Ecological Indicators 173 (2025) 113402

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Ecological condition of mountain lakes in the conterminous United States and vulnerability to human development

Amalia M. Handler [a,1,*], Marc Weber [a], Michael Dumelle [a], Lara S. Jansen [b], James N. Carleton [c], Blake A. Schaeffer [d], Steven G. Paulsen [e], Thomas Barnum [c], Anne W. Rea [g], Anne Neale [f], Jana E. Compton [a]

[a] U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Pacific Ecological Systems Division, Corvallis, OR 97300, USA
[b] Oak Ridge Institute for Science and Education Fellow c/o U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Corvallis, OR 97300, USA
[c] U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Health and Environmental Effects Assessment Division, Washington, DC 20460, USA
[d] U.S. Environmental Protection Agency, Office of Research and Development, Center for Environmental Measurement and Modeling, Watershed and Ecosystem Characterization Division, Durham, NC 27711, USA
[e] Retired, U.S. Environmental Protection Agency, Office of Research and Development, Center for Public Health and Environmental Assessment, Pacific Ecological Systems Division, Corvallis, OR 97300, USA
[f] U.S. Environmental Protection Agency, Center for Public Health and Environmental Assessment, Public Health and Environmental Systems Division, Research Triangle Park, NC 27711, USA
[g] U.S. Environmental Protection Agency, Center for Public Health and Environmental Assessment, Research Triangle Park, NC 27711, USA

A B S T R A C T

Mountain lakes provide cultural, aesthetic, and recreational services across the globe. Despite their recognized importance, there is no consistent definition of a mountain lake, which hampers describing them individually as well as in aggregate. Additionally, it makes it difficult to study and manage this unique population. We develop a rules-based approach for classifying mountain lakes according to the topography of the area draining directly to the lake. We apply the approach to the data from the United States National Lakes Assessment, for which the population is defined as lakes that are at least 1 ha in surface area and at least 1 m deep in the conterminous US (CONUS). Leveraging this national assessment allows for evaluating the condition of mountain lakes relative to all lakes in the CONUS. There are an estimated 12,353 (95 % C.I. 10,529–14,177) mountain lakes that account for 6.4 % of the lake population in the CONUS. Mountain lakes are in better condition than non-mountain lakes for 11 of 12 physical, chemical, and biological indicators (acid neutralizing capacity was the one exception). Approximately 25 % of mountain lakes are classified as eutrophic or hypereutrophic, and nearly 50 % are in fair or poor condition with respect to riparian vegetation and lakeshore disturbance. Mountain lake watersheds have lower proportions of developed land cover (mean $\pm$ 95 % CI: 0.8 $\pm$ 0.1 %) compared to non-mountain lakes (6.7 $\pm$ 0.3 %); however, developed land cover is more concentrated closer to the lakeshore for mountain lakes compared to non-mountain lakes. Coupled with characteristics such as high runoff, low hydraulic conductivity, and shallow bedrock depths, mountain lakes may be more susceptible to the adverse effects of human development and climate change compared to non-mountain lakes. These findings underscore the need for targeted monitoring, conservation, and management strategies to protect these valuable and sensitive lake environments.

1. Introduction

Mountain lakes are widely recognized for their scenic beauty and clear waters (Schirpke et al., 2021). In the ecological literature, mountain lakes are typically characterized by high elevation, cool water temperatures, oligotrophic conditions with high water clarity and low nutrients, seasonal ice cover, and low anthropogenic influence (Catalán et al., 2006; Moser et al., 2019). As freshwater resources upstream of many human communities, mountains lakes are commonly referred to as water towers of the planet (Messerli et al., 2004). In addition, mountain lakes support sensitive and unique biota (Palomo, 2017) have high cultural significance, provide hazard mitigation, and also serve as centers for recreational activity (Ebner et al., 2022a). Since mountain lakes are widely acknowledged as highly valued ecosystems and

* Corresponding author.
E-mail address: Handler.Amalia@epa.gov (A.M. Handler).
1 0000-0001-8372-6488.

https://doi.org/10.1016/j.ecolind.2025.113402
Received 29 January 2025; Received in revised form 7 March 2025; Accepted 24 March 2025
Available online 28 March 2025

components of larger ecosystems, studies of their status and condition as a population are needed (Catalan et al., 2009b; Moser et al., 2019).

Due to their relative remoteness and potential sensitivity, mountain lakes may serve as sentinels to certain anthropogenic stressors including changing climatic conditions and atmospheric deposition (Catalán et al., 2006; Moser et al., 2019). Rising temperatures and reduced ice cover may lead to a variety of changes in processes such as freeze–thaw, albedo, as well as stratification and mixing (Rangwala and Miller, 2012). Atmospheric deposition and watershed runoff may also contribute new chemical pollutants (Machate et al., 2023) such as microplastics (Pastorino et al., 2022). Climate change may result in mountain lakes experiencing more wildfires and drought, lower land stability and increased floods (Palomo, 2017; Stoffel and Huggel, 2012), as well as changes in species composition and shifting treelines with consequences for lake dissolved organic matter (Catalán et al., 2024). In-lake changes include increases in phytoplankton biomass, alterations in phenological patterns, and shifts in composition that potentially favor cyanobacterial blooms that can impact food webs (Jansen et al., 2024; Woolway et al., 2020). Finally, many mountain lakes are directly impacted by human communities, including activities such as development for recreation, residential use, agriculture, and water supply which can impact the lake (Ebner et al., 2022a; Ebner et al., 2022b; Palomo, 2017; Pastorino et al., 2024; Schirpke and Ebner, 2022).

While the importance and vulnerability of mountain lake ecosystems are well-recognized (Moser et al., 2019), there is currently no comprehensive assessment of the condition of mountain lakes as a distinct population. In fact, there is no rigorous and repeatable definition for "mountain lakes" making such a comprehensive assessment challenging. Historically, alpine lakes have received much attention and concern given their relative remoteness and sensitivity to climate change (Catalán et al., 2006). Alpine lakes are generally considered to occur in high elevation mountainous areas, are at or above the treeline, and are influenced by extended periods of snow or ice cover (Catalan et al., 2009a; Thomasson, 1956). In the conterminous US (CONUS), these definitions would exclude all lakes in the eastern half of the country as well as many lakes occurring in areas referred to as mountains across the CONUS that are of high cultural, aesthetic, and recreational value. For example, Lake Tahoe is a commonly cited as an alpine lake (Richards et al., 1991) although the lake setting does not meet most common definitions of alpine lakes. Despite this, Lake Tahoe and many other mountain lakes are undoubtably important systems that warrant study.

For a mountain lake classification, a simple, fixed elevation cutoff does not suffice since mountain regions occur at many different elevations. A cutoff would likely exclude most or all lower lying mountain regions, while being overly inclusive of non-mountain regions such as plateaus (Moser et al., 2019). For example, in the eastern US, there are the Appalachian Mountains, Smoky Mountains, Green Mountains, Adirondack Mountains, Ozark Mountains, Catskill Mountains, among others; yet these mountain ranges rarely are included in discussions of mountain lakes due to their relatively low elevation compared to mountain ranges of the western US (Immerzeel et al., 2020; Moser et al., 2019). A classification system that relies on data aside from elevation will be required to be inclusive of these eastern mountain ranges. Classification systems have been developed for grouping water resources into discrete categories for various purposes based on similarity of chemical, biological, hydrological, morphological, geological, and geographical attributes of the water bodies or their catchments (the area draining directly to the lake). An example is the Strahler stream numbering system used to distinguish headwater streams from larger streams and rivers (Horton, 1945; Strahler, 1952; Strahler, 1957). Classification systems for lakes have focused on their relative position among other lakes in a flow network (Riera et al., 2000) or hydrodynamics (Winter, 1977). Various abiotic factors can be used to describe mountainous locations, including relative elevation, relief, and landscape position within drainage networks (Körner et al., 2011; Sayre et al., 2018). An approach based on these factors can be flexibly applied across varied landscapes to capture mountain regions occurring at varying elevations.

In recognition of the importance of mountain lakes for habitat, water supply, and as centers of recreation and tourism, the goals of this study are: (1) develop a rigorous and repeatable classification system for "mountain" lakes (2) provide an overview of the characteristics of mountain lakes and (3) to estimate the condition of mountain lakes across the CONUS. To achieve this goal, we first develop a rules-based framework for classifying mountain lakes. We then leverage the United States Environmental Protection Agency's (US EPA) National Lakes Assessment (NLA) to estimate the ecological condition of mountain lakes relative to non-mountain lakes. We characterize the patterns of human development near mountain lakes and examine how these development patterns may impact waterbodies in mountainous settings. Finally, we discuss the flexibility of our framework for classifying subpopulations of waterbodies and posit questions for further investigation about mountain lake condition and threats.

2. Methods

We begin by describing the NLA design, data collection, and assessment of condition. We then describe our process for classifying mountain lakes based on surrounding topography. Based on the resulting classification, we estimate the condition of the mountain lakes population and compare this to non-mountain lakes. Finally, we characterize the development patterns among the lakes sampled in the NLA to compare between mountain and non-mountain lakes.

2.1. National lakes assessment

US EPA's National Aquatic Resource Survey (NARS) is a partnership between the EPA and state and tribal authorities to assesses the physical, chemical, and biological condition of waterbodies across the CONUS (https://www.epa.gov/national-aquatic-resource-surveys). The NARS includes the NLA, which quantifies the status and trends in the chemical, physical and biological condition of lakes by surveying a representative set of lakes (Herlihy et al., 2008; Peck et al., 2020) according to a probability-based survey design (Stevens and Olsen, 2003; Stevens and Olsen, 2004). As a result of the probability-based survey design, the status and trends in the broader population of the US can be inferred based on those sampled in the NLA. We chose the NLA for our analysis for three reasons: (1) it is the only existing survey that represents the broad population of lakes across the CONUS; (2) it includes lakes across the many mountainous regions of the CONUS, (3) the broad suite of data collected in the NLA allows us to investigate differences in ecological condition between mountain lakes and non-mountain lakes in the CONUS.

Each NLA samples approximately 1,000 lakes across size classes, nine aggregated ecoregions, and 15 hydrologic units (Herlihy et al., 2008; Peck et al., 2013). For the first NLA in 2007, the target population (i.e., population of interest) included all lakes at least 4 ha in surface area and at least 1 m deep. For the 2012 and all NLA since, the target population was expanded to include all lakes at least 1 ha in surface area and at least 1 m deep. Lakes are sampled once between June and September. At each site, field crews spend one day collecting a suite of data that capture the chemical, physical, and biological condition of each lake. The collection and analysis of these data are described in previous studies (Peck et al., 2013; Peck et al., 2020; Pollard et al., 2018; Yuan et al., 2014) and technical documentation (US EPA, 2011; US US EPA, 2012). Briefly, a vertical profile and surface water samples for chemistry and phytoplankton are collected via boat at the deepest point in the lake. Assessment of the riparian and littoral habitat is conducted from 10 equally spaced locations around the lake perimeter. These data are summarized into key indicators that describe the overall lake condition.

For each indicator, a set of benchmarks or thresholds was developed against which to evaluate the quality of the lake with respect to a given indicator. Some indicators are measurements of a single data type, and others are indices that integrate multiple data types into a composite metric. Indicators are categorized using benchmarks that are based either on established guideline values or the distribution of data for the indicator for selected minimally disturbed or reference site locations (Peck et al., 2020; Stoddard et al., 2006). For the latter, condition thresholds were developed using a reference condition approach. Briefly this approach uses the 5th and 25th (or 95th and 75th) percentiles of the distribution of the indicator scores in a set of regional reference sites. Based on the value of the percentiles, all sampled sites were assigned to good, fair, or poor condition based on these thresholds (see US EPA, 2017 for details).

Total phosphorus is an example of an indicator with benchmarks that are determined based on regional reference sites. Higher phosphorus is associated with poorer condition. For this indicator, total phosphorus concentration from reference sites within a region is used to calculate the 75th and 95th percentiles (Fig. S1). The 75th percentile is the boundary between good and fair condition while the 95th percentile is the boundary between fair and poor condition. These benchmarks are then used to assign condition categories to all lakes sampled with the region. Benchmarks are developed within nine regions of the CONUS that maximize within-region ecological similarity (Herlihy et al., 2008; Stoddard et al., 2008). As a result, the thresholds between condition categories can be different among regions.

For this analysis, we use the NLA conducted in 2007, 2012, and 2017. The total number of unique lakes was 2,251 because some lakes are sampled in multiple survey years. We use 12 of the survey indicators for this analysis: Three biological indicators (trophic status, chlorophyll *a*, benthic macroinvertebrates), four physical indicators (littoral cover, riparian vegetation cover, lake habitat complexity, and lakeshore disturbance), and five chemical indicators (acid neutralizing capacity (ANC), dissolved oxygen, total nitrogen, total phosphorus, and microcystins). Other indicators including atrazine and zooplankton were not collected in 2007 or used substantially different methods from the 2012 and 2017 NLAs and therefore not included in this analysis.

2.2. Classifying mountain lakes

We classified mountain lakes based on the extent of mountainous landforms within a given area around each lake. We classified mountainous areas using the USGS Landforms data that categorizes the CONUS into 10 distinct landforms at 30 m pixel resolution (Sayre et al., 2009a). The landscape of the CONUS is sorted into landforms based on slope and relief characteristics (drainage channels, flat plains, smooth plains, irregular plains, escarpments, low hills, hills, breaks/foothills, low mountains, and high mountains/deep canyons) (Sayre et al., 2009b). Two of these categories (low mountains and high mountains/deep canyons) were used here to classify mountainous areas. There were two sequential steps to the analysis to categorize lakes as either mountain or non-mountain: determining (1) the extent of area around the lake to be considered and (2) the proportion of that area within the extent that is categorized as mountainous (Fig. 1).

For the first component, extent, we considered the area draining directly to the lake, referred to here as the lake catchment. In contrast, the lake watershed includes the entire upstream drainage area. We chose the catchment for the extent rather than the entire watershed because it captures immediate surroundings of the lake and represents direct mountainous influence on the lake ecosystem. We opted not to use the lake watershed since the watershed for many lakes in the NLA extends over large areas and can encompass many upstream lakes that have the capacity to transform conditions from snow-dominated headwater regions to lowland valleys (Pollard et al., 2018). Here, we use the catchment definition developed for LakeCat, a framework for associating geospatial data with lakes across the CONUS (Hill et al., 2018). In this framework, separate methodologies are used for lakes that are connected to the river and stream flow network (on-network lakes) and lakes that lack flowline connections (off-network lakes). For on-network lakes, the lake catchment is defined as any area draining to the specific lake that is not first routed through upstream stream or river flowlines, and more specifically, it is the catchment or set of catchments that intersect with the lake and share a linking identifier with the lake in NHDPlusV2 (McKay et al., 2012). For off-network lakes, the catchment is defined topographically as any area that drains to a lake and excludes areas that drain to topographically upslope lakes. For both on– and off-network lakes, the catchment area excludes area that drains to upstream lakes. See Hill et al. (2018) for detailed methodology. In this analysis, the lake area is excluded from the catchment area. For the sampled NLA lakes, the mean distance between the lake boundary and the catchment boundary had a median of 530 m with 95 % of distances between 76 m and 3,653 m.

For the second analysis component, we calculated the proportion of the lake catchment comprising mountain terrain and used this to classify lakes as either mountain or non-mountain. We explored several different proportion thresholds. We chose to use a proportional threshold to account for the large range in sizes of lake catchments from the NLA. To inform the threshold used for this analysis, we compiled studies of lakes that were referred to as “mountain lakes” or were characterized as occupying a “mountain ecosystem”. Our goal is to identify a threshold that is inclusive of commonly studied mountain lakes. Studies were selected to represent different mountain regions in the US. We processed these example lakes using the above framework to derive the proportion

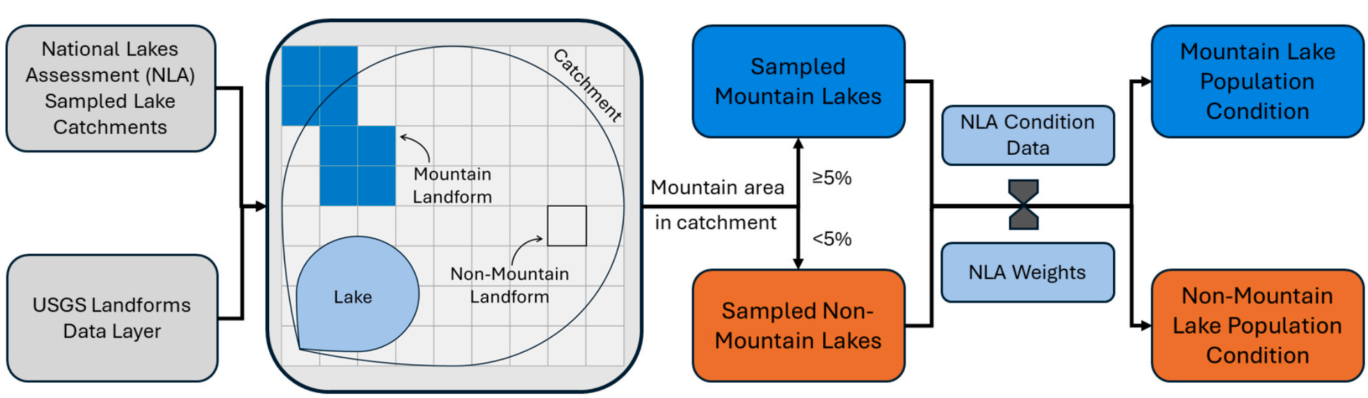

Fig. 1. Schematic diagram of lake classification process. The catchments for the lakes sampled in the 2007, 2012, and 2017 NLAs are overlaid the USGS landforms data to extract the percent of the catchment that is mountain landform. If the proportion mountain area exceeds a chosen percentage threshold, the lake is classified as a mountain lake. If below the threshold, the lake is considered a non-mountain lake. The NLA condition data and sample weights are applied to estimate the condition of all mountain and non-mountain lakes in the CONUS target population (> 1 ha surface area and > 1 m deep).

of the catchment that is mountain terrain. We then chose a threshold based on this analysis that would be inclusive of these example systems. In addition, we tested the thresholds of 1, 5, 10, and 25 % mountainous area within the catchment to explore how the chosen threshold would impact the number of sampled lakes, the estimated population size, and estimated condition of the population for both mountain and non-mountain lakes.

2.3. Mountain lake characteristics

We provide an overview of mountain lake and associated catchment and watershed characteristics with particular attention to differences between eastern and western mountain regions in the CONUS. We extracted the percent mountain landform in the lake catchment, lake elevation, maximum lake depth, and lake area. In addition, for the lake watersheds we show the distribution of the watershed area, mean slope, and land cover including developed, agricultural, forest, and perennial snow and ice (see Table S1 for data sources and citations). We compare lake origin, a metric developed by the NLA to determine which sampled lakes were present prior to European settlement (naturally occurring) versus after European settlement (artificially constructed) (Whittier et al., 2002; US EPA, 2022), among mountain and non-mountain lakes.

To investigate the patterns of human development near lakes, we compare the percent developed area in the watershed and catchment of mountain and non-mountain lakes. We calculated the amount of low, medium, and high intensity development from the National Land Cover Database (NLCD, Dewitz and U.S. Geological Survey, 2021) from 2011 within the lake catchments and watersheds. We used the protected areas database of the US to quantify the proportion of mountain and non-mountain lake catchments that are within the boundaries of National Forest Land and designated Wilderness Areas, and therefore, in regions with restricted development (U.S. Geological Survey, 2024). We used the Microsoft Building Footprints (Microsoft, 2018) as an additional, more detailed measure of development in the catchment and watershed of lakes. The Microsoft Building Footprints can provide higher resolution information about buildings in low development areas (Huang and Jin, 2022).

Finally, we explored several characteristics of mountain lakes that would make them potentially more vulnerable to the impacts of human development. We compared the mean slope, runoff, hydraulic conductivity, and depth to bedrock between mountain and non-mountain lake catchments.

2.4. Mountain lake condition

After developing the classification scheme above for mountain and non-mountain lake categories, estimates of condition were calculated to apply to lake populations in the CONUS. We generated waterbody condition estimates using the NLA design (Peck et al., 2013; Pollard et al., 2018) and the *spsurvey* package (Dumelle et al., 2023a). The indicator data and survey design weights are combined to estimate population parameters and, more broadly, develop complete characterizations of the target population (Dumelle et al., 2023b). We estimated the number of lakes falling into condition categories for mountain lakes, non-mountain lakes, and all lakes in the CONUS by evaluating the percent of lakes and number of lakes falling into good, fair, and poor categories for the biological, chemical, and physical indicators. All data analysis was conducted in the R programming environment (R Core Team, 2023).

3. Results

3.1. Mountain lakes in the conterminous US

In the NLA, 1,781 sampled lakes (79.1 %) have no mountainous terrain within their lake catchment. Among the 470 lakes (20.9 %) that have some mountainous terrain, the percent mountainous area ranges from < 0.01 % to 100 % (median = 39.7 %). Based on the four tested thresholds for mountainous terrain, the number of NLA lakes identified as mountain lakes ranged from 447 lakes for the 1 % mountain area threshold to 316 lakes with a 25 % mountain area threshold (Table 1). Extrapolating to the CONUS population, the estimated mountain lake population size ranged from 13,450 (11,539–15,360) lakes for the 1 % mountain area to 10,235 (8,585–11,884) lakes for the 25 % threshold. Notably, the different thresholds had a much smaller impact on the size of estimated non-mountain lake population. The estimated non-mountain lake population size ranged from 180,203 (164,914–195,493) for the 1 % mountain area threshold to 183,418 (168,047–198,789) lakes for the 25 % threshold. In other words, the population size difference for 1 % versus a 25 % threshold results in a 29 % decrease in the number of mountain lakes versus a 2 % increase in the number of non-mountain lakes. In addition, the mountain area threshold had only a marginal impact on the estimated condition of mountain and non-mountain lake populations (Fig. S2).

To help inform a threshold of mountain terrain that would capture many mountain lakes across the CONUS, we reviewed 19 lakes from previous studies that are identified as “mountain lakes” from the literature (Table 2). These included 14 lakes in western states and 5 lakes in eastern states. The proportion of mountain area in the catchments of these example lakes ranged from 0 to 100 % (median = 49 %). One of the 19 studied lakes (Upper Lake Mary in Arizona) was excluded for containing no mountain terrain in the catchment. Emerald Lake had the lowest percent mountain area that was greater than zero (9 % mountain area). To be inclusive of these commonly studied and cited mountain lakes across the western and eastern portions of the CONUS and to expand on analyses that have historically only included high elevation and alpine lakes, we selected a mountain area threshold of 5 % for this study.

Based on the 5 % threshold for mountain area within the lake catchment, 410 (18 %) of the 2,251 lakes sampled in the 2007, 2012, and 2017 NLA were classified as mountain lakes (Fig. 2). Mountain lake catchments have a median of 48 % mountain area. Based on the 5 % threshold for mountainous terrain in the lake catchment, there are an estimated 12,353 (10,529–14,177) mountain lakes in the CONUS that are at least 1 ha in surface area and 1 m deep compared with 181,300 (165,996–196,604) non-mountain lakes. As a proportion, mountain lakes account for an estimated 6.7 % of lakes in the CONUS.

Most mountain lakes are west of the Mississippi River (n = 337) with only 73 lakes east of the river. Sampled western mountain lakes tend to occur at higher elevations, have steeper mean slopes, and have a higher proportion of their catchment that are mountain landform than lakes in the east (Fig. 3). Western and eastern mountain lakes are comparable in terms of maximum lake depth, lake area, and watershed area with western mountain lakes having a slightly higher maximum range. Western mountain lakes have lower forest cover compared to eastern

Table 1
The number of NLA sampled lakes and the estimated population size of mountain or non-mountain lakes based on different thresholds of mountain area within the lake catchment. Estimated populations refer to lakes of >1 ha and >1 m deep in the conterminous US.

Threshold	Moutain Lakes		Non-Mountain Lakes	
	NLA Sampled	Estimated Population (95 % CI)	NLA Sampled	Estimated Population (95 % CI)
1 %	447	13,450 (11,539–15,360)	1804	180,203 (164,914–195,493)
5 %	410	12,353 (10,529–14,177)	1841	181,300 (165,996–196,604)
10 %	388	11,314 (9,600–13,027)	1863	182,339 (167,024–197,655)
25 %	316	10,235 (8,585–11,884)	1935	183,418 (168,047–198,789)

Table 2
Mountain lakes identified in the literature and the percent mountain terrain within the lake catchment.

Lake Name	State	Mountain Range	Mountain Landform (%)	Citation
Bubb Lake	NY	Adirondack	32	(Driscoll et al., 2003)
Heart Lake	NY	Adirondack	47	(Driscoll et al., 2003)
Mountain Lake	VA	Appalachian	28	(Roningen and Burbey, 2012)
Beartooth Lake	WY	Beartooth	82	(Williamson et al., 2010)
Mowich Lake	WA	Cascade	92	(Brittain and Strecker, 2018)
Crater Lake	OR	Cascade	76	(Larson et al., 2007)
Rondout Reservoir	NY	Catskill	29	(McHale et al., 2017)
Lake Powell	AZ	Colorado Plateau	40	(Stanford and Ward, 1991)
Hoh Lake	WA	Olympics	100	(Sheibley et al., 2014)
The Loch	CO	Rocky	81	(Baron et al., 2021)
Sky Pond	CO	Rocky	78	(Baron et al., 2021)
Flathead Lake	MT	Rocky	42	(Xiong et al., 2022)
Upper Lake Mary	AZ	San Francisco	0	(Button and Blinn, 1975)
Coeur d'Alene Lake	ID	Selkirk & Coeur d'Alene	44	(Horowitz et al., 1995)
Lake Tahoe	CA	Sierra Nevada	49	(Vander Zanden et al., 2003)
Emerald Lake	CA	Sierra Nevada	9	(Sadro et al., 2011)
Castle Lake	CA	Siskiyou	81	(Goldman, 1961)
Upper Carrol Lake	UT	Uinta	91	(Hundey et al., 2016)
Mirror Lake	NH	White	64	(Likens, 2000)

mountain lakes. None of the sampled eastern mountain lake watersheds contain perennial snow or ice cover compared to 20 % of western mountain lakes. Approximately half of sampled mountain lakes are naturally occurring (49 %) versus artificially constructed (51 %). Slightly fewer non-mountain lakes were naturally occurring (45 %) versus artificially constructed (55 %). Mountain lakes often lie in federally protected areas, with 57 % of mountain lake catchments on National Forest land and 22 % in National Wilderness Areas. In contrast, just 7 % and 2 % of non-mountain lake catchments occur in National Forest and Wilderness Areas, respectively. Both western and eastern mountain lakes are low in agricultural and developed land cover; however, the patterns in development differed for mountain lakes and non-mountain lakes, as described below.

While mountain lakes of the CONUS are in less developed regions, development is still present around some lakes. In addition, mountain lakes have characteristics that may increase their vulnerability to impacts from development. Based on building footprints, 41 % of mountain lake catchments are free of buildings compared to only 20 % of non-mountain lakes. In addition, among mountain lakes that did have buildings in the catchment, the median number of buildings is 26 and approximately half the median of 48 for non-mountain lakes. Mountain lakes also had lower mean percent developed land cover within their catchments and watersheds (Fig. 4). Developed land cover within the catchment area is slightly higher for both mountain and non-mountain lake catchments compared to the watershed. When evaluating the ratio of catchment to watershed percent area developed, mountain lakes have a higher mean ratio (2.8 ± 0.2) compared to non-mountain lakes (1.5 ± 0.1). Finally, mountain lakes differ in several characteristics that may contribute to how development can impact these systems. Mountain lake catchments have lower soil hydraulic conductivity, higher annual runoff, and shallower depths to bedrock compared to non-mountain lakes (Fig. 5).

3.2. *Condition of mountain lakes*

For 11 of 12 indicators, mountain lakes are in better condition compared to both non-mountain lakes (Fig. 6) and the population of lakes in the CONUS as a whole (Fig. S3). Since the population of all lakes includes mountain lakes, we present the results in terms of mountain lakes versus non-mountain lakes for ease of presentation and interpretation. A higher proportion of mountain lakes are in good condition (range: 46.3 % to 93.1 %) compared to non-mountain lakes (17.5 % to 78.1 %) for 11 indicators. The one exception was acid neutralizing capacity, with 92.8 % of mountain lakes in good condition compared to 97.7 % of non-mountain lakes. For all indicators, a smaller proportion of mountain lakes are in poor condition (0.0 % to 32.8 %) compared to non-mountain lakes (1.0 % to 53.2 %).

Among biological indicators, the trophic status of nearly half of mountain lakes is oligotrophic compared to under 10 % of non-mountain lakes (Fig. 6). In contrast, eutrophic or hypereutrophic mountain lakes were less common than among non-mountain lakes. Chlorophyll *a* and benthic macroinvertebrates are in good condition for over half of mountain lakes, respectively, versus less than half of non-mountain lakes.

Among the physical habitat indicators, a high percent of mountain lakes were in good condition for littoral cover and lake habitat complexity compared to non-mountain lakes (Fig. 6). Riparian vegetation and lakeshore disturbance were the two indicators with the lowest proportion of mountain lakes in good condition; however, this is still higher than the proportion for non-mountain lakes.

Among the chemical indicators, dissolved oxygen is in good condition for over 90 % of mountain lakes compared to just over 75 % for non-mountain lakes (Fig. 6). Acid neutralizing capacity is the single indicator for which mountain lakes had a lower proportion in good condition compared to non-mountain lakes. For total nitrogen and total phosphorus, nearly double the proportion of mountain lakes are in good condition compared to non-mountain lakes. Finally, microcystin detection is far less prevalent in mountain lakes compared to non-mountain lakes.

4. Discussion

While mountain lakes are important resources, there has not yet been a comprehensive survey of these ecosystems in the CONUS. Prior to the NLA, there were just two national surveys of lakes in the US. The first was the National Eutrophication Survey that focused on lakes with point sources of nutrient pollution (US EPA, 1975) and therefore excluded most mountain lakes. The second was a survey of the impact of acid rain on waterbodies that were poorly buffered and disproportionately included mountain lakes (Eilers et al., 1986; Landers et al., 1988). The NLA is the first survey that focuses on all lakes in the CONUS and, as a result, makes an analysis of this specific subpopulation possible. Based on the NLA, we find that mountain lakes are in better condition than non-mountain lakes with respect to most indicators of physical, chemical, and biological condition. Yet, mountain lakes are not without environmental concerns and sensitivities.

4.1. *Mountain lakes as a subpopulation*

One of the challenges to assessing the status of mountain lakes is classifying lakes as mountainous versus non-mountainous. Elevation is inadequate due to elevated plateaus that lack mountains while steep coastal ranges occur near sea level. In this study, we used local landforms to be inclusive of mountain lakes in the eastern and western

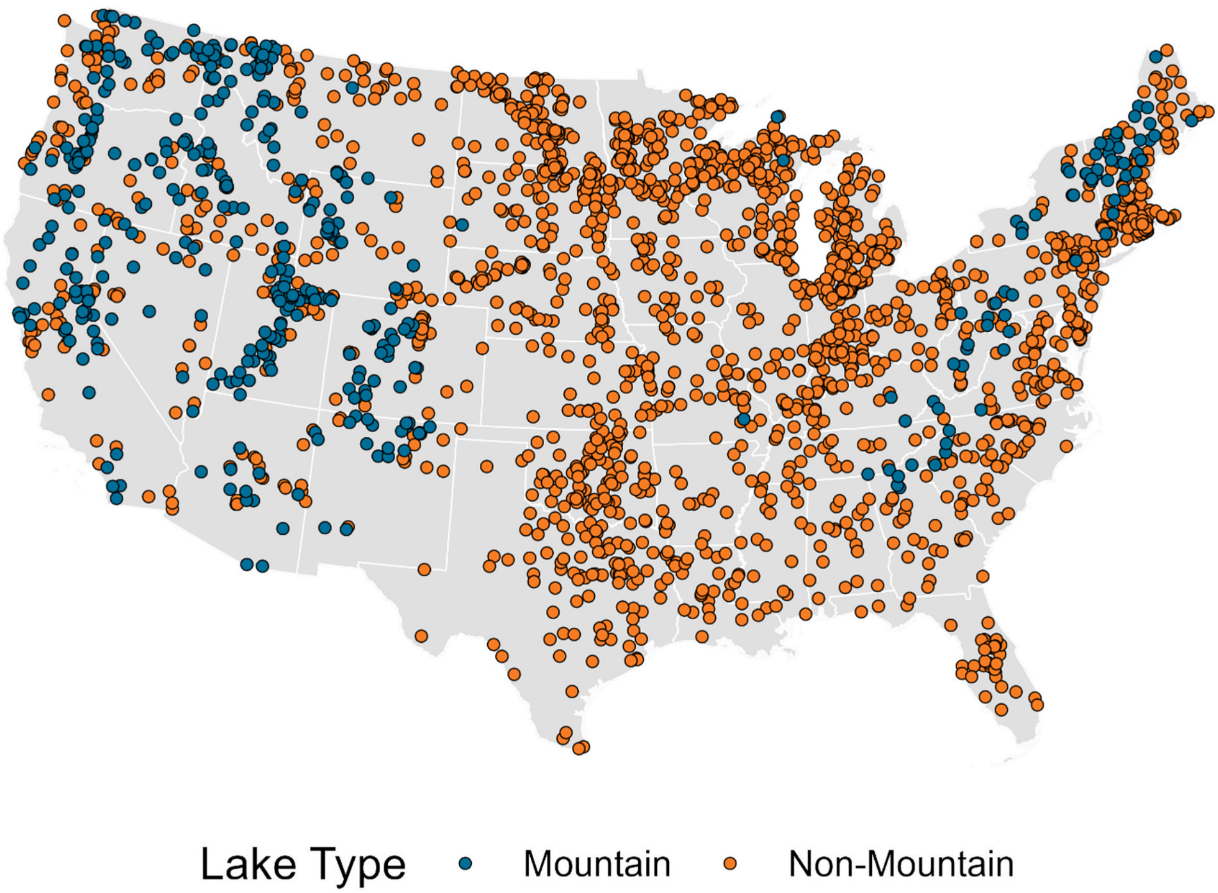

Fig. 2. Lakes sampled in the 2007, 2012, and 2017 National Lakes Assessment. Mountain lakes are identified as having ≥ 5 % mountain landform within their catchment. For easier viewing, mountain lake (in blue) dots are shown on top of the more abundant non-mountain lakes (in orange).

regions of the CONUS. Indeed, we found that eastern mountain lakes occurred at a mean elevation of just 360 m compared to western mountain lakes occurring at a mean of 1,730 m. For comparison, using a 3,000 m (10,000 ft) cutoff for alpine lakes would have only included 41 NLA sampled lakes in the CONUS, eliminating all eastern and most western lakes from the analysis. In addition, numerous studies on the impacts of acid rain deposition focused on remote mountain lakes (Driscoll et al., 2007; Marchetto and Rogora, 2004; Patrick et al., 1998). In contrast, our approach is agnostic to access and protection status thereby allowing us to assess development patterns across the broadly defined subpopulation.

4.2. Mountain lake condition

Mountain lakes are in better condition than non-mountain lakes in the CONUS for almost every indicator. An exception to this is ANC, for which a higher proportion of non-mountain lakes are in good condition compared to mountain lakes. Surface waters in mountainous areas are often relatively poorly buffered, and were disproportionately affected by acid deposition, although following implementation of the Clean Air Act amendments of 1990, acidification and its effects have often been at least partially reversed in mountain lakes and streams of the eastern US (Baldigo et al., 2015; Baldigo et al., 2021; Burns et al., 2006; Driscoll et al., 2016). The lower ANC seen in lakes at higher elevation has been noted and variously attributed to relatively steep slopes, thin soils, unvegetated terrain, and slower rates of bedrock weathering (Berg et al., 2005; Burns et al., 2006; Melack et al., 1985; Nanus et al., 2009; Sullivan et al., 2007). Bedrock weathering, and the corresponding geogenic production of free base cations (an important component of ANC), is expected to be slower in areas underlain by low-solubility, silicious sedimentary or felsic igneous (e.g., granitic) rocks, and higher in areas underlain by limestone or metamorphic rocks (Burns et al., 2006; Clow et al., 2010; Clow and Sueker, 2000; Melack et al., 1985; Nanus et al., 2009; Shaw et al., 2013; Staufer, 1990). Lakes that have been historically impacted by acid deposition which has abated in recent years are generally located in the eastern US and may experience delayed ecological improvement (Baldigo et al., 2015; Baldigo et al., 2021).

While the CONUS mountain lakes are in overall better condition than non-mountain lakes, a substantial proportion of the mountain lake population has challenges with respect to nutrients, trophic status, biological communities, and physical habitat. This is partially a consequence of the inclusion of lakes at lower elevations that are more accessible compared to more remote mountain and alpine lakes that have historically been the focus of other studies (Catalan et al., 2009b; Moser et al., 2019). Over a third of mountain lakes are in fair and poor condition for total nitrogen and phosphorus. This may be in part a result of residential septic systems leaching nutrients to nearby waterbodies (Withers et al., 2014). In addition, elevated nutrients may be due in part to increased atmospheric deposition in some mountain ranges with greater development in adjacent regions and increased dust transport (Baron et al., 2011; Brahney et al., 2015). Additionally, as the climate continues to warm in mountain regions, increasing soil temperatures can result in higher phosphorus leaching (Scholz and Brahney, 2022). The greater availability of nutrients in some mountains likely contributes to 25 % of mountain lakes being classified as eutrophic or hypereutrophic, indicating high primary productivity. While mountain lakes seem unlikely candidates for harmful algal blooms, there are some mountain lakes where harmful algal blooms occur regularly due in part to relatively high phosphorus (Jansen et al., 2024).

One third of mountain lake benthic macroinvertebrate communities

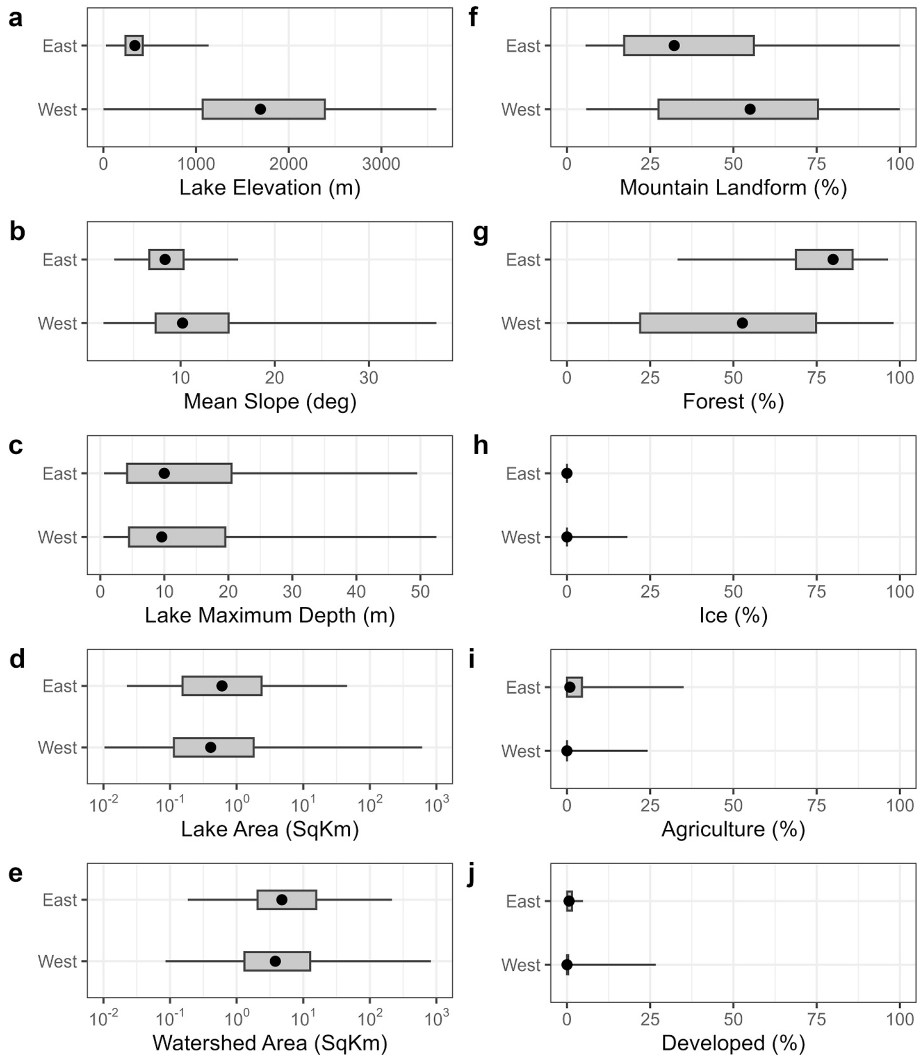

Fig. 3. Boxplots of mountain lake characteristics in the eastern and western United States. The lake elevation (a), catchment mean slope (b), lake maximum depth (c), lake surface area (d), watershed area (e), as well as percent mountain landform in the catchment (f) and amount of forest (g), ice (h), agriculture (i), and developed (j) land cover in the lake watersheds. Boxes represent the 25th and 75th percentiles, whiskers show the full data range, and circles indicate the mean.

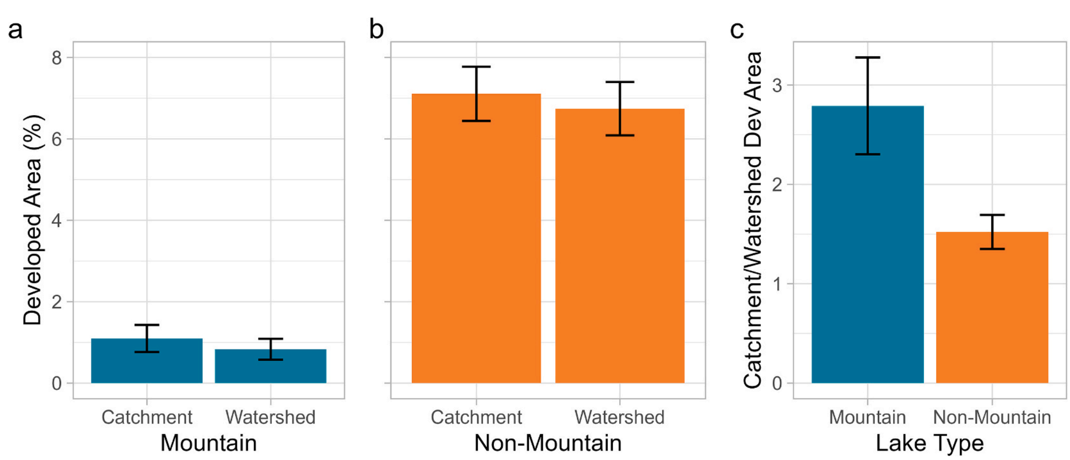

Fig. 4. The mean ± 95 % confidence interval of percent of low, medium, and high intensity development land cover in mountain (a) and non-mountain (b) lake catchment and watershed areas. The mean ratio of the catchment to watershed developed area for mountain and non-mountain lakes (c).

are in fair or poor condition. The impaired conditions of these sensitive taxa may be in due part to the previously mentioned delayed recovery from acidification in some areas. Another pathway is the introduction of non-native fish to numerous historically fishless mountain lakes (Eby et al., 2006). Many of these fish species, such as rainbow trout, predate heavily on benthic macroinvertebrates at least for a period of their life

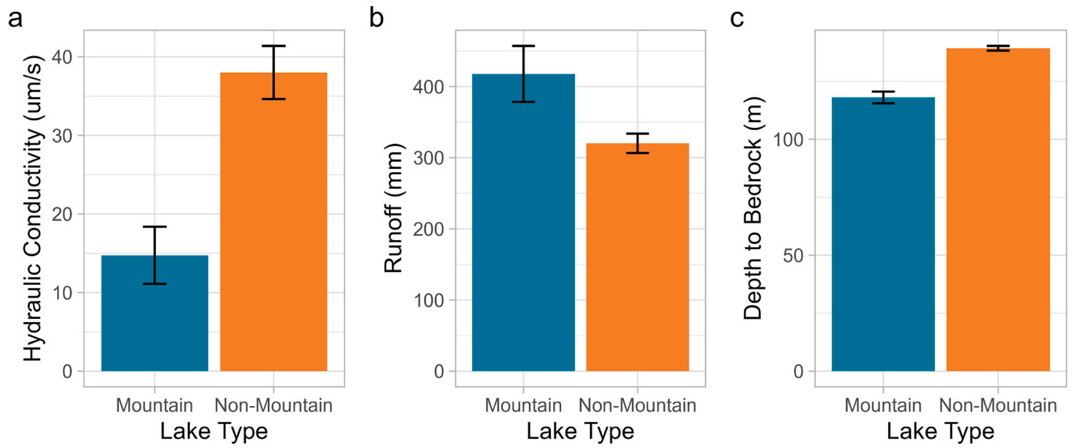

Fig. 5. The mean ± 95 % confidence interval of the soil hydraulic conductivity (a), annual runoff (b), and depth to bedrock for mountain and non-mountain lake catchments.

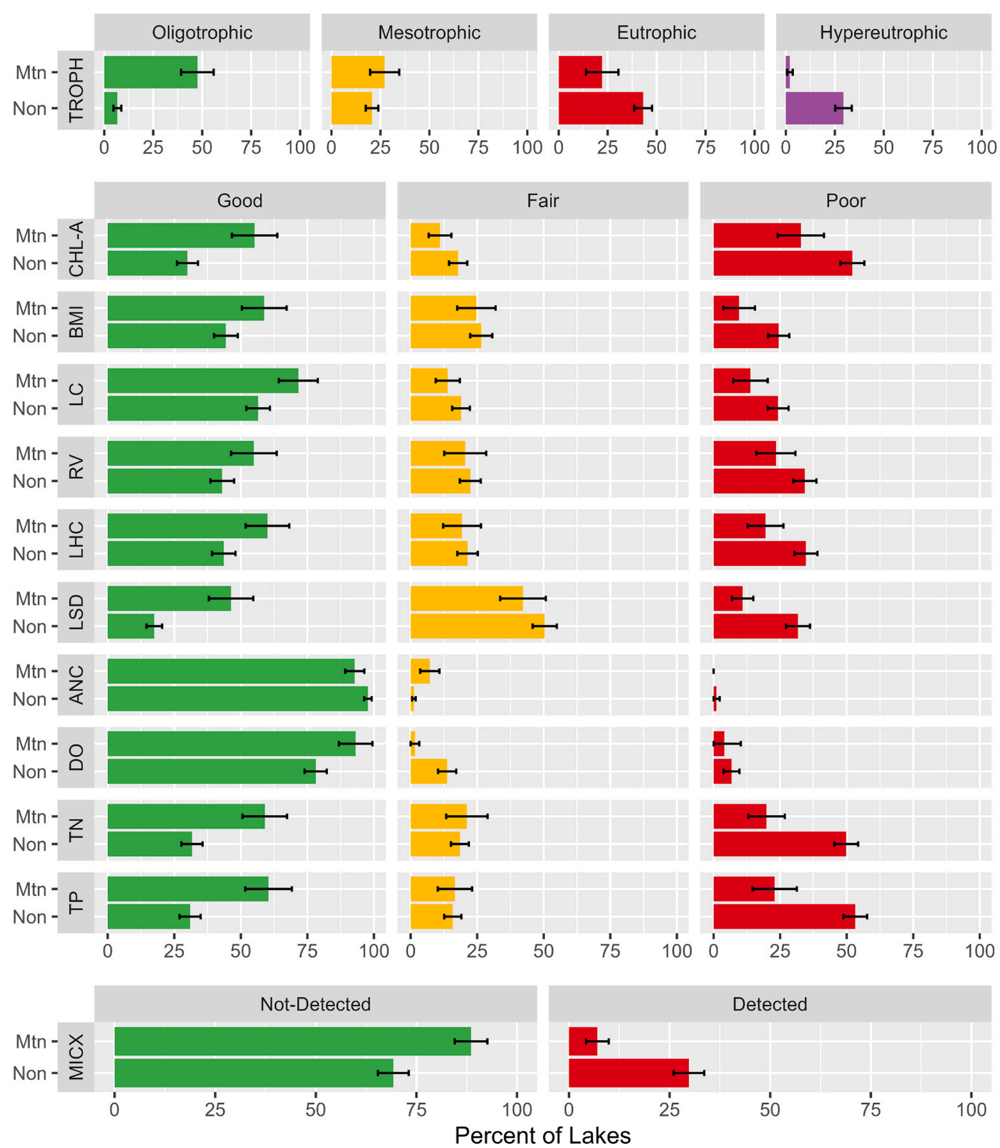

Fig. 6. The mean estimate and 95% confidence interval of the proportion of the population within each condition category for mountain (Mtn) and non-mountain (Non) lakes for the conterminous US with respect to trophic status (TROPH), chlorophyll-a (CHL-A), benthic macroinvertebrates (BMI), littoral cover (LC), lake habitat complexity (LHC), riparian vegetation (RV), lakeshore disturbance (LSD), acid neutralizing capacity (ANC), dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), and microcystin (MICX).

span (Eby et al., 2006). The decline in many lake benthic macroinvertebrates, especially large-bodied taxa, following fish stocking has been observed in multiple mountain ranges (Schilling et al., 2009). Management agencies like the National Park Service are currently mitigating these impacts by removing fish where possible (Chiapella et al., 2018; Schilling et al., 2009). An additional stressor to the littoral benthic invertebrates is the disturbance of the lakeshore. Anthropogenic development of the lakeshore can substantially reduce the productivity and diversity of benthic macroinvertebrates along with altering other biotic communities (Pätzig et al., 2018).

4.3. Mountain lake vulnerability to human development

Although mountain lakes as a population are in better condition relative to non-mountain lakes, more than 50 % of mountain lakes are in fair or poor condition with respect to lakeshore disturbance. While many mountain lakes are in remote settings that limit development and lakeshore disturbance, when including a broader set of mountain lakes such as those occurring in lower-lying mountain ranges, many of these lakes are experiencing substantial lakeshore disturbance.

Mountain lakes have lower proportions of development within the whole watershed compared to non-mountain lakes; however, there is more than twice the percent developed land in mountain lake catchments compared to within the whole lake watershed (Fig. 4). This is consistent with other research demonstrating that development pressures in mountain and alpine systems are substantial. Mountain developments for tourism and hydropower negatively impact lake water quality as well as aesthetics value (Ebner et al., 2022b; Pastorino et al., 2024; Schirpke and Ebner, 2022). Tourism can have a variety of impacts from increased litter to increased sediment loading from road construction (Dokulil, 2014). Furthermore, agriculture within the watershed of oligotrophic mountain lakes can negatively affect water quality through sediment and nutrient runoff while agriculture in adjacent watersheds can negatively affect water quality through atmospheric nutrient deposition (Brahney et al., 2015; Fuhrer et al., 2014). Lower elevation lakes and those outside of protected areas are especially vulnerable to increasing development impacts into the future (Schirpke and Ebner, 2022). Even mountain lakes within protected areas and remote locations are vulnerable to impacts from recreational development and use (Ebner et al., 2022a; Ebner et al., 2022b; Pastorino et al., 2024; Schirpke and Ebner, 2022; Senetra et al., 2020). In summary, mountain lakes, while often more remote than non-mountain lakes, can still be impacted by direct human development.

Mountain lake catchment characteristics may make these systems more vulnerable to lakeshore disturbance from human development compared to non-mountain lakes. The steeper slopes and higher runoff in mountain lake catchments facilitates the flow of pollutants from developed areas to the lake water. This is consistent with studies that have found a relationship between higher slopes and nutrient concentrations in mountain lakes (Kamenik et al., 2001; Sadro et al., 2012). The lower hydraulic conductivity likely indicates lower soil infiltration. When infiltration does occur, there is less soil to store and retain pollutants and sediments, as indicated by shallower depths to bedrock. Taken together, mountain lake catchments may on average convey the pollutants from developed areas more quickly to the lake water with few opportunities for attenuation. Future work should focus on determining how development influences mountain lake condition.

While this analysis focused on characterizing the condition of mountain lakes at a broad, CONUS scale, a promising area of future research is to link environmental drivers to individual mountain lakes using modeling approaches such as machine learning algorithms (James et al., 2013) like random forests (Breiman, 2001) or spatially explicit statistical models that incorporate spatial dependence (Cressie, 1993; Dumelle et al., 2023a; Zimmerman and Ver Hoef, 2024). Such approaches can help build predictive models that can identify individual mountain lakes across the country that have specific water quality challenges.

5. Conclusion

This study solves two problems that build on one another. First, we developed a rules-based approach to classify lakes by landform. Second, this study presents a comprehensive evaluation of the condition of mountain lakes across the CONUS. The process we developed for classifying lakes is flexible and can be adapted to classify waterbodies or even other environmental resources for a variety of purposes by altering the data and spatial extent components of the framework. Our findings reveal that mountain lakes are in better physical, chemical, and biological condition compared to non-mountain lakes across most indicators. However, there are significant environmental challenges within the mountain lake population, including high nutrient levels and eutrophic conditions in a notable proportion of these waterbodies. This study underscores the vulnerability of mountain lakes to human development, particularly near lakeshores. Concentrated lakeshore development, combined with inherent edaphic characteristics such as high runoff and low hydraulic conductivity, heightens the risk of pollutant transfer to mountain lakes. These findings highlight the need for targeted conservation and management strategies to mitigate human impacts and preserve the ecological integrity of mountain lakes, particularly along the lakeshore. With 1.9 billion people living in or directly downstream of mountainous areas (Immerzeel et al., 2020), these water towers of the planet (Messerli et al., 2004) merit research and management. Future research should focus on the mechanisms driving nutrient enrichment and the impact of lakeshore development, informing more effective strategies to protect these vital ecosystems.

CRediT authorship contribution statement

Amalia M. Handler: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marc Weber:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Michael Dumelle:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Lara S. Jansen:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **James N. Carleton:** Writing – review & editing, Writing – original draft. **Blake A. Schaeffer:** Writing – review & editing, Writing – original draft, Conceptualization. **Steven G. Paulsen:** Writing – review & editing, Conceptualization. **Thomas Barnum:** Writing – review & editing, Conceptualization. **Anne W. Rea:** Writing – review & editing, Conceptualization. **Anne Neale:** Writing – review & editing, Conceptualization. **Jana E. Compton:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Steven LeDuc, Joseph Flotemersch, Sylvia Lee, and John Stoddard for their helpful feedback on this analysis. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113402.

Data availability

Data and code for this analysis is available at Data.gov via https://doi.org/10.23719/1532058.

References

Baldigo, B.P., Delucia, M.-B., Keller, W.D., Schuler, G.E., Apse, C.D., Moberg, T., 2015. Contrasting fish assemblages in free-flowing and impounded tributaries to the Upper Delaware River: implications for conserving biodiversity. Advances in Environmental Research 45, 43–70.

Baldigo, B.P., George, S.D., Winterhalter, D.R., McHale, M.R., 2021. Biological and chemical recovery of acidified Catskill Mountain streams in response to the Clean Air Act Amendments of 1990. Atmospheric Environment 249, 118235.

Baron, J.S., Clow, D.W., Oleksy, I.A., Weinmann, T., Charlton, C., Jayo, A., 2021. Long-term ecosystem and biogeochemical research in Loch Vale watershed, Rocky Mountain National Park. Colorado. Hydrological Processes 35, e14107.

Baron, J.S., Driscoll, C.T., Stoddard, J.L., Richer, E.E., 2011. Empirical Critical Loads of Atmospheric Nitrogen Deposition for Nutrient Enrichment and Acidification of Sensitive US Lakes. BioScience 61, 602–613.

Berg, N.H., Gallegos, A., Dell, T., Frazier, J., Procter, T., Sickman, J., et al., 2005. A Screening Procedure for Identifying Acid-Sensitive Lakes from Catchment Characteristics. Environmental Monitoring and Assessment 105, 285–307.

Brahney, J., Mahowald, N., Ward, D.S., Ballantyne, A.P., Neff, J.C., 2015. Is atmospheric phosphorus pollution altering global alpine Lake stoichiometry? Global Biogeochemical Cycles 29, 1369–1383.

Breiman, L., 2001. Random forests. Machine Learning 45, 5–32.

Brittain, J.T., Strecker, A.L., 2018. The Interactive Effect of Multiple Stressors on Crustacean Zooplankton Communities in Montane Lakes. Water Resources Research 54, 939–954.

Burns, D.A., McHale, M.R., Driscoll, C.T., Roy, K.M., 2006. Response of surface water chemistry to reduced levels of acid precipitation: comparison of trends in two regions of New York, USA. Hydrological Processes 20, 1611–1627.

Button, K.S., Blinn, W., 1975. Planktonic Diatom Fluctuations in a Northern Arizona Mountain Lake. The Southwestern Naturalist 20, 397–408.

Catalán, J., Camarero, L., Felip, M., Pla, S., Ventura, M., Buchaca, T., et al., 2006. High mountain lakes: Extreme habitats and witnesses of environmental changes. Limnética 25, 551–584.

Catalan, J., Curtis, C.J., Kernan, M., 2009. Remote European mountain lake ecosystems: regionalisation and ecological status. Freshwater Biology 54, 2419–2432.

Catalán, N., Rofner, C., Verpoorter, C., Pérez, M.T., Dittmar, T., Tranvik, L., et al., 2024. Treeline displacement may affect lake dissolved organic matter processing at high latitudes and altitudes. Nature Communications 15, 2640.

Chiapella, A.M., Nielsen-Pincus, M., Strecker, A.L., 2018. Public perceptions of mountain lake fisheries management in national parks. Journal of Environmental Management 226, 169–179.

Clow, D.W., Nanus, L., Huggett, B., 2010. Use of regression-based models to map sensitivity of aquatic resources to atmospheric deposition in Yosemite National Park, USA. Water Resources Research 46.

Clow, D.W., Sueker, J.K., 2000. Relations between basin characteristics and stream water chemistry in alpine/subalpine basins in Rocky Mountain National Park. Colorado. Water Resources Research 36, 49–61.

Cressie, N., 1993. Statistics for spatial data. John Wiley & Sons.

Dewitz, J., and U.S. Geological Survey, 2021. National Land Cover Database (NLCD) 2019 Products (ver. 3.0, February 2024): U.S. Geological Survey data release, https://doi.org/10.5066/P9KZCM54.

Dokulil, M.T., 2014. Environmental Impacts of Tourism on Lakes. In: Ansari, A.A., Gill, S. S. (Eds.), Eutrophication: Causes, Consequences and Control, Volume 2. Springer, Netherlands, Dordrecht, pp. 81–88.

Driscoll, C.T., Driscoll, K.M., Fakhraei, H., Civerolo, K., 2016. Long-term temporal trends and spatial patterns in the acid-base chemistry of lakes in the Adirondack region of New York in response to decreases in acidic deposition. Atmospheric Environment 146, 5–14.

Driscoll, C.T., Driscoll, K.M., Roy, K.M., Dukett, J., 2007. Changes in the chemistry of lakes in the Adirondack region of New York following declines in acidic deposition. Applied Geochemistry 22, 1181–1188.

Driscoll, C.T., Driscoll, K.M., Roy, K.M., Mitchell, M.J., 2003. Chemical Response of Lakes in the Adirondack Region of New York to Declines in Acidic Deposition. Environmental Science & Technology 37, 2036–2042.

Dumelle, M., Higham, M., Ver Hoef, J.M., 2023a. spmodel: Spatial statistical modeling and prediction in R. PLOS ONE 18, e0282524.

Dumelle, M., Kincaid, T., Olsen, A.R., Weber, M., 2023b. spsurvey: Spatial Sampling Design and Analysis in R. Journal of Statistical Software 105, 1–29.

Ebner, M., Fontana, V., Schirpke, U., Tappeiner, U., 2022a. Stakeholder perspectives on ecosystem services of mountain lakes in the European Alps. Ecosystem Services 53, 101386.

Ebner, M., Schirpke, U., Tappeiner, U., 2022b. How do anthropogenic pressures affect the provision of ecosystem services of small mountain lakes? Anthropocene 38, 100336.

Eby, L.A., Roach, W.J., Crowder, L.B., Stanford, J.A., 2006. Effects of stocking-up freshwater food webs. Trends in Ecology & Evolution 21, 576–584.

Eilers, J.M., Kanciruk, P., McCord, R.A., Overton, W.S., Hook, L., Blick, D.J., et al., 1986. Western Lake Survey, Phase i: Characteristics of Lakes in the Western United States, Vol 2. US Environmental Protection Agency, Washington DC.

Fuhrer, J., Smith, P., Gobiet, A., 2014. Implications of climate change scenarios for agriculture in alpine regions — A case study in the Swiss Rhone catchment. Science of the Total Environment 493, 1232–1241.

Goldman, C.R., 1961. The Contribution of Alder Trees (Alnus Tenuifolia) to the Primary Productivity of Castle Lake. California. Ecology 42, 282–288.

Herlihy, A.T., Paulsen, S.G., Van Sickle, J., Stoddard, J.L., Hawkins, C.P., Yuan, L.L., 2008. Striving for Consistency in a National Assessment: the Challenges of Applying a Reference-Condition Approach at a Continental Scale. 27, 860–877.

Hill, R.A., Weber, M.H., Debbout, R.M., Leibowitz, S.G., Olsen, A.R., 2018. The Lake-Catchment (LakeCat) Dataset: characterizing landscape features for lake basins within the conterminous USA. Freshwater Science 37, 208–221.

Horowitz, A.J., Elrick, K.A., Robbins, J.A., Cook, R.B., 1995. Effect of mining and related activities on the sediment trace element geochemistry of Lake Coeur D'Alene, Idaho, USA part II: Subsurface sediments. Hydrological Processes 9, 35–54.

Horton, R.E., 1945. Erostional development of streams and their drainage basins; Hydrophysical approach to quantitative morphology. GSA Bulletin 56, 275–370.

Huang, Y., Jin, Y., 2022. Aerial Imagery-Based Building Footprint Detection with an Integrated Deep Learning Framework: Applications for Fine Scale Wildland–Urban Interface Mapping. Remote Sensing 14, 3622.

Hundey, E.J., Russell, S.D., Longstaffe, F.J., Moser, K.A., 2016. Agriculture causes nitrate fertilization of remote alpine lakes. Nature Communications 7, 10571.

Immerzeel, W.W., Lutz, A.F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al., 2020. Importance and vulnerability of the world's water towers. Nature 577, 364–369.

James, G., Witten, D., Hastie, T., Tibshirani, R., 2013. An introduction to statistical learning. Springer, New York.

Jansen, L.S., Sobota, D., Pan, Y., Strecker, A.L., 2024. Watershed, lake, and food web factors influence diazotrophic cyanobacteria in mountain lakes. Limnology and Oceanography 69, 681–699.

Kamenik, C., Schmidt, R., Kum, G., Psenner, R., 2001. The Influence of Catchment Characteristics on the Water Chemistry of Mountain Lakes. Arctic, Antarctic, and Alpine Research 33, 404–409.

Körner, C., Paulsen, J., Spehn, E.M., 2011. A definition of mountains and their bioclimatic belts for global comparisons of biodiversity data. Alpine Botany 121, 73–78.

Landers, D.H., Overton, W.S., Linthurst, R.A., Brakke, D.F., 1988. Eastern Lake Survey, regional estimates of lake chemistry. Environmental Science & Technology 22, 128–135.

Larson, G.L., Hoffman, R.L., McIntire, D.C., Buktenica, M.W., Girdner, S.F., 2007. Thermal, chemical, and optical properties of Crater Lake, Oregon. In: Larson, G.L., Collier, R., Buktenica, M.W. (Eds.), Long-Term Limnological Research and Monitoring at Crater Lake, Oregon: A Benchmark Study of a Deep and Exceptionally Clear Montane Caldera Lake. Springer, Netherlands, Dordrecht, pp. 69–84.

Likens, G.E., 2000. A long-term record of ice cover for Mirror Lake, New Hampshire: effects of global warming? SIL Proceedings 1922–2010 (27), 2765–2769.

Machate, O., Schmeller, D.S., Schulze, T., Brack, W., 2023. Review: mountain lakes as freshwater resources at risk from chemical pollution. Environmental Sciences Europe 35, 3.

Marchetto, A., Rogora, M., 2004. Measured and modelled trends in European mountain lakes: results of fifteen years of cooperative studies. Journal of Limnology 63, 55–62.

McHale, M.R., Burns, D.A., Siemion, J., Antidormi, M.R., 2017. The response of soil and stream chemistry to decreases in acid deposition in the Catskill Mountains, New York, USA. Environmental Pollution 229, 607–620.

McKay, L., Bondelid, T., Dewald, T., Johnston, J., Moore, R., Rea, A., 2012. NHDPlus Version 2. User Guide.

Melack, J.M., Stoddard, J.L., Ochs, C.A., 1985. Major Ion Chemistry and Sensitivity to Acid Precipitation of Sierra Nevada Lakes. Water Resources Research 21, 27–32.

Messerli B. Viviroli D. Weingartner R. Mountains of the world: vulnerable water towers for the 21st century 2004 29 34.

Microsoft. US Building Footprints. In: Microsoft, editor, 2018.

Moser, K.A., Baron, J.S., Brahney, J., Oleksy, I.A., Saros, J.E., Hundey, E.J., et al., 2019. Mountain lakes: Eyes on global environmental change. Global and Planetary Change 178, 77–95.

Nanus, L., Williams, M.W., Campbell, D.H., Tonnessen, K.A., Blett, T., Clow, D.W., 2009. Assessment of lake sensitivity to acidic deposition in national parks of the Rocky Mountains. Ecological Applications 19, 961–973.

Palomo, I., 2017. Climate Change Impacts on Ecosystem Services in High Mountain Areas: A Literature Review. Mountain Research and Development 37 (179–187), 9.

Pastorino, P., Elia, A.C., Pizzul, E., Bertoli, M., Renzi, M., Prearo, M., 2024. The old and the new on threats to high-mountain lakes in the Alps: A comprehensive examination with future research directions. Ecological Indicators 160, 111812.

Pastorino, P., Prearo, M., Pizzul, E., Elia, A.C., Renzi, M., Ginebreda, A., et al., 2022. High-mountain lakes as indicators of microplastic pollution: current and future perspectives. Water Emerging Contaminants & Nanoplastics 1, 3.

Patrick S, Battarbee RW, Wathne B, Psenner R. Measuring and modelling the dynamic response of remote mountain lake ecosystems to environmental change: an introduction to the MOLAR project. HeadWater'98 Conference. 248. IAHS, Meran/Merano, Italy, 1998, pp. 403-410.

Pätzig, M., Vadeboncoeur, Y., Brauns, M., 2018. Lakeshore modification reduces secondary production of macroinvertebrates in littoral but not deeper zones. Freshwater Science 37, 845–856.

Peck, D.V., Olsen, A.R., Weber, M.H., Paulsen, S.G., Peterson, C., Holdsworth, S.M., 2013. Survey Design and Extent Estimates for the National Lakes Assessment. 32, 1231–1245.

Peck DV, Paulsen SG, Kaufmann PR, Herlihy AT. Jewels across the Landscape: Monitoring and Assessing the Quality of Lakes and Reservoirs in the United States. In: Kevin S, editor. Water Quality. IntechOpen, Rijeka, 2020, pp. Ch. 6.

Pollard, A.I., Hampton, S.E., Leech, D.M., 2018. The Promise and Potential of Continental-Scale Limnology Using the U.S. Environmental Protection Agency's National Lakes Assessment. Limnology and Oceanography Bulletin 27, 36–41.
R Core Team. R: A Language and Environment for Statistical Computing. Version 4.3.2 (2023-10-31 ucrt). R Foundation for Statistical Computing, Vienna, Austria, 2023.
Rangwala, I., Miller, J.R., 2012. Climate change in mountains: a review of elevation-dependent warming and its possible causes. Climatic Change 114, 527–547.
Richards, R., Goldman, C., Byron, E., Levitan, C., 1991. The mysids and lake trout of Lake Tahoe: A 25-year history of lake changes in the fertility, plankton, and fishery of an alpine lake. American Fisheries Society Symposium 9, 30–38.
Riera, J.L., Magnuson, J.J., Kratz, T.K., Webster, K.E., 2000. A Geomorphic Template for the Analysis of Lake Districts Applied to the Northern Highland Lake District 43:, 301–318.
Roningen, J.M., Burbey, T.J., 2012. Hydrogeologic controls on lake level: a case study at Mountain Lake, Virginia, USA. Hydrogeology Journal 20, 1149–1167.
Sadro, S., Melack, J.M., MacIntyre, S., 2011. Depth-integrated estimates of ecosystem metabolism in a high-elevation lake (Emerald Lake, Sierra Nevada, California). Limnology and Oceanography 56, 1764–1780.
Sadro, S., Nelson, C.E., Melack, J.M., 2012. The Influence of Landscape Position and Catchment Characteristics on Aquatic Biogeochemistry in High-Elevation Lake-Chains. Ecosystems 15, 363–386.
Sayre R, Comer P, Cress JJ, Warner H. Conterminous United States Terrestrial Ecosystems: U.S. Geological Survey data release. In: Survey USG, editor, 2009a.
Sayre, R., Comer, P., Warner, H., Cress, J., 2009b. A New Map of Standardized Terrestrial Ecosystems of the Conterminous United States. Professional Paper. u.s. Geological Survey 17.
Sayre, R., Frye, C., Karagulle, D., Krauer, J., Breyer, S., Aniello, P., et al., 2018. A New High-Resolution Map of World Mountains and an Online Tool for Visualizing and Comparing Characterizations of Global Mountain Distributions. Mountain Research and Development 38 (240–249), 10.
Schilling, E.G., Loftin, C.S., Huryn, A.D., 2009. Effects of introduced fish on macroinvertebrate communities in historically fishless headwater and kettle lakes. Biological Conservation 142, 3030–3038.
Schirpke, U., Ebner, M., 2022. Exposure to global change pressures and potential impacts on ecosystem services of mountain lakes in the European Alps. Journal of Environmental Management 318, 115606.
Schirpke, U., Scolozzi, R., Tappeiner, U., 2021. "A Gem among the Rocks"—Identifying and Measuring Visual Preferences for Mountain Lakes. Water 13, 1151.
Scholz, J., Brahney, J., 2022. Evidence for multiple potential drivers of increased phosphorus in high-elevation lakes. Science of the Total Environment 825, 153939.
Senetra, A., Dynowski, P., Cieślak, I., Źróbek-Sokolnik, A., 2020. An Evaluation of the Impact of Hiking Tourism on the Ecological Status of Alpine Lakes—A Case Study of the Valley of Dolina Pięciu Stawów Polskich in the Tatra Mountains. 12, 2963.
Shaw, G.D., Cisneros, R., Schweizer, D., Sickman, J.O., Fenn, M.E., 2013. Critical Loads of Acid Deposition for Wilderness Lakes in the Sierra Nevada (California) Estimated by the Steady-State Water Chemistry Model. Water, Air, & Soil Pollution 225, 1804.
Sheibley, R.W., Enache, M., Swarzenski, P.W., Moran, P.W., Foreman, J.R., 2014. Nitrogen Deposition Effects on Diatom Communities in Lakes from Three National Parks in Washington State. Water, Air, & Soil Pollution 225, 1857.
Stanford JA, Ward JV. Limnology of Lake Powell and the chemistry of the Colorado River. Colorado River ecology and dam management: Proceedings of a symposium May 24–25, 1990. Santa Fe. National Academies Press, New Mexico, p. 1991.
Staufer, R.E., 1990. Granite weathering and the sensitivity of alpine lakes to acid deposition. Limnology and Oceanography 35, 1112–1134.
Stevens Jr, D.L., Olsen, A.R., 2003. Variance estimation for spatially balanced samples of environmental resources. Environmetrics 14, 593–610.
Stevens Jr, D.L., Olsen, A.R., 2004. Spatially Balanced Sampling of Natural Resources. Journal of the American Statistical Association 99, 262–278.
Stoddard, J.L., Herlihy, A.T., Peck, D.V., Hughes, R.M., Whittier, T.R., Tarquinio, E., 2008. A process for creating multimetric indices for large-scale aquatic surveys. Journal of the North American Benthological Society 27, 878–891.
Stoddard, J.L., Larsen, D.P., Hawkins, C.P., Johnson, R.K., Norris, R.H., 2006. Setting expectations for the ecological condition of streams: The concept of reference condition. Ecological Applications 16, 1267–1276.
Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. Progress in Physical Geography: Earth and Environment 36, 421–439.
Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. GSA Bulletin 63, 1117–1142.
Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38, 913–920.
Sullivan, T.J., Webb, J.R., Snyder, K.U., Herlihy, A.T., Cosby, B.J., 2007. Spatial Distribution of Acid-sensitive and Acid-impacted Streams in Relation to Watershed Features in the Southern Appalachian Mountains. Water, Air, and Soil Pollution 182, 57–71.
Thomasson, K., 1956. Reflections on Arctic and Alpine Lakes. Oikos 7, 117–143.
U.S. Geological Survey. Gap Analysis Project (GAP), 2024, Protected Areas Database of the United States (PAD-US) 4. In: Survey USG, editor, 2024.
US EPA. National Eutrophication Survey Methods, 1973-1976. Working Paper No. 175. US Environmental Protection Agency, 1975.
US EPA, 2011. 2012 National Lakes Assessment. Field Operations Manual. EPA 841-B-11-003. U.S. Environmental Protection Agency, Washington, D.C..
US EPA, 2012. 2012 National Lakes Assessment. Laboratory Operations Manual. EPA-841-B-11-004. U.S. Environmental Protection Agency, Washinton, DC.
US EPA, 2017. National Lakes Assessment 2012: Techical Report. EPA 841-R-16-114. U. S. Environmental Protection Agency, Washington, D.C..
US EPA, 2022. National Lakes Assessment 2017: Technical Support Document. EPA 841-R-22-001. U.S. Environmental Protection Agency, Washington, D.C..
Vander Zanden, M.J., Chandra, S., Allen, B.C., Reuter, J.E., Goldman, C.R., 2003. Historical Food Web Structure and Restoration of Native Aquatic Communities in the Lake Tahoe (California-Nevada) Basin. Ecosystems 6, 274–288.
Whittier, T.R., Larsen, D.P., Peterson, S.A., Kincaid, T.M., 2002. A comparison of impoundments and natural drainage lakes in the Northeast USA*. Hydrobiologia 470, 157–171.
Williamson, C.E., Salm, C., Cooke, S.L., Saros, J.E., 2010. How do UV radiation, temperature, and zooplankton influence the dynamics of alpine phytoplankton communities? Hydrobiologia 648, 73–81.
Winter, T.C., 1977. Classification of the hydrologic settings of lakes in the north central United States. Water Resources Research 13, 753–767.
Withers, P.J., Jordan, P., May, L., Jarvie, H.P., Deal, N.E., 2014. Do septic tank systems pose a hidden threat to water quality? Frontiers in Ecology and the Environment 12, 123–130.
Woolway, R.I., Kraemer, B.M., Lenters, J.D., Merchant, C.J., O'Reilly, C.M., Sharma, S., 2020. Global lake responses to climate change. Nature Reviews Earth & Environment 1, 388–403.
Xiong, X., Tappenbeck, T.H., Wu, C., Elser, J.J., 2022. Microplastics in Flathead Lake, a large oligotrophic mountain lake in the USA. Environmental Pollution 306, 119445.
Yuan, L.L., Pollard, A.I., Pather, S., Oliver, J.L., D'Anglada, L., 2014. Managing microcystin: identifying national-scale thresholds for total nitrogen and chlorophyll a. Freshwater Biology 59, 1970–1981.
Zimmerman, D.L., Ver Hoef, J.M., 2024. Spatial linear models for environmental data. CRC Press.