based on Omernik level 3 ecoregions.

sites sampled to the entire target population of approximately 112,000 lakes targeted by the survey within the conterminous USA. The spatial distribution of sampled lakes in the 2012 survey is shown in **Figure 1**. For more details on survey designs as applied to aquatic resources, see [21, 26–30].

3.3 Response design

The way in which an individual lake is sampled for the various indicators is considered the "response design" [19]. In some cases, as with water samples, this is rather simple. For other indicators, such as physical habitat indicators, the response design is more complex. The NLA consists of two response designs at each lake. A standard single station located at approximately the deepest point in the lake (or midpoint of a reservoir) is used to collect (1) a depth profile of temperature, dissolved oxygen, pH, and conductivity; (2) surface water samples for chemical analyses and phytoplankton; (3) vertical plankton net tows to collect zooplankton; and (4) a sediment core sample. These samples result in data on zooplankton, chlorophyll *a*, acid neutralizing capacity (ANC), conductivity, total nitrogen, total phosphorus, anions/cations, dissolved oxygen, water transparency, temperature, pH, cyanobacteria, atrazine, sediment mercury (total and methyl), and microcystin. Riparian and littoral zone observations are collected at 10 equally spaced locations around the lake perimeter. Benthic macroinvertebrate samples are also collected at these littoral sites around the lake. Details of the collection process can be found in [29] and a similar document tied to each lake survey (**Table 1**).

4. Methods

The methods for the NLA are described in great detail in its supporting documentation (e.g., see [30–34]). A brief summary of critical elements of the approach follows.

4.1 Data acquisition (field and laboratory)

The NLA has developed field protocols intended to be applied consistently at all lakes and reservoirs sampled. This is in contrast to the approach implemented in the European Union to accomplish the objectives of the Water Framework Directive, which employs various methods to arrive at analogous assignments of water body condition (e.g., see [35]). The NLA protocols are also designed to be implemented by field crews who are not all experienced limnologists or aquatic biologists. Many (80–90) field crews (comprised of state and contractor crew employees) are required to sample the selected lakes during a summer sampling window (index period) from June through September. It is important to note that inferences made from the data are estimates of condition found during that index period and do not apply, necessarily, to other parts of the year. In essence, these are "snapshots" of conditions in the lake population during the summer growing season. Standardized field and laboratory protocols are used to collect and process the samples. Standardized field forms, either paper or electronic, are used by the crews to record measurements and observations. The samples that are collected are sent to processing laboratories for analyses. The field and laboratory data are sent to a central repository for inclusion into the data sets (see [30] for details). A comprehensive quality assurance program is developed and implemented for all field, laboratory, data analysis, and data management activities in the NLA to ensure that results are of known and adequate quality to be used in the assessment (e.g., see [33]).

4.2 Indicator development and evaluation

For the benthic macroinvertebrate and zooplankton samples, a comprehensive analysis and evaluation process was used to construct a multimetric index (MMI) of biological integrity for that assemblage. The process was based on general approaches described in [36, 37]. Metrics were developed using autecology information, taxonomic composition, taxonomic diversity, functional feeding groups, habitat preferences and tolerance to disturbance. The rationale and descriptions for each of these indicators can be found in [30, 38–42].

The approach used to measure and describe various dimensions of littoral and riparian physical habitat is described in [43–46]. These measurements result in indicators of lake habitat complexity, shallow water habitat alteration, riparian vegetation cover, lakeshore disturbance, and lake drawdown exposure in the littoral zone [30, 45, 46]. The shallow water habitat alteration indicator is based on visual estimates of the areal cover of several types of natural cover (e.g., snags, macrophytes, overhanging vegetation) observed in the littoral zone around each lake. The riparian vegetation cover indicator is based on visual estimates of vegetation cover and structure in three layers of riparian vegetation observed around each lake. The lakeshore disturbance indicator is based on visual estimates of the presence and proximity of several types of human disturbance (e.g., agricultural activities, residences, marinas) to the lake margin observed around each lake. The lake habitat complexity indicator is based on the mean value of the shallow water habitat alteration and riparian vegetation cover indicators.

For each of the physical, chemical, and biological indicators used in the assessment, a set of benchmarks or thresholds was developed against which to evaluate the quality of the lake relative to that indicator. For the NLA, expected values were developed for each indicator within each of the 9 aggregated ecoregions shown in **Figure 1** based on the distribution of measured values (observed scores), or observed/expected values (calculated scores) of the indicator in the set of least-disturbed reference lakes within that region. Condition thresholds were developed using the 5th and 25th (or 95th and 75th) percentiles of the distribution of the indicator scores in the set of regional reference sites, as described in the NLA 2012 technical report [30], and all sampled sites were assigned to good, fair, or poor condition based on those thresholds. More detailed discussions of the concepts underpinning behind the use of reference sites to model regional or individual lake expected indicator values in least-disturbed reference sites can be found in [25, 45, 47, 48].

4.3 Population estimates

The analytical goal of the assessment is to produce estimates of the number of lakes (or percent of lake number) falling into a condition class or stressor level based on the indicator data and the weights from the survey design [49]. Examples of how this was done for lakes and wetlands are presented in [21, 50]. The weight assigned to an individual lake is an estimate of the number of lakes in the target population represented by that lake and is used to develop a cumulative picture of the total target population. Status of the total lake population can be assessed for each of the indicators measured, whether they are biological, chemical, or physical. These population estimates represent the assessment of biological, chemical, and physical integrity goals expressed in the CWA.

4.4 Ranking of stressors

The final element of the assessment is intended to answer another key NLA question—"What is the relative importance of the different stressors impacting lakes?" This element ranks the potential stressors to biological condition that were measured during the survey. This assessment element is not intended to determine the "cause" of poor conditions at an individual lake but rather to evaluate and then rank the relative improvement in national status that might be gained, biologically, if one were to eliminate the adverse influence of each stressor through policy changes or management efforts. The quantitative approach borrowed from the medical literature to derive relative rankings is outlined in [51, 52]. This approach first requires a "relative extent" estimate (for each stressor) represented by the proportion of lakes in poor condition for that stressor. Then, the "relative risk" to biological indicators associated with poor conditions of each stressor indicators is calculated. Relative risk is the ratio of the percentage of lakes in poor biological condition in the subset of lakes that have high stress (poor condition), divided by the percentage of lakes in poor biological condition in the subset of lakes with stressor condition not classified as poor. Combining relative risk with relative extent of lakes with poor biological condition allows the calculation of "attributable risk," that is, the potential reduction in the percentage of lakes with poor biological condition if all of the lakes with poor stressor condition were to be restored so that they would be in good or fair stressor condition. These estimates are calculated for each stressor indicator and ranked relative to one another to see where the greatest improvement in biological condition might be expected.

5. National and regional status estimates

The results presented here are examples of a few of the ways to present and interpret the results from the NLA. We do not present a comprehensive assessment of lake condition based on NLA results here (see [34]). The first objective of the NLA is to describe the biological integrity of lakes within the conterminous USA. Based on a pelagic zooplankton multimetric index (MMI) of biological integrity, only 53 ± 7% of lakes in the conterminous USA ("National") are considered to be in good condition (**Figure 2**). A greater percentage of the natural lakes are in good condition (61 ± 10%) when compared with man-made lakes (43 ± 8%; **Figure 2**).

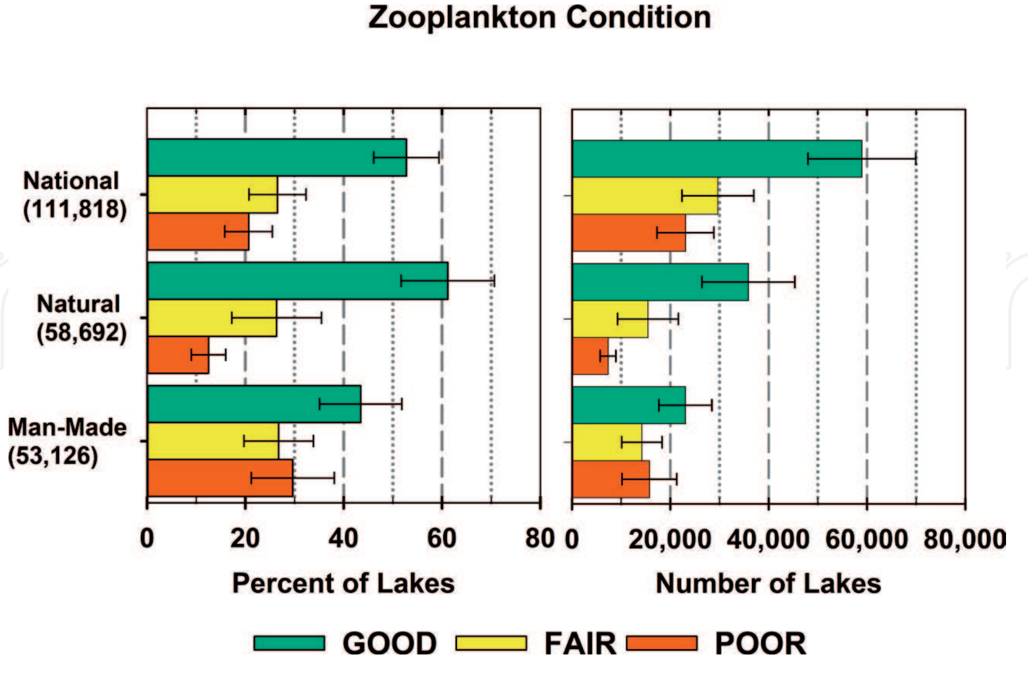

Figure 2.
Status of lake biological condition for the 2012 National Lakes Assessment based on a multimetric index (MMI) for the zooplankton assemblage. Results are presented nationally and by lake origin type (natural versus man-made) in the conterminous United States (i.e., lower 48 states). Estimates are presented as percent of lakes in each condition class (good, fair, or poor relative to regional determination of least-disturbed condition) and as the absolute numbers of lakes. Values in parentheses are the estimated number of target lakes in the population. Error bars are 95% confidence intervals.

Estimates produced for the 9 aggregated ecoregions allow one to consider regional patterns of condition in the context of the national estimates (**Figure 3**). Four regions (the Northern Appalachians, the Upper Midwest, the Southern Plains, and the Western Mountains) have more than 60% of their target population of lakes in good condition based on the zooplankton MMI. Three other regions (the Southern Appalachians, the Northern Plains, and the Xeric West) have a higher percentage of lakes in their target population in poor condition than good condition based on the zooplankton MMI (**Figure 3**).

Comparing regional and national estimates addresses the public's questions about whether poor conditions are distributed uniformly across the country or focused regionally. Such information allows for identifying and prioritizing those areas where the greatest need exists to address a specific problem. However, because the quality of least-disturbed sites varies regionally, direct comparisons among aggregated ecoregions need to be interpreted cautiously in terms of the lake population in one region having "better" (or "worse") lake condition than the lake population in another region.

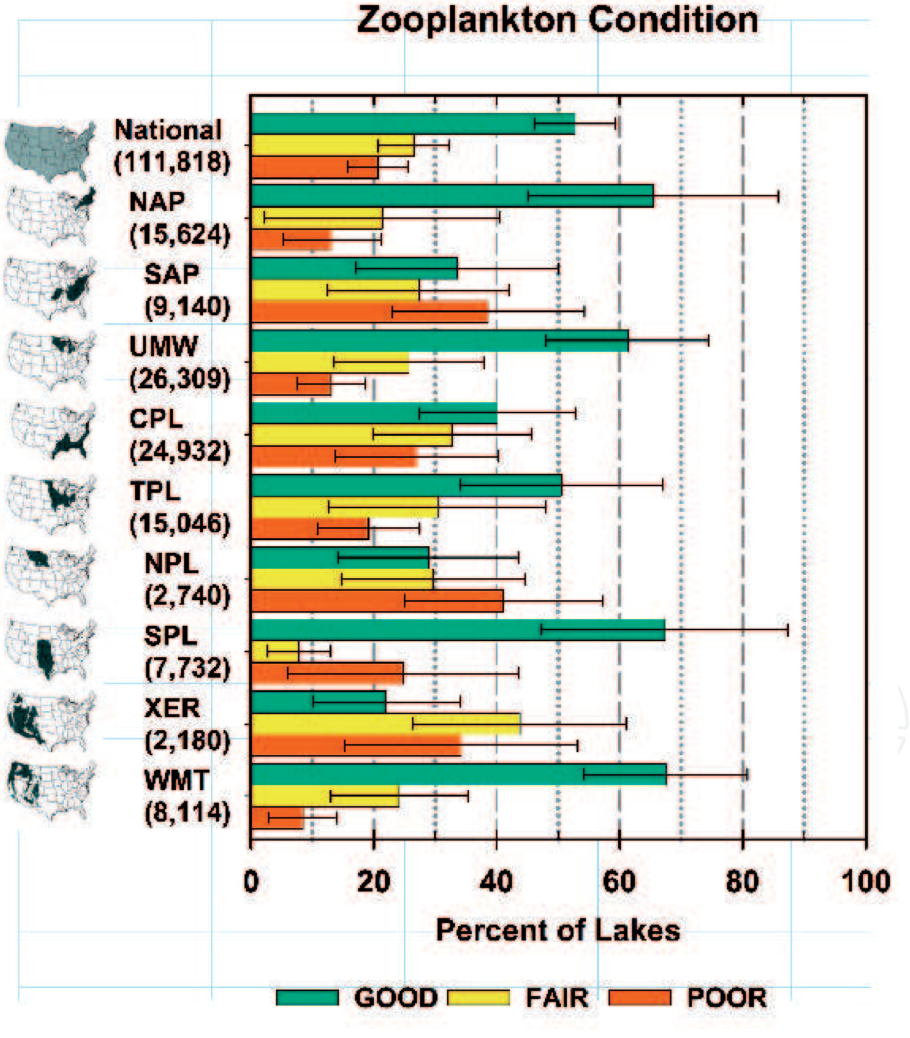

Figure 3.
Status of lake biological condition for the 2012 National Lakes Assessment based on a multimetric index (MMI) for the zooplankton assemblage. Results are presented nationally and for 9 aggregated ecoregions of the conterminous United States (i.e., lower 48 states). Estimates are presented as percent of lakes in each condition class (good, fair, or poor relative to regional determination of least-disturbed condition). Values in parentheses are the estimated number of lakes in the target population. Error bars are 95% confidence intervals. Aggregated ecoregion codes: NAP, Northern Appalachians; SAP, Southern Appalachians; UMW, Upper Midwest; CPL, Coastal Plain; TPL, Temperate Plains; NPL, Northern Plains; SPL, Southern Plains; XER, Xeric West; and WMT, Western Mountains.

Similar assessments can be made for any of the stressor indicators. Lake condition based on two nutrients (total phosphorus and total nitrogen) appears to be similar nationally, with less than 50% of all lakes with nutrient concentrations low enough to be considered in good condition (**Figure 4**). For both nutrients, man-made lakes have a lower percentage of lakes in good condition, and a greater percentage of lakes in poor condition, than natural lakes (**Figure 4**). Despite the fact that regions differ greatly in their proportion of natural versus man-made lakes, the national patterns observed for total phosphorus (TP) and total nitrogen (TN) are remarkably similar for the two types of lakes.

When we focus on a single nutrient, total phosphorus, 45% of the lakes in the conterminous USA are classified in good condition relative to regional expectations (**Figure 5**). Almost 55% of natural lakes were in good condition based on total phosphorus concentrations, compared with about 30% of man-made lakes (**Figure 4**). Across the 9 ecological regions, the Southern Appalachians, the Northern Plains, and Southern Plains exhibited the smallest percentages of lakes in good condition relative to total phosphorus with 23, 10, and 28% of the lakes classified in good condition, respectively (**Figure 5**).

Figure 6 shows comparable results at the national scale for the four measures of physical habitat quality in lakes—lake habitat complexity, shallow water habitat alteration, riparian vegetation cover, and lakeshore disturbance. In each case,

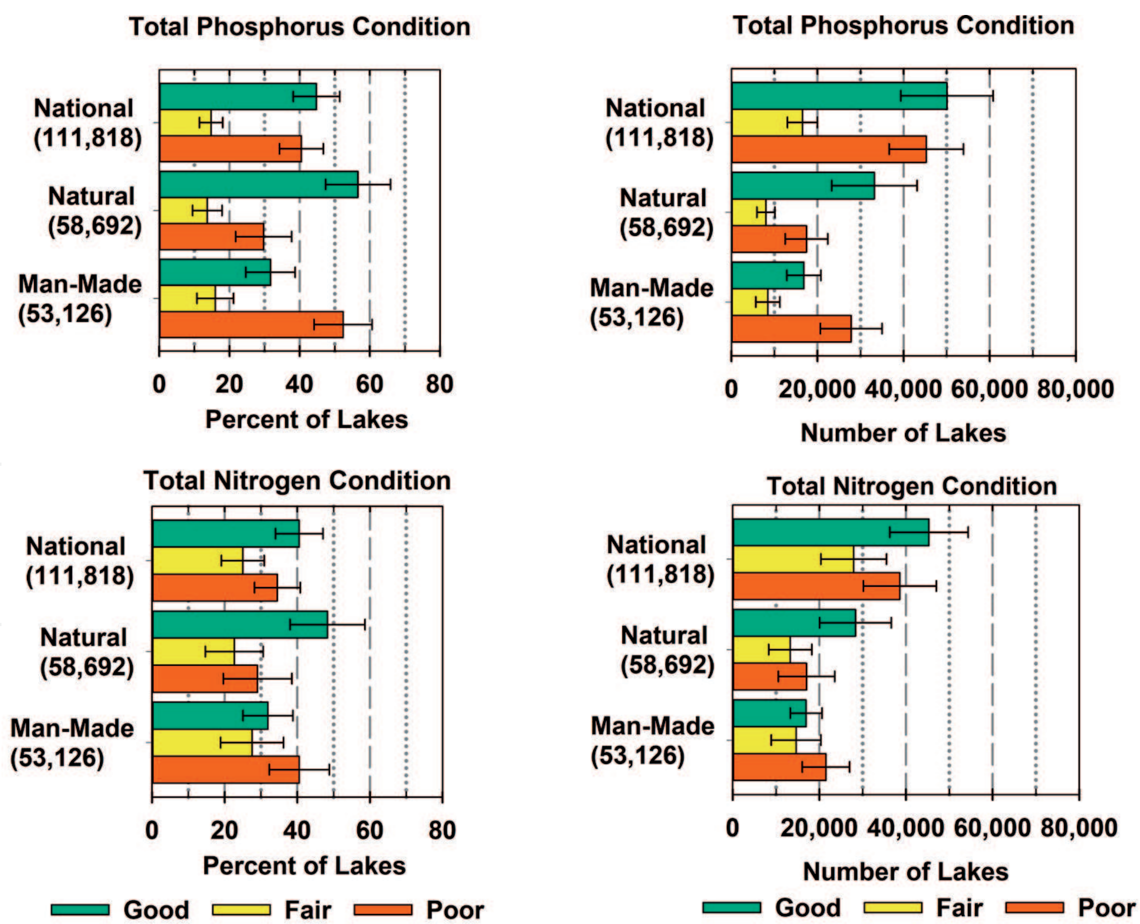

Figure 4.
Status of lake condition for the 2012 National Lakes Assessment based on total phosphorus and total nitrogen concentrations. Results are presented nationally and by lake origin type (natural versus man-made). Estimates are presented as the percent of lakes in each condition class (good, fair, poor relative to regional determination of least-disturbed condition) and as the absolute numbers of lakes. Values in parentheses are the estimated number of target lakes in the population. Error bars are 95% confidence intervals.

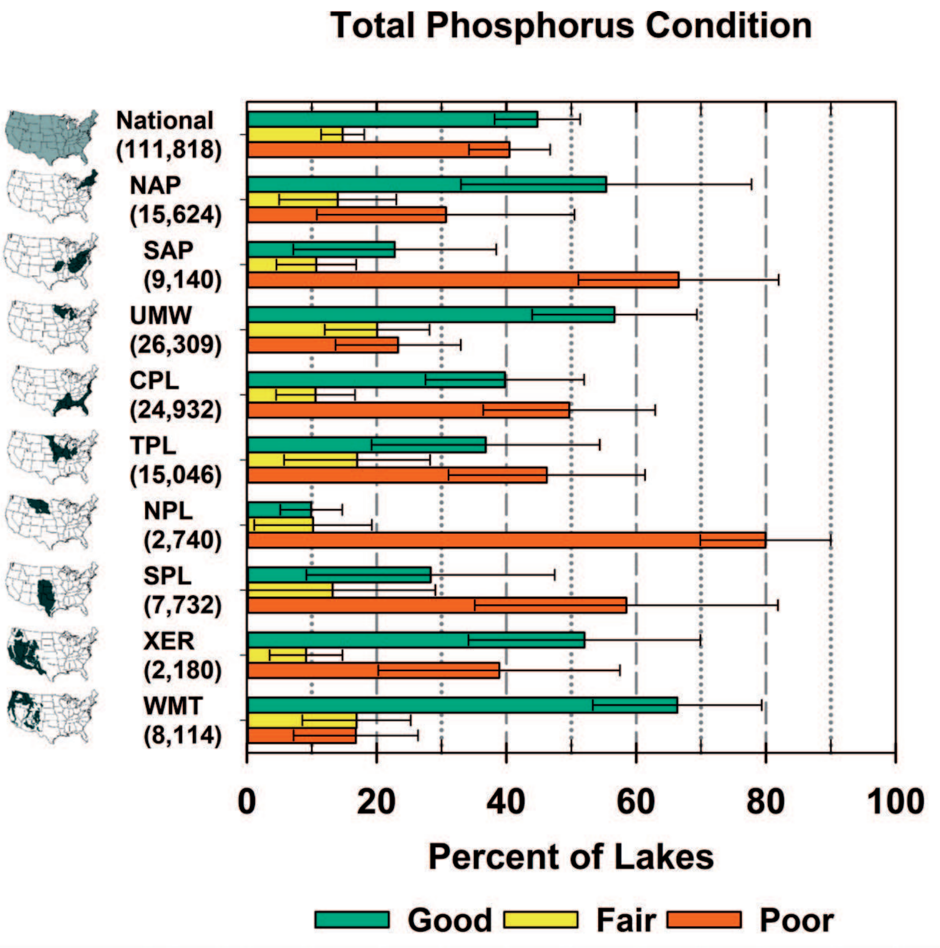

Figure 5.
Status of lake condition for the 2012 National Lakes Assessment based on total phosphorus concentrations. Results are presented nationally and for nine aggregated ecoregions of the conterminous United States (i.e., lower 48). Estimates are presented as percent of lakes in each condition class (good, fair, or poor relative to regional determination of least-disturbed condition). Error bars are 95% confidence intervals. Aggregated ecoregion codes: NAP, Northern Appalachians; SAP, Southern Appalachians; UMW, Upper Midwest; CPL, Coastal Plain; TPL, Temperate Plains; NPL, Northern Plains; SPL, Southern Plains; XER, Xeric West; and WMT, Western Mountains.

no more than 55% of the lakes in the country are in good condition for the respective physical habitat indicator. Nationally, the percent of lakes in good condition ranged from 28% (lakeshore disturbance) to 55% (riparian vegetation cover). Except for the shallow water habitat indicator, the percentage of natural lakes in good condition was greater than the percentage of man-made lakes in good condition.

Lake trophic state is a general indicator of lake productivity; the National Secchi Dip-In [11] provides an excellent overview that is based primarily on [53]. For the NLA, trophic state was estimated using phytoplankton chlorophyll *a* concentration, and condition was assigned using a single set of benchmarks across all ecoregions. **Figure 7** shows that nationally, about 10% of the lakes are classified as oligotrophic (chlorophyll *a* < 2 μg/L), and about 20% of the lakes are classified as hypereutrophic (chlorophyll *a* > 30 μg/L). The population of natural lakes appears to be less productive (i.e., have a larger percentage of lakes classified oligotrophic and mesotrophic) than the population of man-made lakes, which have a greater percentage of lakes classified as eutrophic and hypereutrophic (**Figure 7**). Across the 9 ecoregions, the largest percentage of oligotrophic lakes (nearly 60%) occurs in the Western Mountains (**Figure 8**). The Southern Plains has >40% of lakes classified as hypereutrophic, while the Temperate Plains has >30% of lakes classified as hypereutrophic (**Figure 8**).

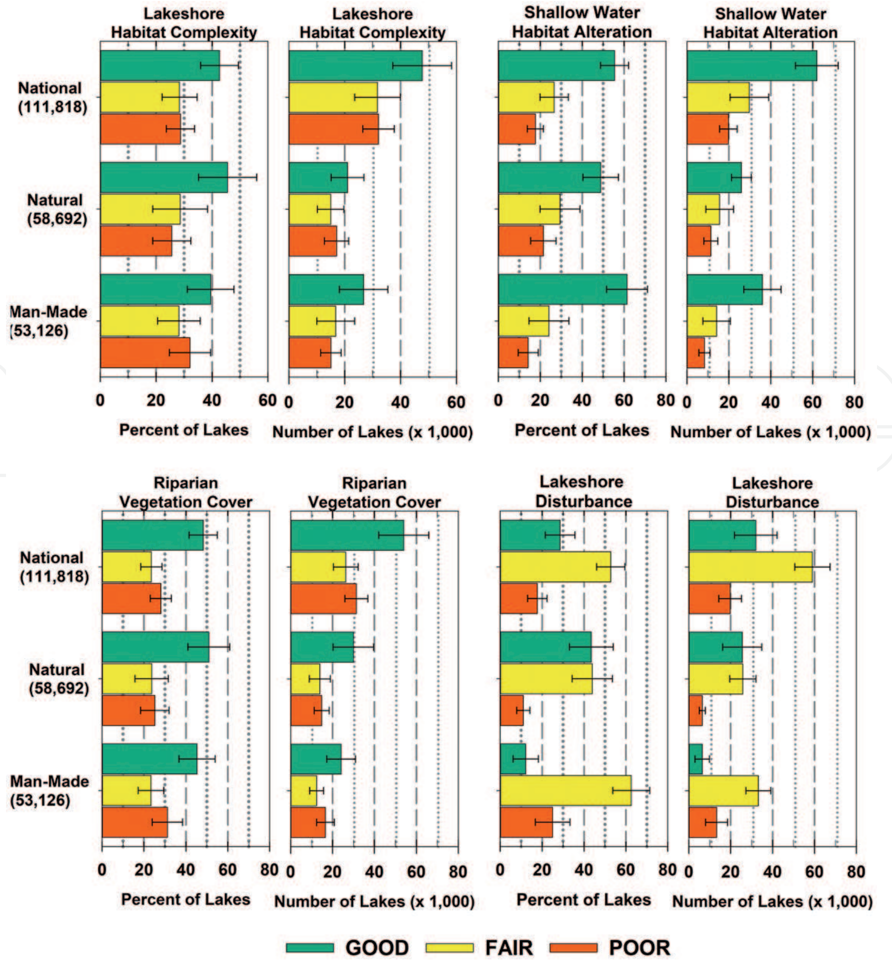

Figure 6.
Status of lake condition based on four indicators of physical habitat measured in the 2012 National Lakes Assessment: lakeshore habitat complexity, shallow water habitat alteration, riparian vegetation cover, and lakeshore disturbance. Results are presented nationally and by lake origin type (natural versus man-made). Estimates are presented as percent of lakes in each condition class (good, fair, poor relative to regional determination of least-disturbed condition) and absolute numbers of lakes. Values in parentheses are the estimated number of lakes in the target population. Error bars are 95% confidence intervals.

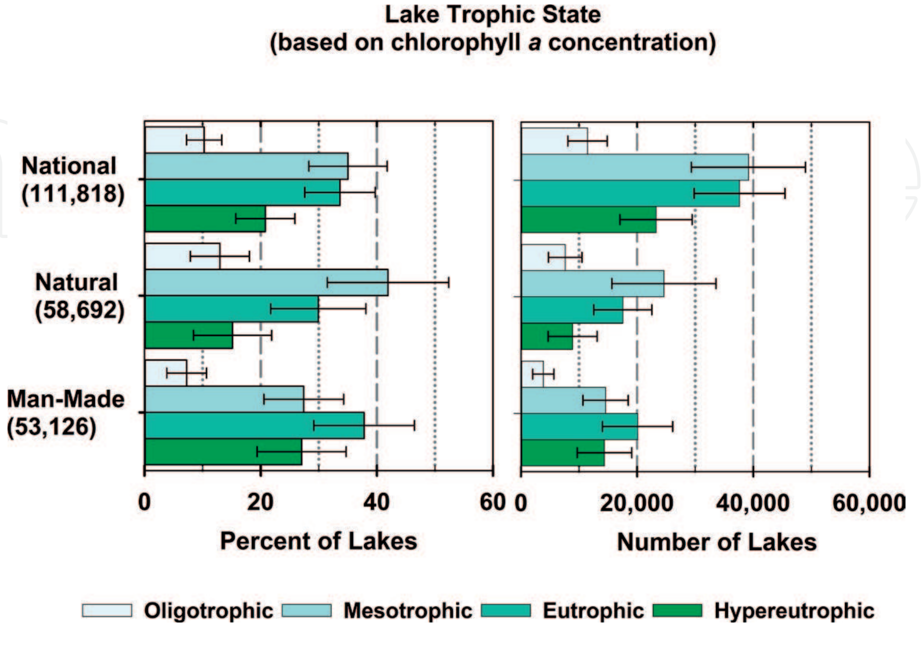

Figure 7.
Status of lake trophic state for the 2012 National Lakes Assessment. Trophic classes are based on chlorophyll a concentration. Results are presented nationally and by lake origin type. Estimates are presented as the percent of lakes and as the absolute number of lakes in each trophic category. Values in parentheses are the estimated number of lakes in the target population. Error bars are 95% confidence intervals.

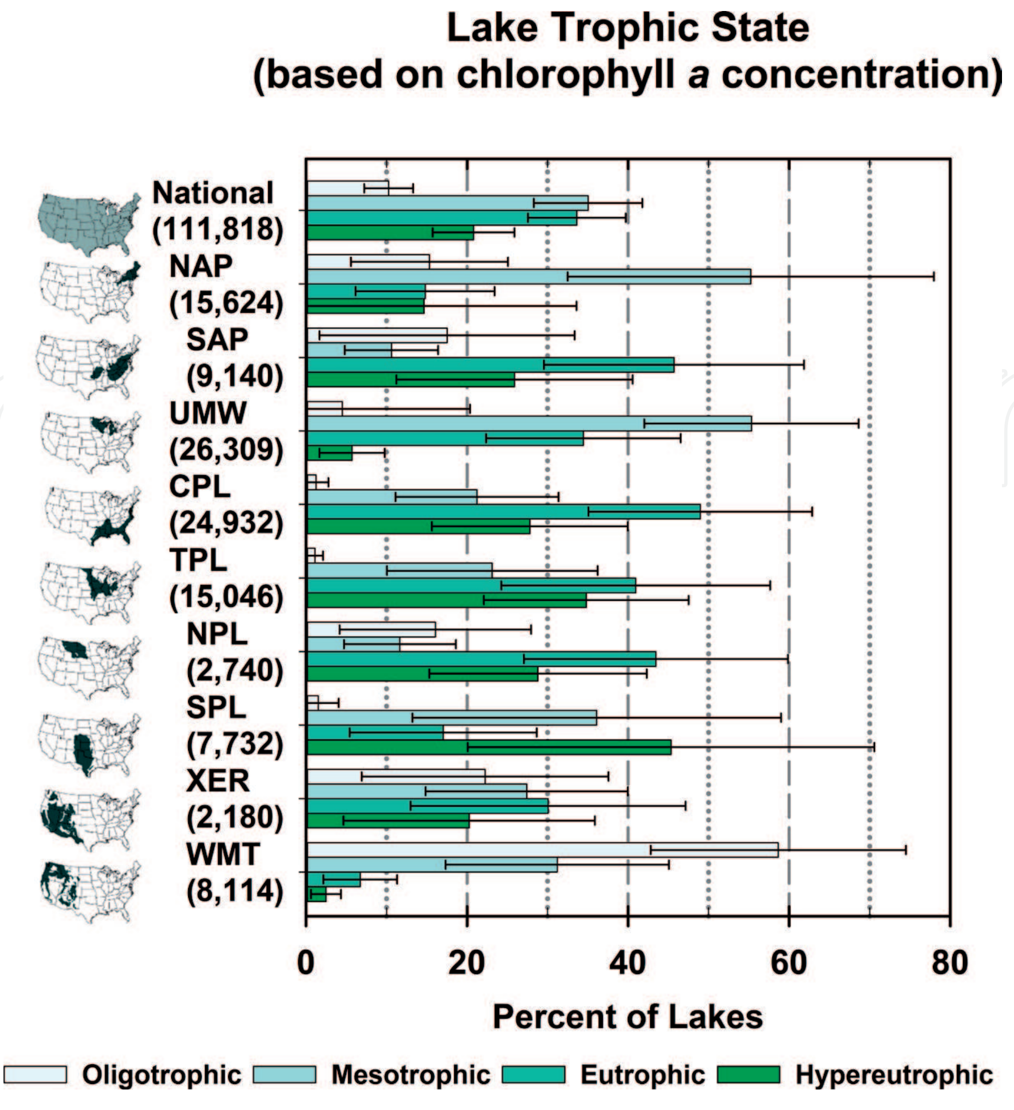

Figure 8.

Status of lake trophic state for the 2012 National Lakes Assessment. Trophic classes are based on chlorophyll a concentration. Results are presented nationally and for nine aggregate ecoregions. Estimates are presented as the percent of lakes in each trophic category. Values in parentheses are the estimated number of lakes in the target population. Error bars are 95% confidence intervals. Aggregated ecoregion codes: NAP, Northern Appalachians; SAP, Southern Appalachians; UMW, Upper Midwest; CPL, Coastal Plain; TPL, Temperate Plains; NPL, Northern Plains; SPL, Southern Plains; XER, Xeric West; and WMT, Western Mountains.

6. Change and trend estimates

Historically, the monitoring community has been focused on tracking trends at individual locations. The historic graphs of CO_2 levels at Mauna Loa [54] and decreases in water clarity resulting from increases in primary productivity in Lake Tahoe [55] are excellent examples. Tracking conditions at individual locations can be quite useful and is akin to tracking the weight or obesity status of an individual (i.e., useful for that individual but their use in large-scale policy discussions depends entirely on the circumstance). The Mauna Loa data clearly provide strong evidence for global increases in CO_2 given atmospheric circulation. In contrast, the isolated nature of individual lakes such as Lake Tahoe does not lend support for interpreting the Lake Tahoe water clarity data as a signal of a national or a global increase in lake productivity. The changes and trends that the NLA seeks to track are population trends…conceptually similar to asking the human health question

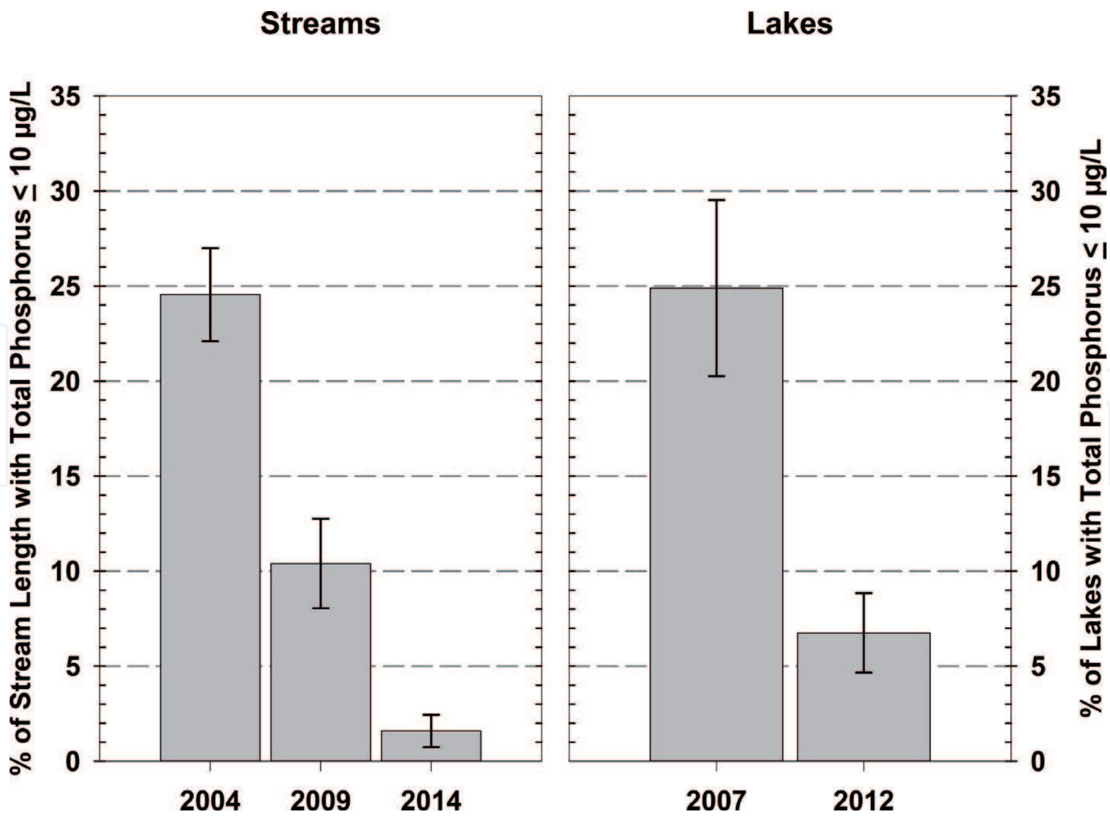

Figure 9.
Changes in total phosphorus (TP) in dilute streams and lakes across the conterminous USA based on the initial surveys of the National Rivers and Streams Assessment and the National Lakes Assessment. Data from [55]. Error bars are 95% confidence intervals.

"Has the number or percent of the population that is obese increased?". For the NLA, that translates to "Has the percent of lakes in poor (or good) condition class changed over time?"...essentially, is there a change in status over time? The current NLA online tools and reports show both status and changes. The best published examples of the intent of the NLA are [56, 57]. In [57], the authors document an increase in total phosphorus across the country that is especially evident in low nutrient lakes and streams. **Figure 9** displays the results discussed in that paper, showing that over the three initial stream surveys conducted as part of the NARS, the percentage of the total length of the stream population that had total phosphorus concentrations less than 10 μg/L decreased from 24.5% to just 1.6% between 2004 and 2014. Lakes were only surveyed twice during this period and showed a similar pattern with 24.9% of lakes with total phosphorus concentrations below 10 μg/L in 2007 decreasing to 6.7% of the lakes in that low nutrient category in 2012 (**Figure 9**). While it may be too early to know if these unidirectional changes and trends will persist, they are excellent examples of the types of population changes and trends that the NLA (and the NARS assessments in general) are intended to identify.

7. Stressor rankings

While the results presented above are useful for describing status and trends in lake conditions, they do not address the potential associations of different stressors with biological condition. When studying individual lakes, we are used to asking questions about the cause or combination of causes of the problem we have found. This is similar to asking "Why am I over-weight or gaining weight?" In population-level or policy-level discussions, it is not about finding a specific cause of problems, but rather finding some way to rank the various causes. In the context of assessing obesity, of all the causes of increasing weight in the U.S., what is their relative importance, and which would result in the largest improvements in the obesity situation if it were tackled? The NLA, and the NARS more broadly, have adapted tools from the human health field (relative risk and attributable risk) to address this question [51, 52].

Three pieces of information are needed to rank stressors according to importance and pervasiveness. The first is relative extent—a measure of how widespread a particular stressor or potential cause of problems is. How many lakes, for example, have high (or poor) levels of total phosphorus? This is shown in the left panel of **Figure 10**. From the figure, one can see that 40% of the lakes have total phosphorus at levels high enough to be considered poor. Similar information is presented for the other stressors nationally and separately for natural and man-made lakes.

The second piece of information is an estimate of the relative risk posed to biological condition (e.g., as assessed using the zooplankton MMI) by each stressor (**Figure 10**, center panel). This provides an estimate of the impact of a particular stressor on the zooplankton community when the stressor occurs at high levels (poor stressor condition). At a relative risk of 1, zooplankton are equally likely to be in poor condition if the stressor is at high levels (poor stressor condition) or at low to medium levels (good and fair stressor condition). At a relative risk of 2,

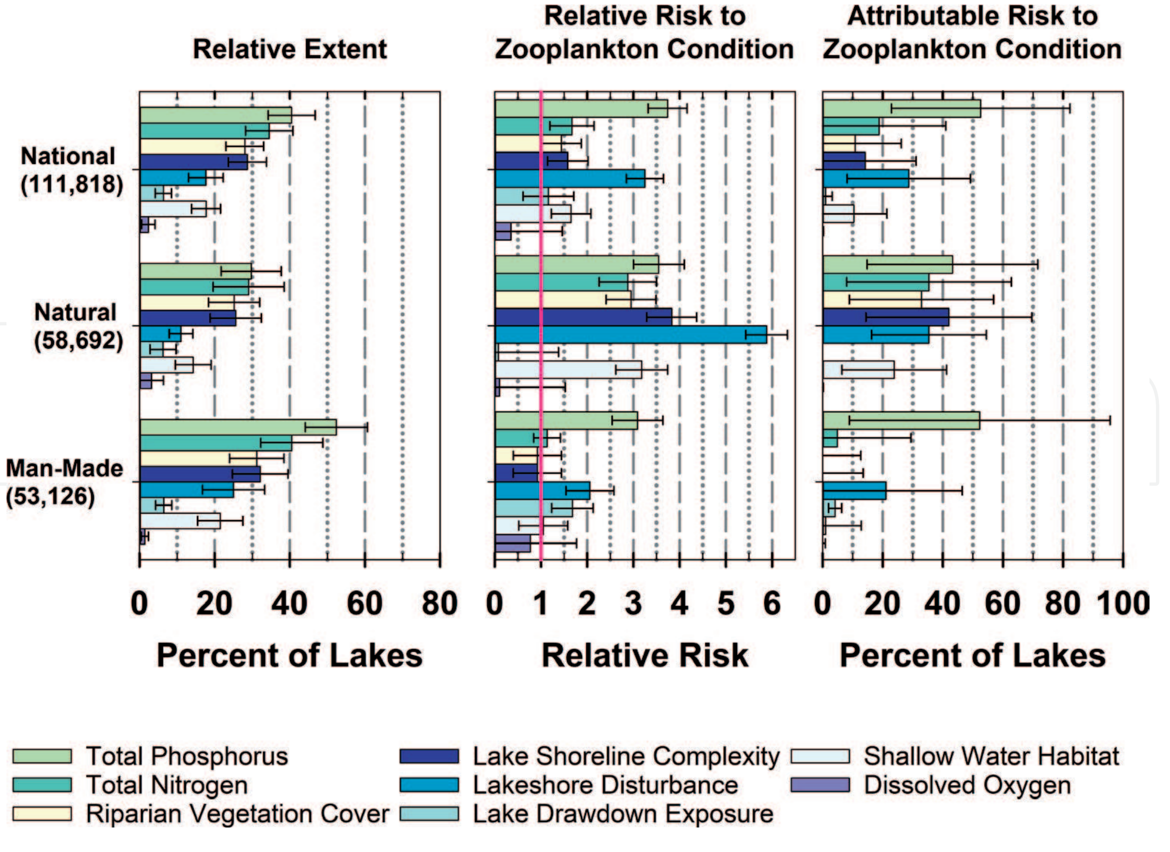

Figure 10.
Estimates for ranking stressors relative to their impact on the zooplankton assemblage for the 2012 National Lakes Assessment. Results are presented nationally and by lake origin type. Solid line represents a relative risk of 1, below which a stressor poses no risk to the biological assemblage. Error bars are 95% confidence intervals.

the zooplankton community is two times as likely to be in poor condition in the presence of high stressor levels as it is to be in poor condition with low to medium levels of the stressor. Nationally, zooplankton communities are more than 3.5 times as likely to be in poor condition with high levels of total phosphorus than with low to medium levels of total phosphorus.

The third piece of information combines the relative extent values and relative risk values to generate an attributable risk (AR) estimate (**Figure 10**, right panel). This answers the question: "How much of an improvement in lake biological condition would be seen if all the total phosphorus values in poor condition were improved to fair or good condition?". In the case of the potential risk of total phosphorus to lake biological condition as represented by the zooplankton community, we would expect a 52% reduction in the number of lakes in the target population in poor biological condition for zooplankton if the total phosphorus concentrations in these lakes were decreased enough to change the stressor condition from poor to either fair or good. The point of calculating the attributable risk is to generate an estimate of the potential benefit in zooplankton communities determined the same way for all stressors. Ranking via AR allows a consistent and relevant approach for providing a relative ranking of the stressors. **Figure 10** suggests that for natural and man-made lakes combined, the greatest potential benefit to the pelagic zooplankton community would result from nutrient control or reducing lakeshore disturbance. In natural lakes, the attributable risks to zooplankton from poor shoreline habitat complexity, riparian vegetation condition, excessive shoreline disturbance, and nutrients (total nitrogen and total phosphorus) are all at high values (between 32 and 43%). These results are consistent with abundant research showing that near-shore habitat alteration and increased nutrient loading are associated, and further suggest that near-shore habitat protection and restoration may be a fruitful strategy for controlling nutrients and improving zooplankton biointegrity.

8. Tracking specific threats and emerging threats

Among the biggest challenges and frustrations in monitoring is the time lag in addressing specific or new threats. When the acid rain issues arose in the 1980s, among the first questions raised was "How big is the problem?". Sadly, a reluctance to invest the time to assemble the technical experts to design and then implement a survey prompts premature policy decisions in the absence of solid information. While it is not possible to design a survey that anticipates every single problem that will arise, it is possible to design a survey that answers key questions about the health of our lakes and the relative importance of currently known stressors. The NLA does this well, in part because of the flexibility to adapt the survey design to new threats (e.g., see [58]). Additionally, the NLA serves as a platform from which to launch initial investigations into emerging issues to understand the nature of their size and distribution as well as track past and ongoing threats. The NLA continues to track the trophic state of lakes across the country (**Figure 10**). While the specific cause of eutrophication may have shifted from point sources to nonpoint sources it is still important to track this status as a key measure of how we manage our lakes. As other threats emerge, the NLA provides a platform to track their extent in lakes. Currently, harmful algal blooms and the toxins they produce (e.g., microcystin), mercury, and atrazine are among the specific stressors being tracked via NLA. The NLA 2012 website [59] has excellent presentations to explore the breadth of these threats.

9. Conclusions

Until the early 2000s, the history of monitoring lakes in the United States had been a succession of reactive efforts to assess particular stressors to determine how widespread they were and what policies, if any, should be adopted to tackle them. This strategy was moderately effective with domestic point source discharges like sewage treatment plants and with the deposition of acidic compounds as a result of sulfur and nitrogen compounds into the atmosphere. But many stressor-response problems are more complex, both in regional distribution and in likely causes. The NLA was initiated in 2007 to provide a more holistic and comprehensive approach to monitoring the quality of our lakes and the stressors impacting them while still allowing a platform to track specific lake stressors of concern as they emerge.

Acknowledgements

The authors gratefully acknowledge the tremendous effort and collaboration on the part of the USEPA Office of Water, the USEPA Office of Research and Development, and numerous state, federal, tribal, and contractor organizations that provide field, laboratory, and data analysis support for the National Lakes Assessment. The authors appreciate the constructive reviews of earlier drafts by D. Adams, F. John, and J. Markwiese. This chapter has been subjected to Agency review and has been approved for publication. The views expressed in this chapter are those of the author(s) and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency. Any mention of trade names, products, or services does not imply an endorsement by the U.S. Government or the U.S. Environmental Protection Agency. The EPA does not endorse any commercial products, services, or enterprises.

Conflict of interest

The authors declare no conflict of interest.

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References

[1] MacGonigle JN. The geography of the Southern Peninsula of the United States. National Geographic. 1896;**7**(12):381-394. Available from: https://archive.org/details/nationalgeograph71896nati/page/382/mode/2up/search/Lakes+of+Florida [Accessed: 03 March 2020]

[2] Federal Water Pollution Control Act—Amendments of 1972. Pub. Law No. 33 U.S.C. §1251 et seq. 1972. Available from: https://www.govinfo.gov/content/pkg/STATUTE-86/pdf/STATUTE-86-Pg816.pdf [Accessed: 24 March 2020]

[3] H. John Heinz Center for Science, Economics, the Environment. The state of the Nation's Ecosystems: Measuring the Lands, Waters, and Living Resources of the United States. New York: Cambridge University Press; 2002. 288 p

[4] O'Malley R, Negra C. Filling the Gaps: Priority Data Needs and Key Management Challenges for National Reporting on Ecosystem Condition. Washington, DC: The H. John Heinz Center for Science, Economics and the Environment; 2006. 111 p. Available from: https://www.researchgate.net/publication/307509444_Filling_the_gaps_Priority_data_needs_and_key_management_challenges_for_national_reporting_on_ecosystem_condition [Accessed: 24 March 2020]

[5] National Research Council. Environmental Monitoring. Vol. IV. Washington, DC: National Academy of Sciences; 1977

[6] Paulsen SG, Hughes RM, Larsen DP. Critical elements in describing and understanding our nation's aquatic resources. Journal of the American Water Resources Association. 1998;**34**(5):995-1005

[7] GAO (Government Accountability Office). Water Quality: Key EPA and State Decisions Limited by Inconsistent and Incomplete Data. Gaithersburg, Maryland: Resources, Community, and Economic Development Division, Government Accountability Office; 2000. Report No.: GAO/RCED-00-54

[8] GAO (Government Accountability Office). Better Monitoring Techniques are Needed to Assess the Quality of Rivers and Streams. Vol. 1. Washington, DC: Community, and Economic Development Division, Government Accountability Office; 1981. Report No.: GAO/CED-81-30

[9] National Research Council. Ecological Indicators for the Nation. Washington, DC: National Academy Press; 2000

[10] Gakstatter JH, Allum MO, Omernik JM. Lake Eutrophication: Results from the National Eutrophication Survey. Corvallis, Oregon: U.S. Environmental Protection Agency, Office of Research and Development, Laboratory CER; 1975. Report No.: EPA 645/R-75/001

[11] North American Lake Management Society. National Secchi Dip-In webpage: NALMS. 2019. Available from: https://www.nalms.org/secchidipin/ [Accessed: 20 February 2020]

[12] Landers DH, Overton WS, Linthurst RA, Brakke DF. Eastern Lake survey, regional estimates of lake chemistry. Environmental Science & Technology. 1988;**22**(2):128-135

[13] Eilers JM, Brakke DF, Landers DH, Kellar PE. Characteristics of lakes in mountainous areas of the western United States. Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie. 1988;**23**:144-151

[14] Kaufmann PR, Herlihy AT, Mitch ME, Messer JJ, Overton WS.

Stream chemistry in the eastern United States: Synoptic survey design, acid-base status, and regional patterns. Water Resources Research. 1991;**27**:611-627

[15] Hughes RM, Paulsen SG, Stoddard JL. EMAP-surface waters: A multiassemblage, probability survey of ecological integrity in the U.S.A. Hydrobiologia. 2000;**422/423**:429-443

[16] Larsen DP, Stevens DL, Selle AR, Paulsen SG. Environmental monitoring and assessment program: EMAP-surface waters, a northeast lakes pilot. Lake and Reservoir Management. 1991;**7**(1):1-11

[17] Whittier TR, Larsen DP, Peterson SA, Kincaid TM. A comparison of impoundments and natural drainage lakes in the Northeastern USA. Hydrobiologia. 2002;**470**:157-171

[18] Whittier TR, Paulsen SG, Larsen DP, Peterson SA, Herlihy AT, Kaufmann PR. Indicators of ecological stress and their extent in the population of northeastern lakes: A regional-scale assessment. Bioscience. 2002;**52**(3):235-247

[19] Hughes RM, Peck DV. Acquiring data for large aquatic resource surveys: The art of compromise among science, logistics, and reality. Journal of the North American Benthological Society. 2008;**27**(4):837-859

[20] Peterson SA, Urquhart NS, Welch EB. Sample representativeness: A must for reliable regional lake condition estimates. Environmental Science & Technology. 1999;**33**(10):1559-1565

[21] Peck DV, Olsen AR, Weber MH, Paulsen SG, Peterson C, Holdsworth SM. Survey design and extent estimates for the National Lakes Assessment. Freshwater Science. 2013;**32**(4):1231-1245

[22] Downing JA. Emerging global role of small lakes and ponds: Little things mean a lot. Limnetica. 2010;**29**(1):9-24

[23] Downing JA, Prairie YT, Cole JJ, Duarte CM, Tranvik LJ, Striegl RG, et al. The global abundance and size distribution of lakes, ponds, and impoundments. Limnology and Oceanography. 2006;**51**(5):2388-2397

[24] USEPA (United States Environmental Protection Agency). Visiting a Regional Office Webpage. Washington, DC: US EPA; 2020. Available from: https://www.epa.gov/aboutepa/visiting-regional-office [Accessed: 13 March 2020]

[25] Herlihy AT, Paulsen SG, Sickle JV, Stoddard JL, Hawkins CP, Yuan LL. Striving for consistency in a national assessment: The challenges of applying a reference-condition approach at a continental scale. Journal of the North American Benthological Society. 2008;**27**(4):860-877

[26] Larsen DP. Sample survey design issues for bioassessment of inland aquatic ecosystems. Human and Ecological Risk Assessment: An International Journal. 1997;**3**(6):979-991

[27] Stevens DL, Olsen AR. Spatially restricted surveys over time for aquatic resources. Journal of Agricultural, Biological and Environmental Statistics. 1999;**4**:415-428

[28] Stevens DL Jr, Olsen AR. Variance estimation for spatially balanced samples of environmental resources. Environmetrics. 2003;**14**:593-610

[29] Stevens DL Jr, Olsen AR. Spatially balanced sampling of natural resources. Journal of the American Statistical Association. 2004;**99**(465):262-278

[30] USEPA (United States Environmental Protection Agency). National Lakes Assessment 2012:

Technical Report. Washington, DC: U.S. Environmental Protection Agency, Office of Water; 2017. Report No.: EPA/841/R-16/114

[31] USEPA (United States Environmental Protection Agency). 2012 National Lakes Assessment Field Operations Manual. Washington, DC: U.S. Environmental Protection Agency, Office of Water; 2012. Report No.: EPA/841/B-11/003

[32] USEPA (United States Environmental Protection Agency). 2012 National Lakes Assessment Field Operations Manual. Washington, DC: U.S. Environmental Protection Agency, Office of Water; 2012. Report No.: EPA/841/B-11/004

[33] USEPA (United States Environmental Protection Agency). 2012 National Lakes Assessment. Quality Assurance Project Plan. Washington, DC: U.S. Environmental Protection Agency, Office of Water. 2012. Report No.: EPA 841-B-11-006

[34] USEPA (United States Environmental Protection Agency). National Lakes Assessment 2012: A Collaborative Survey of Lakes in the United States. Washington, DC: U.S. Environmental Protection Agency, Office of Water and Office of Research and Development; 2016. Report No.: EPA 841/R-16/113

[35] Birk S, Bonne W, Borja A, Brucet S, Courrat A, Poikane S, et al. Three hundred ways to assess Europe's surface waters: An almost complete overview of biological methods to implement the Water Framework Directive. Ecological Indicators. 2012;**18**:31-41

[36] Stoddard JL, Herlihy AT, Peck DV, Hughes RM, Whittier TR, Tarquinio E. A process for creating multimetric indices for large-scale aquatic surveys. Journal of the North American Benthological Society. 2008;**27**(4):878-891

[37] Van Sickle J. Correlated metrics yield multimetric indices with inferior performance. Transactions of the American Fisheries Society. 2010;**139**:1802-1917

[38] Hughes RM, Noss RF. Biological diversity and biological integrity: Current concerns for lakes and streams. Fisheries. 1992;**17**(3):11-19

[39] O'Connor RJ, Walls TE, Hughes RM. Using multiple taxonomic groups to index the ecological condition of lakes. Environmental Monitoring and Assessment. 2000;**61**(2):207-229

[40] Stemberger RS, Larsen DP, Kincaid TM. Sensitivity of zooplankton for regional lake monitoring. Canadian Journal of Fisheries and Aquatic Sciences. 2001;**58**:2222-2232

[41] Stemberger RS, Lazorchak JM. Zooplankton assemblage responses to disturbance gradients. Canadian Journal of Fisheries and Aquatic Sciences. 1994;**51**:2435-2447

[42] Stemberger RS, Miller EK. A zooplankton-N:P-ratio indicator for lakes. Environmental Monitoring and Assessment. 1998;**51**(1):29-51

[43] Kaufmann PR, Hughes RM, Van Sickle J, Whittier TR, Seeliger CW, Paulsen SG. Lakeshore and littoral physical habitat structure: A field survey method and its precision. Lake and Reservoir Management. 2014;**30**(2):157-176

[44] Kaufmann PR, Hughes RM, Whittier TR, Bryce SA, Paulsen SG. Relevance of lake physical habitat indices to fish and riparian birds. Lake and Reservoir Management. 2014;**30**(2):177-191

[45] Kaufmann PR, Peck DV, Paulsen SG, Seeliger CW, Hughes RM, Whittier TR, et al. Lakeshore and littoral physical habitat structure in a national lakes

assessment. Lake and Reservoir Management. 2014;**30**(2):192-215

[46] Fergus CE, Brooks JR, Kaufmann PR, Herlihy AT, Pollard AI, Weber MH, et al. Lake water levels and associated hydrologic characteristics in the conterminous U.S. Journal of the American Water Resources Association. 2020. DOI: 10.1111/1752-1688.12817

[47] Herlihy AT, Sobota JB, McDonnell TC, Sullivan TJ, Lehmann S, Tarquinio E. An a priori process for selecting candidate reference lakes for a national survey. Freshwater Science. 2013;**32**(2):385-396

[48] Stoddard JL, Larsen DP, Hawkins CP, Johnson RK, Norris RH. Setting expectations for the ecological condition of streams: The concept of reference condition. Ecological Applications. 2006;**16**:1267-1276

[49] Kincaid TM, Olsen AR. Spsurvey: Spatial survey design and analysis. R Package version 3.3. 2016. Available from: https://cran.r-project.org/web/packages/spsurvey/index.html [Accessed: 24 March 2020]

[50] Olsen AR, Kincaid TM, Kentula ME, Weber MH. Survey design to assess condition of wetlands in the United States. Environmental Monitoring and Assessment. 2019;**191**(1):268

[51] Van Sickle J, Stoddard JL, Paulsen SG, Olsen AR. Using relative risk to compare the effects of aquatic stressors at a regional scale. Environmental Management. 2006;**38**(6):1020-1030

[52] Van Sickle J, Paulsen SG. Assessing the attributable risks, relative risks, and regional extents of aquatic stressors. Journal of the North American Benthological Society. 2008;**27**(4):920-931

[53] Carlson RE, Simpson J. A Coordinator's Guide to Volunteer Lake Monitoring Methods. Madison, Wisconsin: North American Lake Management Association; 1996

[54] Earth Systems Research Laboratory GMD. Global Greenhouse Gas Reference Network-Trends in Atmospheric Carbon Dioxide. Boulder, Colorado: NOAA; 2020. Available from: https://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html [Accessed: 18 March 2020]

[55] Tahoe Environmental Research Center. Tahoe: State of the Lake Report 2019. Davis, California: University of California-Davis; 2019. Available from: https://tahoe.ucdavis.edu/stateofthelake [Accessed: 19 March 2020]

[56] Larsen DP, Urquhart NS, Kugler DL. Regional-scale trend monitoring of indicators of trophic condition of lakes. Water Resources Bulletin. 1995;**31**:117-139

[57] Stoddard JL, Van Sickle J, Herlihy AT, Brahney J, Paulsen S, Peck DV, et al. Continental-scale increase in lake and stream phosphorus: Are oligotrophic systems disappearing in the United States? Environmental Science & Technology. 2016;**50**(7):3409-3415

[58] Ferrey ML, Heiskary S, Grace R, Hamilton MC, Lueck A. Pharmaceuticals and other anthropogenic tracers in surface water: A randomized survey of 50 Minnesota lakes. Environmental Toxicology and Chemistry. 2015;**34**(11):2475-2488

[59] USEPA. National Lakes Assessment 2012 webpage. Washington, DC: U.S. Environmental Protection Agency; 2016. Available from: https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2012-results [Accessed: 20 February 2020]