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Water clarity measures as indicators of recreational benefits provided by U.S. lakes: Swimming and aesthetics

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ABSTRACT

Lakes provide recreational benefits related to water quality. Using data from the 2007 and 2012 United States National Lake Assessments (N = 2067 lake visits), we developed indicators for three benefits: swimming, general recreational value, and aesthetic appeal. For two combined ecoregions (“Mountains” and “Plains”) we related objective measures of water clarity, including Secchi depth, turbidity, and water-column chlorophyll-*a* concentration to subjective visual assessments of recreational benefit quality. There were significant associations between water clarity measures and visual assessments from which we derived water-clarity based thresholds between benefit quality classes (exceptional, high, low, marginal) for each benefit type. More variation in Secchi depth and turbidity was explained by benefit quality than was variation in chlorophyll-*a*. Threshold values were different between combined ecoregions. Compared to lakes in the Mountains ecoregion, recreational users of Plains lakes have lower expectations for water clarity. Thresholds were generally in accord with water clarity thresholds and guidance derived from published regional studies. Including indicators of the quality of benefits humans receive from lakes in assessments of lake conditions can increase public participation in decision-making and reveal changes in benefit quality over time.

1. Introduction

Lakes provide recreational benefits related directly and indirectly to water quality, including swimming, boating, fishing, and the aesthetic experience of viewing the lake. Assessments of lake water quality for reporting on the condition of lake ecosystems are most often based on biophysical indicators and reference condition-based thresholds (Herlihy et al., 2013) rather than on indicators of human benefits. There have been attempts (discussed in Section 4.4) to develop empirical indicators or set assessment thresholds using information on how recreational beneficiaries perceive the recreational value of lakes as a function of water quality, but these studies are few (West et al., 2015). In most lake assessment reporting, water quality indicators are generally not linked to the recreational benefits provided by the sample lakes.

The use of environmental indicators that are directly meaningful to people improves communication across social boundaries and increases public participation in decision-making (Heiskary and Walker, 1988; USEPA, 2009; Keeler et al., 2012; Boyd et al., 2015; West et al., 2016). By directly meaningful, we imply the indicator requires minimal translation for people to understand the connection to things they value. Unlike nutrient or ion concentration, water clarity is an attribute of lake water that is readily understood by a non-expert audience. Water clarity may be perceived as a reliable surrogate measure for how safe and suitable the water appears to be for contact recreation (e.g., Is the bottom visible? Is the water “clean”?). Beyond swimming, the aesthetic appeal of the lake setting itself may also depend in part on the visual clarity of the water. The use of perception surveys to develop indicators of benefits follows from the idea that “behavior [or use] is based on preferences formed from perceptions” and “people’s perceptions of environmental amenities should therefore provide the most accurate estimates of the values attached to those amenities (Artell et al., 2013).”

In this paper, we examined how perceptions of a lake’s suitability for recreation or its aesthetic appeal can be related to biophysical indicators of water clarity: Secchi depth, turbidity, and chlorophyll-*a* concentration. We showed how these relationships can be used to derive thresholds in recreational benefit quality for lakes of the

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conterminous United States. These water clarity thresholds, when calibrated for regional variation, can be used for regional assessment of lake ecosystem benefits and, in some contexts, as supporting evidence for deriving new water quality criteria for lake uses. This approach has been used to support development of water quality thresholds for several US states (Heiskary and Walker, 1988; Smeltzer and Heiskary, 1990; Hoyer et al., 2004; Smith et al., 2015). Ours is the first attempt to use national-scale water clarity and lake benefit quality perception data (e.g., relative suitability for swimming or "swimmability") to derive thresholds for assessing the quality of recreational benefits provided by US lakes.

We used the results of two national-scale lake condition assessments to address questions related to the quality of benefits provided by freshwater lakes: 1. How are subjective characterizations based on visual assessment of recreational value related to Secchi depth, turbidity, and water column chlorophyll-*a* concentration? 2. Are thresholds in water clarity based on recreational benefits consistent across ecoregions? 3. Are thresholds for water clarity based on different benefit types (e.g., swimming, other recreation, and aesthetic values) consistent and equally "protective?" Our overarching goal was to specify indicators of and thresholds for the quality of recreational benefits from lakes based on ecosystem attributes causally linked to ecosystem processes.

2. Methods

2.1. Lake ecosystem benefits

In this paper, we follow the hierarchical classification of ecosystem beneficiaries set forth in the Final Ecosystem Goods and Services Classification System (FEGS-CS) developed by the United States Environmental Protection Agency (USEPA) (Landers and Nahlik, 2013). FEGS-CS is explicitly organized around human beneficiaries of the environment and the attributes of ecosystem outputs directly relevant to human well-being. The FEGS in this case is lake water for recreation. The relevant attribute of lake water is visual water clarity. The applicable beneficiary class is "recreational." The four relevant beneficiary subclasses we considered included 1) waders, swimmers, and divers; 2) boaters; 3) recreational anglers; and 4) experiencers and viewers. There are other attributes of lake ecosystems like nutrient concentration that are causally linked to water clarity (Wetzel, 2001; Jones et al., 2008), but they are unlikely to be valued directly by most recreational beneficiaries (Ringold et al., 2013).

Ecosystem benefits are defined as the impacts, positive or negative on human well-being of the FEGS (Landers and Nahlik, 2013). Lakes, in combination with built capital such as beaches and boat ramps, and human capital (i.e., people able to appreciate the lake) provide opportunities for socialization, physical activity, engagement with nature, and other sensory experiences that promote physical health, reduce stress, enhance mood, and generally increase well-being (Bowler et al., 2010; Völker and Kistemann, 2011; Keniger et al., 2013; de Bell et al., 2017). Because we lack reliable data on recreational demand or built capital for our sample of lakes, we are not necessarily reporting on the quality of realized recreational benefits, but on the potential recreational benefits provided by these lakes.

For each beneficiary subclass, we used a visual assessment rating as the perception of benefit quality for a recreational activity related to water clarity as a proxy for benefit quality, or the relative impact on human welfare: perceived swimming benefit quality for swimmers, perceived general recreational benefit quality, and perceived aesthetic benefit quality for lake experiencers and viewers.

2.2. Datasets and indicators

Data used in this study are from the U.S. National Lakes Assessments (NLA) of 2007 and 2012 and are publicly available (https://www.epa.gov/national-aquatic-resource-surveys/nla; accessed 31 January 2018). The NLA is a quinquennial statistical survey of the ecological condition of the lakes of the conterminous U.S., designed to provide national and regional estimates of lake condition.

Water quality sampling and visual assessments were conducted by a single field crew for each lake during May-September. Crews generally included 3–5 trained personnel from state agencies or contracting vendors. Most crews sampled lakes within a single state. Larger states had multiple crews. In 2007 and 2012 there were 83 and 88 field crews, respectively. Overlap in personnel between assessments is not known. Mean (± 95% CI) number of lakes sampled per crew from which data are included in this paper was 14 ± 3 in 2007 and 13 ± 2 in 2012. Because training was standardized and each crew sampled relatively few lakes, we made no effort to partition analysis by crew.

From NLA data, we extracted water quality data and visual assessments of recreational benefits provided by each lake. Water clarity metrics included Secchi depth (m), turbidity (nephelometric turbidity units [NTU]), and water column chlorophyll-*a* (μg/L). Secchi depth was determined *in situ* using a 20–cm diameter weighted black and white disk. Turbidity was determined within 72 h by automated analysis (TitraSip, Man-Tech, Guelph, ON, Canada) or manual analysis using a turbidity meter for high turbidity samples (USEPA, 1987). Pheophytin-corrected chlorophyll-*a* was determined by flourometry within 30 days. Field and laboratory methods for water clarity metrics are described in detail elsewhere (USEPA, 2011, 2012). We did not use Secchi depth measurements when the disk could be seen resting on the bottom. We did not substitute lake depth for Secchi depth in these cases because this results in the underestimation of Secchi depth in clear shallow lakes. We therefore had missing Secchi depth measurements at five and nine percent of lakes in 2007 and 2012, respectively. In the 2007 NLA, lakes ≥4 ha were included in the sample; in 2012, lakes ≥1 ha were included in the sample. We did not distinguish the approximately 10% of lakes sampled in both NLAs. About 100 lakes were revisited during each assessment, but we only used data from the first visit to the lake in each assessment unless otherwise specified. Data from about 1120 lakes in each assessment year were analyzed. We did not distinguish between natural and man-made lakes in our analyses. In both assessment years, 55% of sampled lakes were man-made. We treat the 2007 and 2012 NLAs as replicate studies, and we generally do not combine the data except to illustrate general points related to application of results.

Visual assessments were conducted for three attributes of each lake: "swimmability", "recreational value", and "aesthetic appeal". For swimmability, crews were instructed to "record a subjective impression of the aesthetics of swimming in this lake" as either "good", "fair" or "not swimmable" (USEPA, 2012). This visual assessment metric was meant to reflect aesthetics or "pleasantness" of swimming rather than water safety or access, so the wording "not swimmable" is potentially misleading since no barrier to water contact is implied – it may be aesthetically unpleasant and unsafe, but water contact is physically possible. For recreational value, crews were instructed to base their scoring of "excellent", "good", "fair", or "poor" on the lake's "ability to support recreational uses such as swimming, fishing, and boating." The intention was for crews to "record their overall impression of the lake as a site for recreation." For aesthetic appeal, crews were instructed to rate the lake from 1 to 5 based on aesthetic appeal by integrating their overall impressions with "any factors that disturb you" such as trash, algal growth, "weed" abundance, or overcrowding. Scores of 1–5 corresponded, respectively, to "enjoyment nearly impossible", "level of enjoyment substantially reduced", "enjoyment slightly impaired", "there are minor aesthetic problems [but] it is otherwise excellent for swimming, boating, and enjoyment", and "it is beautiful and could not be any nicer." The wording for the NLA aesthetic appeal assessment scoring is very similar to lake and river user survey questions used in previous state-scale assessment (e.g., Smeltzer and Heiskary, 1990; Smith et al., 2015).

The subjective perceptions of benefit quality (i.e., the scoring based on visual assessment) are proxies for lake benefits. Swimmability is a proxy for full-body water contact recreation; recreational value is proxy for all water borne recreation, including swimming; aesthetic appeal is a proxy for the non-specific recreational benefits for lake viewers and experiencers or "aesthetics." For most lake users, there is overlap among these benefits because there is overlap in the specific beneficiary role they actualize during a lake experience. We use the term benefit quality rather than value (a word actually used in the survey instructions) so that we do not imply economic valuation.

2.3. Regional classification

Clarity of freshwater water bodies of the conterminous Unites States varies greatly. Data compiled by Bigham-Stephens et al. (2015) showed the median Secchi depth varied nearly eight-fold across states from 0.6 m for Louisiana and Mississippi to about 4.7 m for Montana and Maine. We suspected thresholds in benefit quality would also vary regionally because beneficiaries in different regions likely have different expectations about what biophysical condition is acceptable with respect to recreational benefits from lakes (Hoyer et al., 2004). Our default regional classification of lakes was the nine aggregate "Level III Nutrient Ecoregions" (Omernik and Griffith, 2014) which are used in EPA national aquatic resource surveys for reporting results and setting reference expectations (https://www.epa.gov/national-aquatic-resource-surveys/nla). Because of the small number of lakes sampled in several Level III ecoregions and the difficulty of applying nine sets of thresholds, we examined the data for opportunities to reduce the number of regional classes. We compared the mean and variation in water clarity measures for each assessment year to determine if there were groups of ecoregions with similar water clarity attributes that could be combined for further analysis. We used *t*-tests to determine if putative regional groupings had distinct water clarity.

2.4. Combined visual assessment classes

Based on the wording of the visual observation categories (see Section 2.2) we combined the visual assessments into three categories. For recreational value, we combined "fair" and "poor" recreational value. For aesthetic appeal, we combined "beautiful" and "excellent", and we combined "enjoyment reduced" and "enjoyment impossible." This allowed us to derive thresholds for all benefits using the same method (described in Section 2.6).

2.5. Association between water clarity and visual assessments

We used one-way analysis of variance to test if mean water clarity was different among combined benefit classes. Water quality data were right skewed (i.e., means were generally much higher than medians). We therefore $\log_{10}$-transformed water quality data prior to analysis. We ran models for all lakes by year and for combined ecoregions by year. We used model R^2 to assess the proportion of variance in water clarity explained by the ANOVA for each clarity measure (Secchi depth, turbidity, and chlorophyll-*a*) as a relative estimate of the reliability of each indicator.

2.6. Deriving thresholds

We derived thresholds to demarcate the relative quality of the benefits provided by each lake, and, in aggregate, by the lakes of a region. Before defining thresholds, we removed lakes smaller than 4 ha from the 2012 data (only lakes ≥4 ha were sampled in 2007). We set thresholds based on percentiles of the distribution of measured values for water clarity measures. How thresholds may be derived for benefit quality classes depends on the degree of overlap in measured water clarity metrics among classes. Preliminary plots of the NLA data revealed overlap in the distribution of water clarity metrics, especially

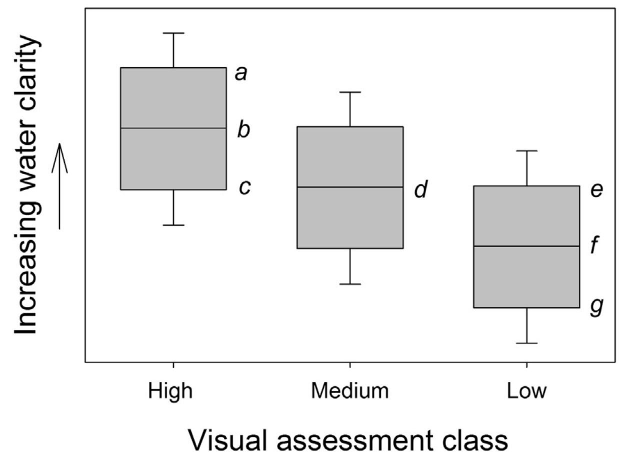

Fig. 1. Simulated data illustrating how thresholds were derived from NLA data. Labels *a, c, e, and g* refer to quartiles of the distribution; *b, d, and f* refer to medians. Mean values for c and *e* across assessment years (not shown here) define the threshold between low and high benefit quality. Mean values for *a* and for *g* across assessment years define the thresholds between high and exceptional benefit quality and between low and marginal benefit quality, respectively. See Section 2.6 for details.

between high and medium visual assessment categories and between low and medium assessment classes. In the case of overlap among categories (Fig. 1), there is no non-arbitrary way to derive two thresholds to demarcate three benefit quality classes. By arbitrary, we mean the thresholds are not closely linked to the actual distributions corresponding to a crew's perceptions. For example, if we used the median of the high and low benefit quality distributions (*b* and *f* in Fig. 1) to define thresholds for three classes, half the observers that scored lakes high and half the observers that scored lakes low, would be defining the threshold for the medium benefit quality.

We suspect the overlap arises in part because for most observers, even trained field crews, the consistency in visual classification is better at the ends of the gradient. The best and worst-appearing lakes for swimming or aesthetic appeal are more apparent and easier to distinguish than finer distinctions among lakes in intermediate apparent condition. Consequently, thresholds that rely on the water clarity distribution of lakes in medium conditions may be inherently less reliable than thresholds based on the high and low benefit quality distribution. We instead used a quartile-based method where the mean across assessment years of Q1 for the high benefit quality class and Q3 for the low benefit quality category (*c* and *e* in Fig. 1) defined the threshold between low- and high-quality benefits. In addition, we used Q3 for the high benefit quality class and Q1 for the low benefit class to define exceptional and marginal benefit quality classes, respectively (i.e., *a* and *g* in Fig. 1). This results in three thresholds and four classes with the following characteristics: the three-quarters of the lakes visually scored as high (> Q1) and three quarters of lakes that were scored as low (< Q3) would be classed as providing high or exceptional and low or marginal quality of benefits, respectively. The distribution of lakes scored as medium would not be used to set criteria, but the best medium-scoring lakes (> *d* in Fig. 1) would be classed as high benefit quality and the worst medium scoring lakes would be classed as low benefit quality.

These formulae apply for Secchi depth, which increases with increasing water quality; the meaning of Q3 and Q1 would be reversed for turbidity and chlorophyll-*a*. Because the thresholds are based on upper and lower percentiles of the distribution, we removed outlier values using a filter based on the interquartile range (IQR) for each year and combined ecoregion (USEPA, 2017). Values were removed if they were greater than Q3 + (1.5 * IQR). Low filter values were all negative and not relevant. We removed, on average, 6% of Secchi depth observations, and 11% of turbidity and chlorophyll-*a* observations as outliers. As far as we know, this method of deriving thresholds from water clarity data has not be used elsewhere.

2.7. Concordance

To help quantify the reliability of visual assessments, we tested concordance of assessments, defined as the agreement in the visual assessment classification between visits for lakes revisited during an NLA assessment. We also determined the concordance between benefits, defined as agreement in the visual assessment class between benefits; high swimmability and high aesthetics, for example. We used the Chi-squared test of independence to determine if concordance occurred more often than would be expected by chance.

2.8. Regional estimates

In the NLA survey, each lake has a known probability of being sampled from the population of lakes in the conterminous U.S. (USEPA, 2017) and has an associated sample weight (the inverse if the probability of being sampled). The sample weights were used to calculate unbiased estimates of biophysical measures at a regional scale. Weights were summed across sites assigned a benefit quality class using the thresholds derived herein to generate regional estimates of lake benefit quality. The calculations were made using the R package spsurvey (Kincaid and Olsen, 2013) which supports the methods of Diaz-Ramos et al. (1996).

3. Results

3.1. Classification of lakes

Mean Secchi depth for both 2007 and 2012 indicated three classes: very deep Secchi depth (> 4 m; Western Mountains), deep Secchi depth (> 1.5 m; Appalachians, Upper Midwest, and Xeric), and shallow Secchi depth (plains; Fig. 2). Mean turbidity indicated two classes, low turbidity (< 10 NTU; mountains ecoregions and Upper Midwest), and high turbidity (plains and Xeric). Mean chlorophyll-*a* indicated two classes: low chlorophyll *a* (< 30 µg/L; mountains, Upper Midwest, and Xeric) and high chlorophyll-*a* (plains). Classification of Xeric lakes was ambiguous. Although Xeric lakes grouped with the deep Secchi depth ecoregions, they were grouped with high turbidity ecoregions, and were highly variable for chlorophyll-*a*. We inspected visual assessment scores for lakes in the Xeric ecoregion and they were clearly grouped with lakes in the plains ecoregions. To minimize circular reasoning, we only used the ecoregional variation in visual assessment to confirm the classification of lakes in the ambiguous Xeric ecoregion. The combined ecoregions were otherwise based only on water clarity measures. We reclassified the original nine ecoregions into two combined ecoregions of mountains + Upper Midwest (hereafter, "Mountains"), and plains + Xeric ("Plains"). The combined ecoregions with all lakes mapped are shown in Fig. 3. Two-sample comparisons between combined ecoregions regions in water clarity metrics were significant for every metric in both years ($|t| \geq 13$; $P < 0.001$). Sampled lakes in the Mountains combined ecoregion were, on average, less nutrient enriched, deeper, smaller in area, and had higher riparian forest cover than sampled lakes in the Plains combined ecoregion. Degree of riparian development was similar between combined ecoregions (Table 1).

3.2. Association between perception of benefit quality and water clarity indicators

Mean water clarity was different among combined assessment classes in all cases (ANOVA, $P < 0.001$; Table 2). For all lakes, and for lakes in each combined ecoregion, the proportion of variation in water clarity explained by the model was in nearly always (≥92% of cases) greater for Secchi depth and turbidity than for chlorophyll-*a*. Also, the proportion of variation in water clarity explained by the model was greater for the Mountains combined ecoregion than for the Plains combined ecoregion in nearly every case. Fig. 4 provides a graphic overview of the data used in our analysis. It shows the consistent trends between each water clarity measure and the original and combined visual assessment classes.

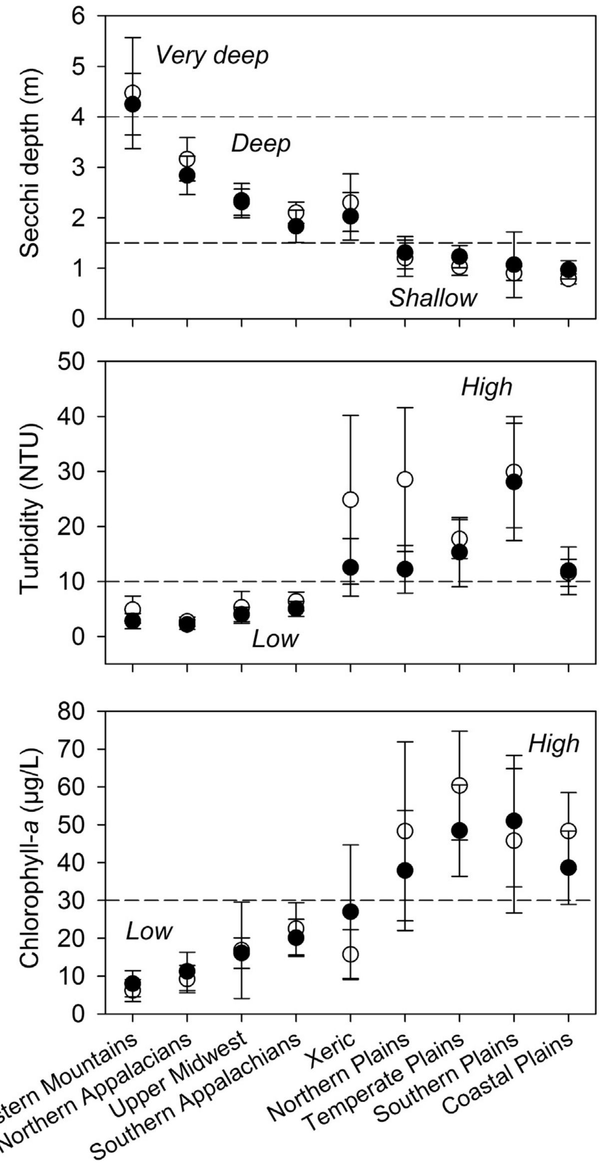

Fig. 2. Mean (± 95% CI) lake water clarity metric values by year and Level III ecoregion. Open symbols: 2007; filled symbols: 2012. Horizontal dashed lines separate regions into putative combined regional classifications.

3.3. Concordance between lake visits and between benefit types

For lakes revisited during an assessment, water clarity during the first visit explained, on average about 72% of the variation in clarity during the second visit across measures and assessment years (based on R^2 from data in Appendix A). Overall, mean concordance (agreement in the visual assessment classification between visits) was lower (61% agreement) for lakes classified as medium benefit quality on the first visit (Fig. 5a–c) than for lakes classified as high or low benefit quality on the first visit (70% agreement). Concordance in visual assessments

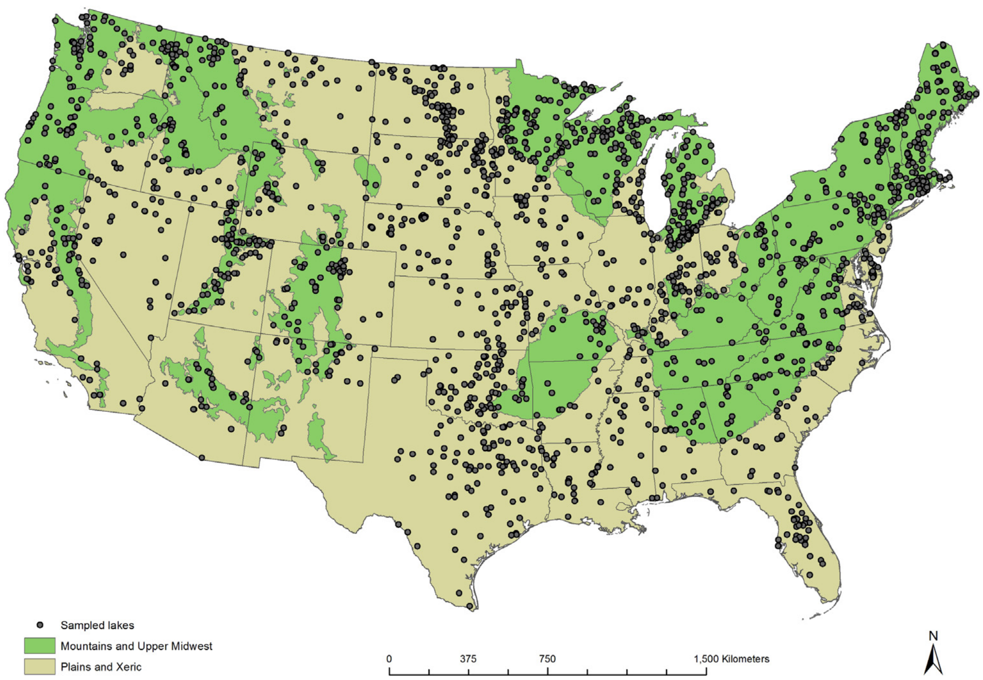

Fig. 3. Combined ecoregions and lakes sampled during the 2007 and 2012 National Lake Assessments.

Table 1
Selected biophysical attributes of sampled lakes by assessment year (2007, 2012), and combined ecoregion. Buffer refers to a 500-m wide riparian zone around the wetted perimeter of each lake. Asterisk indicates where the difference between combined ecoregions was not significant in a two-sample *t*-test (P > 0.05). Data $\log_{10}$-transformed prior to analysis.

Variable	2007 Mountains		2007 Plains		$\lvert t \rvert$
	N	Mean ± 95% CI	N	Mean ± 95% CI	
Chlorophyll-*a* (μg/L)	579	12.3 ± 3.7	573	44.3 ± 6.6	17.3
Turbidity (NTU)	581	4.5 ± 1.1	576	21.4 ± 3.7	21.2
Secchi depth (m)	538	3.2 ± 0.2	553	1.2 ± 0.1	21.2
Total N (μg/L)	581	532 ± 65	576	1799 ± 230	19.3
Total P (μg/L)	581	29.4 ± 6.1	576	185.4 ± 29.4	22.6
Depth (m)	566	12.7 ± 1.0	573	6.3 ± 0.6	13.3
Lake area (ha)	581	800 ± 434	576	1655 ± 820	2.1
Forest in 500 m buffer (%)	581	55.2 + 2.4	574	15.5 ± 1.9	27.3
Developed in 500 m buffer (%)	581	4.6 + 0.9	574	5.8 ± 1.1	1.2*
	2012 Mountains		2012 Plains		
Chlorophyll-*a* (μg/L)	561	12.4 ± 2.0	563	40.1 ± 5.9	13.3
Turbidity (NTU)	549	3.3 ± 0.9	542	15.3 ± 2.8	17.6
Secchi depth (m)	491	3.0 ± 0.2	522	1.3 ± 0.2	17.5
Total N (μg/L)	566	565 ± 49	564	1724 ± 293	17.7
Total P (μg/L)	566	43.0 ± 5.8	564	190.1 ± 30.9	18.2
Depth (m)	562	9.7 ± 0.8	558	5.7 ± 0.6	10.6
Lake area (ha)	566	429 ± 380	564	1295 ± 790	3.8
Forest in 500 m buffer (%)	565	56.3 ± 2.4	564	17.3 ± 2.1	25.6
Developed in 500 m buffer (%)	565	4.5 ± 1	564	6.1 ± 1.3	2.0

was significant between visits for all benefits in both 2007 and 2012 ($X^2 > 39$, $P < 0.0001$) meaning that lakes rated in a particular assessment class on the first visit were rated the same on the second visit more often than would be expected by chance.

There was significant concordance in visual assessments among benefits in both 2007 and 2012 ($X^2 \geq 367$, $P < 0.0001$) meaning lakes that rated high (or low) for one benefit tended to rate the same for other benefits. The concordance was consistently lowest for medium benefit quality, partly supporting our suspicion that assessment is more reliable for high and low benefit quality (Section 2.6). For example, about 70% of lakes classified as having low swimmability were also classified as having low recreational value and 54–64% of lakes classified as having high swimmability also had high recreational value, whereas only about 50% of lakes were classified as medium for both benefits (Fig. 5d). Discordance was highest for lakes classified as having medium recreational value, but for which about 60% were classified as having high aesthetic appeal (Fig. 5f, horizontal arrow). Low aesthetic appeal showed low concordance with low swimmability and low recreational value (≈47%; Fig. 5e and f; vertical arrows) suggesting a disconnect between aesthetic appeal and other benefits for some lakes.

Examining non-water clarity attributes of lakes with low swimmability (Fig. 5e) by aesthetic appeal class (Table 3) reveals that lakes

Table 2
Association between subjective classification of benefit quality for three benefit types (swimmability, recreational value, and aesthetic appeal) each with three combined visual assessment classes (low, medium, and high) and lake water clarity metrics by assessment year and combined ecoregion. All models were significant ($P < 0.05$). Values are R^2 statistics for one-way analysis of variance. Mean total degrees-of-freedom (df) is the mean df across the three water clarity metrics. Data were log_{10}-transformed prior to analysis.

Water clarity measure	Swimmability			Recreational value			Aesthetic appeal		
	All lakes	Mountains	Plains	All lakes	Mountains	Plains	All lakes	Mountains	Plains
2007									
Secchi depth (m)	0.28	0.26	0.20	0.26	0.31	0.12	0.21	0.24	0.09
Turbidity (NTU)	0.25	0.22	0.18	0.24	0.28	0.11	0.22	0.25	0.10
Chlorophyll-*a* (μg/L)	0.18	0.18	0.09	0.18	0.23	0.05	0.14	0.19	0.03
Mean total df	1115	555	565	1106	544	562	1112	559	562
2012									
Secchi depth (m)	0.23	0.21	0.15	0.20	0.17	0.13	0.21	0.22	0.13
Turbidity (NTU)	0.19	0.14	0.14	0.15	0.10	0.12	0.21	0.18	0.15
Chlorophyll-*a* (μg/L)	0.16	0.15	0.10	0.12	0.10	0.06	0.17	0.20	0.08
Mean total df	1054	547	554	1035	507	527	1053	519	534

with low swimmability but high aesthetic appeal had a higher mean percent forest in a 500-m buffer around the lake (37%), than lakes with low swimmability and low aesthetic appeal (17%). Likewise, lakes with high aesthetic appeal had a lower mean percent developed land cover (3.2%), then lakes with low aesthetic appeal (9%). Lakes with low swimmability and high aesthetic appeal tended to be deeper, and were more often natural lakes in the Mountains combined ecoregion than lakes with low aesthetic appeal.

3.4. Thresholds

To illustrate the sources of variation in the derivation of thresholds from percentiles, we plotted the data distribution by combined visual assessment class, year, and combined ecoregion for Secchi depth (Fig. 6). Plots for turbidity and chlorophyll-*a* are similar. Overlap among combined visual assessment classes is apparent, especially for low versus medium and medium versus high classes. The color-coded horizontal lines demarcate the replicate quartile estimates used to calculate the threshold values as means. The plots show the two sources of variability in the derived thresholds: variation in Secchi depth associated with assessment year, and overlap in Secchi depth associated with high and low visual assessment classes. Both types of variation were higher for lakes in the Plains combined ecoregion reflecting higher inter-assessment variation in biophysical measures and the weaker relationship between perception of recreational benefit quality and Secchi depth than in the Mountains ecoregion (Table 1).

Over most of the range of values, Plains benefit quality classes as demarcated by the derived threshold were offset from Mountains

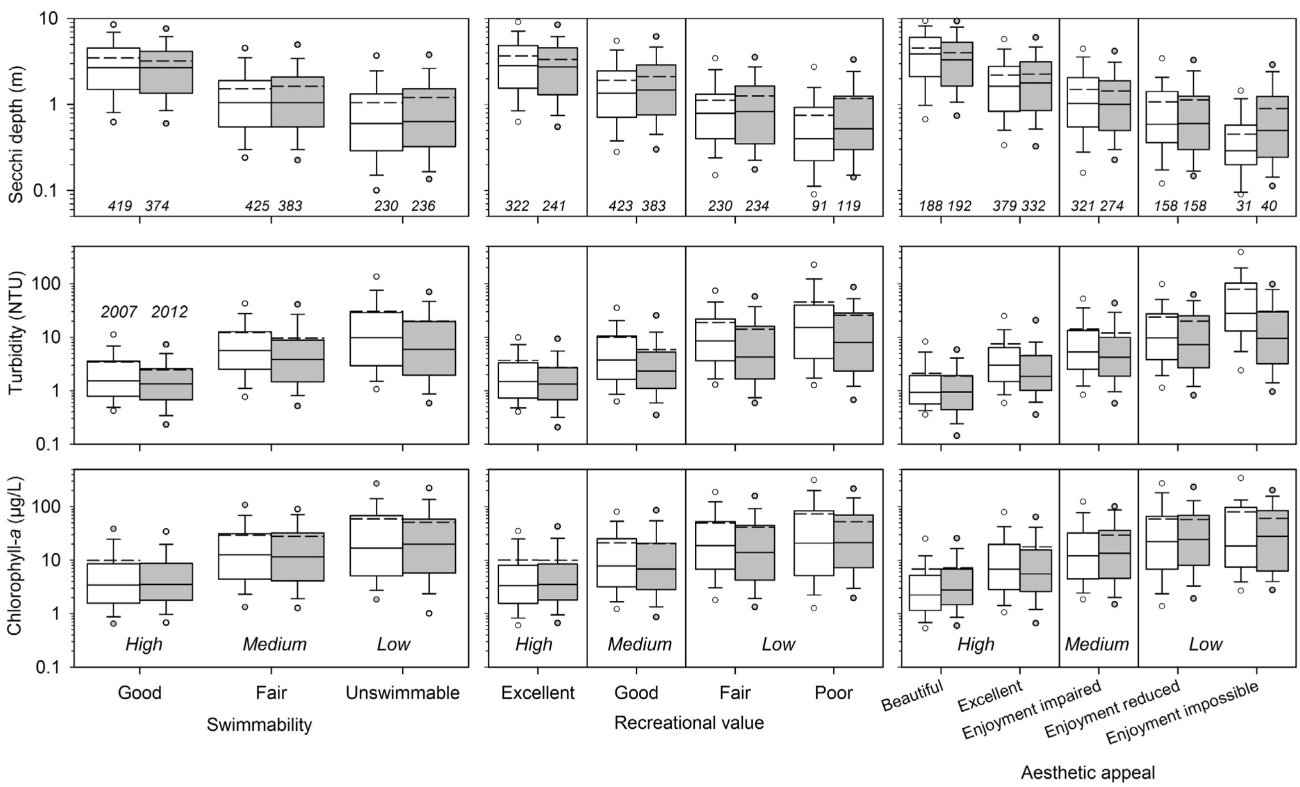

Fig. 4. Distribution of lake water clarity metric values by visual assessment rating, and year. Box plots show, from top to bottom, 95th, 90th, 75th (Q3), median, 25th (Q1), 10th, and 5th percentiles (outliers not shown). Dashed line is the mean. Vertical lines and labels within plots indicate combined visual assessment classes. Values on plots for Secchi depth are sample sizes. Open boxes are for assessment year 2007: filled boxes are for assessment year 2012. Vertical axes are log-scale for better comparisons among groups because data are strongly right skewed.

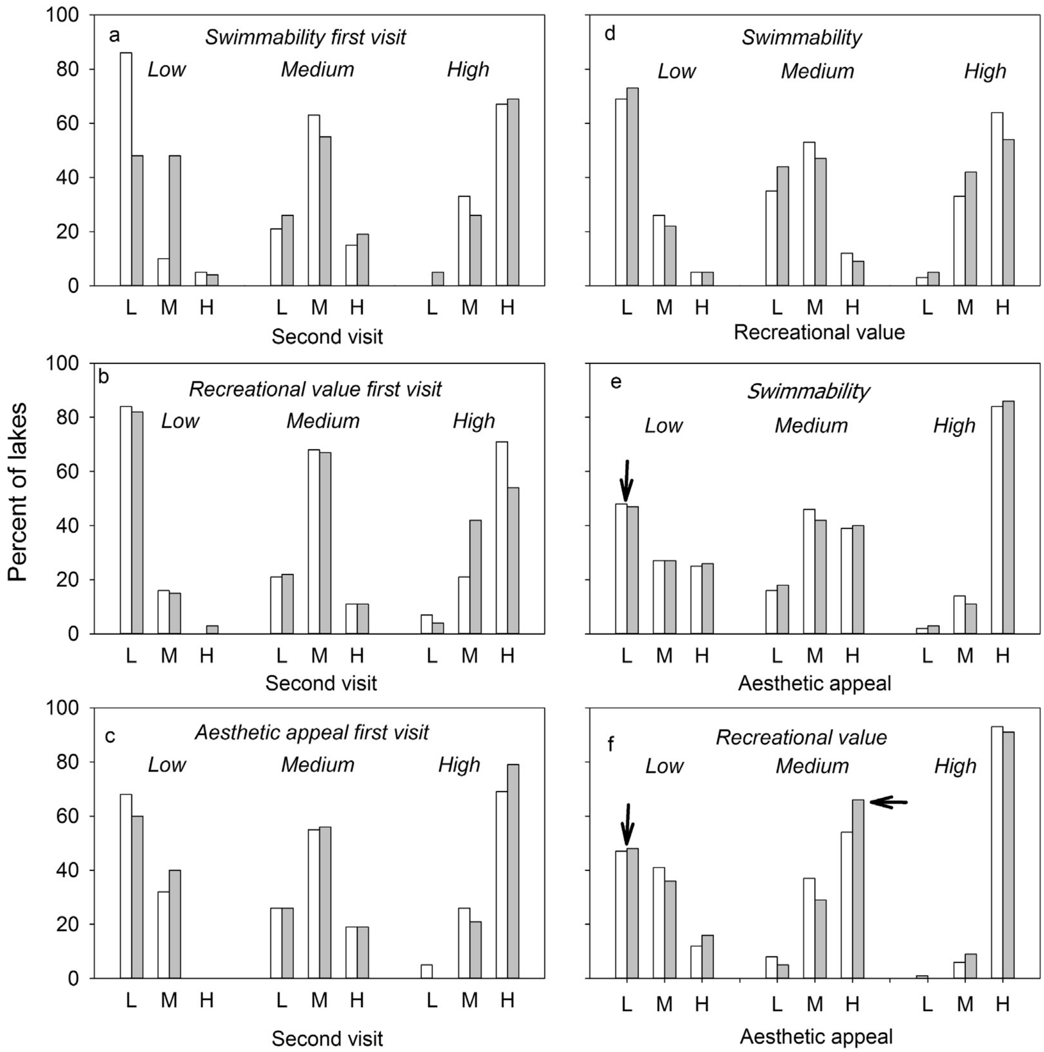

Fig. 5. Concordance between lake visits (plots a–c) and between visual assessment ratings ([L]ow, [M]edium, and [H]igh) for combined visual assessment classes (plots d–f). Bar heights show the percentage in each classification for one visit or benefit that was in each classification for a second visit or benefit. Bars in each group sum to 100 by year. Open bars are 2007; filled bars are 2012. Vertical arrows in plots e and f refer to low concordance between low aesthetic appeal and low swimmability and recreational value. Horizontal arrow in plot f refers to the highest discordance observed in the study.

Table 3
Attributes of lake classed by visual assessment as having low swimmability by aesthetic appeal class. Classes correspond to Fig. 5e. For perfect agreement between benefit types, concordance = 100%.

Attribute	High aesthetic appeal $N = 132$	Medium aesthetic appeal $N = 140$	Low aesthetic appeal $N = 245$
Concordance (%)	26	27	47
Mean depth (m)	5.9 ± 1.2	3.7 ± 0.7	3.0 ± 0.4
Mean lake area (ha)	158.0 ± 109	300 ± 296	234 ± 196
Mean % Forest in 500 m buffer	36.9 ± 6.2	23.0 ± 4.7	16.8 ± 3.1
Mean % developed in 500 m buffer	3.2 ± 2.0	9.4 ± 3.7	8.7 ± 2.4
Natural lakes (%)	46.2	42.1	34.7
In Mountains ecoregion (%)	48.5	36.4	29.0

classes by about one class (Fig. 7; a tabulation of derived thresholds is given in Appendix B). For all three water clarity metrics, the threshold between high and low benefit quality for Mountains (e.g., 2.1, 1.5, and 3.6 for swimming; Fig. 7) was similar to the threshold between high and exceptional benefit quality for Plains lakes (1.8, 1.6, and 3.1). Likewise, the threshold between low and marginal benefit quality for the Mountains ecoregion corresponded to the threshold between high and low for Plains lakes. Variability among the quartile values used to estimate thresholds was very high in the case of chlorophyll-*a* thresholds demarcating high and low recreational benefit quality for lakes in the Plains combined ecoregion (Fig. 7). Variability was also high for turbidity thresholds demarcating low and marginal benefit quality. In all cases except chlorophyll-*a* in Plains lakes, the thresholds for swimming and recreation were slightly higher for Secchi depth and lower for turbidity and chlorophyll-*a*, then analogous thresholds for aesthetics.

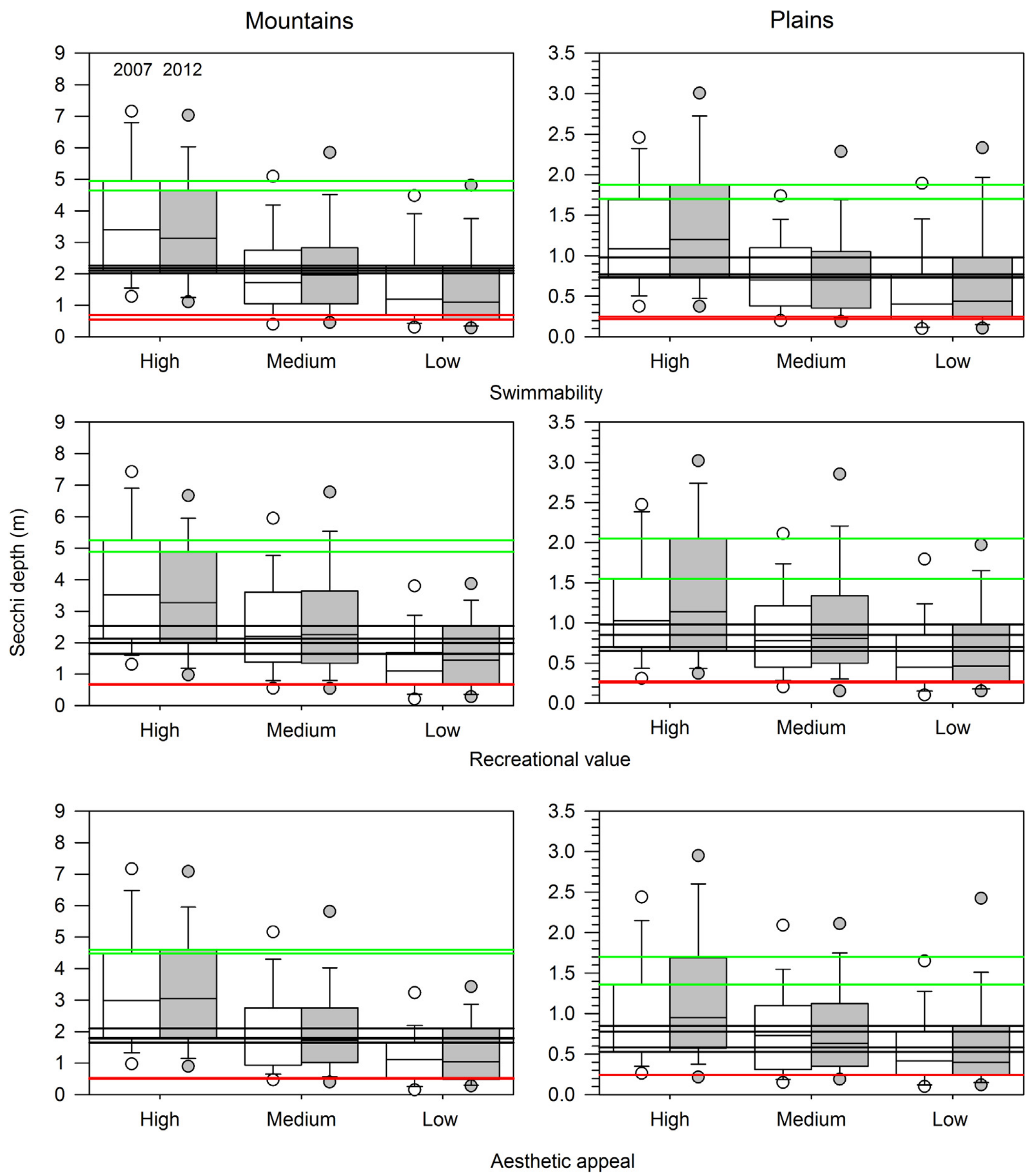

Fig. 6. Distribution of lake Secchi depth by visual assessment class, water clarity ecoregion, and assessment year for each benefit type. Box plots show, from top to bottom, 95th, 90th, 75th (Q3), median, 25th (Q1), 10th, and 5th percentiles. Open boxes are for assessment year 2007: filled boxes are for assessment year 2012. Horizontal green lines show the derived thresholds between high and exceptional benefit quality; horizontal black lines show the derived thresholds between high and low benefit quality; horizontal red lines show the derived thresholds between low and marginal benefit quality.

4. Discussion

4.1. Biophysical indicators

Of Secchi depth, turbidity, and chlorophyll-*a* concentration, Secchi depth is probably the most translatable from scientists to non-experts because distances in feet or meters are more familiar units than degree of side scattering of light (turbidity) or concentration of algal pigments (Davies-Colley and Smith, 2001). We suspect inferences and assessment findings from applying benefit quality thresholds based on Secchi depth are likely to be readily accepted by beneficiaries and decision-makers working on issues related to benefits provided by lakes, including public health, economic activity, and community revitalization. The other water clarity measures and indicators of drivers, including nutrients, remain important for understanding and managing lakes and their watersheds.

Color is an indicator of optical water quality that is included in the publicly-accessible 2012 NLA data (https://www.epa.gov/national-aquatic-resource-surveys/nla; accessed 31 January 2018), but we have not attempted to assess its usefulness as an indicator of recreational benefits from lakes. Studies by D. G. Smith and his colleagues (Smith and Davies-Colley, 1992; Smith et al., 1991, 1995) showed that color was sometimes an important factor in the perception of recreational suitability of waterbodies, but that as an indicator, color was harder interpret than optical clarity, and was confounded by turbidity and humic staining. In general, yellow and yellow-green appearing water were perceived as less suitable for recreation than green–blue and blue appearing water. A survey by Lee (2017) showed that in some waterscapes, color may override clarity as indicator of aesthetic value.

A combined metric derived by combining scaled values for all three

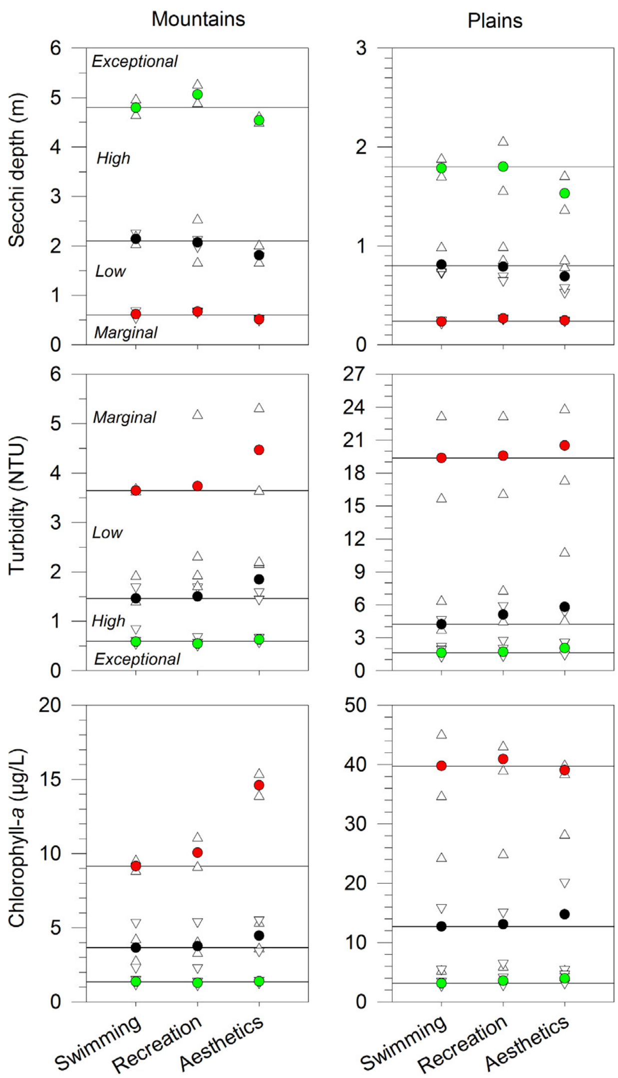

Fig. 7. Lake water clarity threshold values and benefit quality classes by combined ecoregion for three benefits derived using the method illustrated in Figs. 1 and 6. Upward facing triangles are Q1 values; downward facing triangles are Q3 values. Circles are means. Horizontal lines demarcate thresholds between benefit quality classes based on thresholds for swimming.

water clarity metrics could be created and it might have some advantages over single measures. It might, for example, be useful in Plains regions with high spatiotemporal variation in water quality where the water clarity measures are often weakly correlated. Set against this advantage are the problems of translating the social meaning to non-experts of an aggregate indicator with arbitrary units and the likelihood that for many potential applications and datasets one or more constituent metrics would be missing.

4.2. Thresholds in benefit quality

Smith et al. (2015) reported that primary contact recreation in streams, including swimming, was more sensitive to water clarity than secondary contact recreation (which, in streams, often includes fishing). We did not observe this pattern in the NLA data. Thresholds for benefit quality were very similar for swimming and recreational value (Fig. 7). A possible explanation for this is that in making visual assessments for recreational value ("ability to support recreational uses such as swimming, *fishing*, and boating"), crews did not consider fish production or the likelihood of fishing success as a factor in rating lakes, but instead focused on the pleasantness of the fishing experience. Indicators of fish assemblage composition or abundance are not sampled in NLA. As a result, the presence of trained fishery biologists on lake sampling crews was likely inconsistent at best. In any case, the derived thresholds for general recreational benefit quality and swimming benefit quality are essentially the same and the indicators probably reflect similar lake attributes. Implications of this for application of our findings are discussed below (Section 4.5).

Thresholds for aesthetic benefit quality were consistently less protective than the other benefits (Fig. 7). We surmise that crews' perception of aesthetic appeal of a lake integrates more than just water clarity. Our results suggest (Table 3) that perception of riparian land cover may override water clarity as a determinant of aesthetic appeal for some lakes. We speculate that because attributes of the lake setting besides water clarity are important, the degree of water clarity required for each aesthetics benefit quality class is "relaxed." Other research on public perception of aquatic ecosystems, including the waterbody, riparian and adjacent landscape, which have mostly been done for rivers, has shown that multiple factors other than water clarity are often important determinants of aesthetic preferences. These may include negative indicators such as litter or obvious pollution (House, 1996), unnaturalness of the setting (House and Sangster, 1991), or positive natural features such as trees and native vegetation (Nassauer et al., 2001; Junker and Buchecker, 2008).

4.3. Potential error and bias

There are several potential sources of error in the biophysical and visual assessment data. Secchi depth measures may be sensitive to cloud cover, sun angle, water surface conditions (West et al., 2015), and degree of training. The inherent problem of the Secchi disk visible on the lake bottom of shallow lakes argues for the adoption of other or additional water clarity measurement methods in lake assessments (Davies-Colley and Smith, 2001; West et al., 2015). Sources of variation in visual assessments may include training, weather, time of day, observer biases and other factors (Coughlin, 1976). Overall, concordance in assessments between visits for a subsample of lakes (Fig. 5a–c) was about 70% for lakes that scored as high or low benefit quality on the first visit. However, this does not necessarily reflect variability in how crews assessed lakes between visits since variation in water clarity at the time of the first visit only explained 71% of the variability in the second visit and there were many cases of appreciable change in a lake's water clarity between visits (Appendix A), presumably due to algae blooms or high flow events.

An individual's socioeconomic status, knowledge, experience, and context factors (e.g., their location on a particular lake) may influence how they perceive recreational benefits (Coughlin, 1976; Brush, 1976; Artell et al., 2013). Our study relied on visual assessments by trained field crews, whose perceptions may be different from a random sample of lake users (Smith et al., 2015). Field crews generally spent only a day on each lake, and therefore generally did not swim or fish in – they did not themselves enjoy a recreational benefit from – the specific lake they were assessing, nor did they likely own property on the lake. Furthermore, they likely did not have inter- or intra-seasonal experience of lake clarity. On the other hand, because each crew sampled multiple lakes in each NLA, they probably had a better appreciation than the general public of the conditions in each lake relative to the regional norm. Smith et al. (2015) felt survey crews' background knowledge "had likely altered [crew's] opinions on water quality from the opinion of the general public", and that "crews may provide more sensitive results compared to the general public opinion." Smith et al. (2015) felt that because survey crews working across New York State were not acclimated to specific waterbodies, the information would be reliable for state-scale inferences. Smeltzer and Heiskary (1990) reported on perceptions of lakes based on surveys of trained citizen volunteers. They acknowledge a potential bias owing to the high environmental awareness and motivation of volunteers compared to a random sample of lake users. They felt, however, that this bias was "entirely appropriate" and citizen scientists provided an "ideal data base for developing… lake standards." Relative to most lake users, who we presume recreate in one or a few favored lakes each year, NLA crews were unlikely to be emotionally attached to or otherwise predisposed to overvalue the benefits of favorite or "home" lakes (Coughlin, 1976). Most crews were state or sub-state level and likely reflected the regional expectation for water clarity.

4.4. Previous studies

Our classification of lakes into combined level III ecoregions for water clarity, Mountains and Plains (Fig. 3), very closely corroborates the findings of Bigham-Stephens et al. (2015) for their extensive Secchi disk dataset. We conclude that our combined ecoregions are a robust approximation of a consistent spatial pattern in continental water clarity driven by edaphic factors (geology and climate) and human uses (agriculture).

Our study extends the efforts of earlier workers who examined links between water clarity and human perception of lake recreational suitability for developing indicators and thresholds for lake management (Kishbaugh, 1994; Hoyer et al., 2004), for nutrient criteria development (Heiskary and Walker, 1988; USEPA, 2000; Heiskary and Wilson, 2008), and for development of other guidance (Smith et al., 1991; 1995). Our contribution uses recent U.S. national-scale data and we have placed it in an explicit ecosystem benefits context.

Direct comparisons across studies are difficult because most published values are means for recreational benefit classes or individual user survey questions rather than thresholds. Our Secchi depth thresholds were within the ranges reported elsewhere (Appendix C) except for our threshold between low and marginal benefit quality (0.2–0.3 m) for lakes in the Plains combined ecoregion. We could not find comparable values in the literature for this region. We generally corroborate two studies (Smeltzer and Heiskary, 1990; Smith et al., 1991) that found important thresholds in benefit quality for a Secchi depth near 2 m (the threshold between high and low benefit quality in our study) for lakes in the Mountains ecoregion (or its analog elsewhere). Data in Smeltzer and Heiskary (1990) suggest a higher (more protective) value may apply in Vermont than in Minnesota, USA. Our thresholds between high and low benefit quality lakes in the Plains ecoregion (0.7–0.8 m) corroborate two plains studies (Hoyer et al., 2004; Burden et al., 1985). Our Secchi depth threshold for exceptional benefit quality in Mountains lakes (4.5–5.1) generally comports with mean values for "beautiful, could not be any nicer" for lakes in Vermont, USA (Smeltzer and Heiskary, 1990). As shown in Fig. 2, NLA lakes in the mountains ecoregion with water clarity indicating exceptional benefits were mostly located in the western U.S.

Fewer comparable values were available for chlorophyll-*a*, especially for lakes in the Mountains ecoregion (Appendix C). Smeltzer and Heiskary (1990) suggested a nuisance level threshold for Lake Champlain of 8 μg/L at which chlorophyll-*a* "frequently produces perceptions of use impairment." This value falls in our low benefit quality class, and is below the marginal benefit quality threshold of about 10 μg/L for swimming. Published values for Plains lakes indicating good or only slightly impaired suitability for recreation (7–14 μg/l, Burden et al., 1985, Hoyer et al., 2004) fell in the range of our high benefit quality class. Published values for Plains lakes for a threshold between marginal and acceptable (> 32 μg/L) were in the range of our low benefit quality class. While there was broad agreement between our findings and the literature, we recommend circumspection in the application of our chlorophyll-*a* threshold in the Plains ecoregion. Variation associated with the thresholds was relatively high compared to Secchi depth (Fig. 7) and the association between measured chlorophyll-*a* and visual assessments was relatively weak (Table 1)

Published perception-based turbidity thresholds we found were for rivers. From stream data in Smith et al. (2015) we interpolated a threshold between high and low benefit quality of 3.4 NTU for New York, USA. From Arkansas, USA river data in West et al. (2016) we interpolated a threshold between high and low benefit quality of about 10 NTUs. These values are higher (less protective) than the thresholds we derived for lakes in the Mountains ecoregion (< 1.5 NTU, Fig. 7). Reservoirs are well represented in the NLA in both combined ecoregions (55% of lakes overall) so our thresholds are applicable to that lake type. It may be that turbidity is perceived differently in streams with respect to benefits than in lakes and reservoirs.

The literature provides strong support for our finding that perceptions of benefit quality are scaled lower for eutrophic lakes in the plains where water clarity is often lower than more oligotrophic lakes in mountainous regions where water clarity is usually relatively high (Smeltzer and Heiskary, 1990; Heiskary and Walker,1988). We interpret this as a difference in human expectations about the quality of benefits provided by these different ecosystems based on experience of the prevailing condition of lakes in the region. Burden et al. (1985) suggested that regional variation in perception of water quality in Louisiana, USA lakes was influenced by regional variation in the traditional uses of lakes. For example, regional variation in the relative importance of commercial fishing, which may be most profitable in eutrophic systems with low water clarity.

4.5. Application

Because both swimmability and recreational value included consideration of the swimming benefit quality (Section 2.1), the meaning of the derived thresholds for these benefits is confounded. We suspect that visual assessments for both swimmability and recreational value are reflecting similar lake attributes. Applying the threshold for general recreational benefit quality is potentially misleading since it is unclear how or if recreational fishing quality was integrated into visual assessments of recreational value. Fish production and recreational fishing success quality are often related to lake tropic status which is usually inversely related to water clarity (Bachmann et al., 1996; 2012). This suggests an inherent tension among some lake benefits with respect to indicators based on water clarity. Additional research will be required to develop indicators of recreational fishing benefits directly relevant to human well-being and easily understood by non-expert audiences. We therefore recommend that only our thresholds for swimmability and aesthetics be used for assessment of lake benefit quality.

Lake property owners are direct beneficiaries of lakes (Landers and Nahlik, 2013). Quantification of the monetary benefits lake property owners receive is generally achieved using hedonic modelling where changes in lake attributes, including water clarity, are used to predict changes in property value (e.g., Poor et al., 2001; Keeler et al., 2012; Clapper and Caudill, 2014; reviewed by Nicholls and Crompton, 2018). Lake experiencers and viewers, the beneficiary subclass for aesthetic benefits (Section 2.1) includes Lakeshore property owners. Future meta-analyses may reveal if water clarity thresholds based on perceptions of aesthetic benefit quality are aligned with variation on lakeshore property value associated with the same biophysical indicators.

Our thresholds apply across large combined ecoregions, and they may obscure some important intra-regional variation in how recreational benefits are perceived in relation to water quality as noted by Smeltzer and Heiskary (1990) for Minnesota versus Vermont lakes. Also, we did not develop separate thresholds for natural lakes and

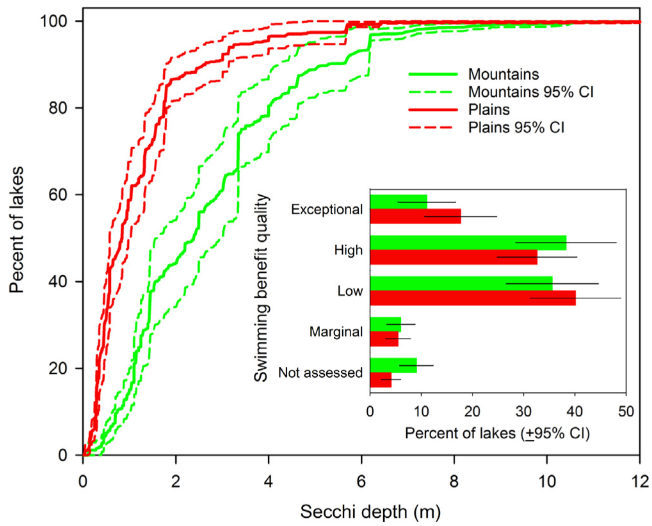

Fig. 8. Regional estimates of Secchi depth for each combined ecoregion for the 2012 National Lakes Assessment. Main plot shows the cumulative distribution function for each ecoregion. Values on the vertical axis are the percent of lakes with less than or equal the Secchi depth value on the horizontal axis. The inset plot shows the percent of lakes in each swimming benefit quality class based on the thresholds in Fig. 7 and Appendix B. Not assessed means Secchi depth was missing or the disk was visible on the bottom of the lake.

reservoirs. Lakes and reservoirs in the US differ in water clarity and trophic status (Bachmann et al., 2017) and, presumably in recreational benefit quality as well. In our analyses, we have assumed that within each combined ecoregion, beneficiaries perceive benefit quality in relation to water clarity similarly for both natural lakes and reservoirs. We did not attempt to account for variation in the surface area of lakes. However, there is anecdotal evidence that lake property owners are more sensitive to water clarity of larger lakes (Boyle and Taylor, 2001), and Walsh et al. (2011) showed that marginal change in property value with improved water clarity was positively related to lake area. Finally, because our thresholds are based on measurements made during a single visit during the summer, their application in other assessment or decision-making contexts should be circumspect. For example, if seasonal variation in water clarity is a relevant concern, our thresholds may not be appropriate.

An advantage of using biophysical thresholds based on the perception of benefits is that water clarity measures can serve as linking indicators to "measure those things that directly affect people's welfare [and] facilitate social interpretations of ecological condition and change (Boyd et al., 2015)." Linking indicators allow for managers and decision makers to connect policy drivers to benefits via causal linkages in an ecological system. A local-scale example might be a policy that allows development of a lake watershed, which increases nutrient loading, which decreases water clarity (e.g., Secchi depth), which is an indicator of benefit quality linking directly to human wellbeing through recreation. Regional or national examples of policy drivers might include changes in climate, energy policy, or nutrient criteria. Indicator thresholds based on human perception of benefit quality provides cognitive benchmarks (e.g., high vs. low; low vs. marginal benefit quality) that improve communication with non-expert audiences. Communication of science using linking indicators that are proximal to social welfare such as the quality of lake recreational benefits is likely to engender more participation in public policy than would indicators of ecological condition based on less accessible biophysical measures such as water chemistry (Boyd et al., 2015; Olander et al. 2017).

4.6. National assessment

As an example of how a water clarity indicator and derived thresholds can be applied to the national-scale assessment of the recreational benefit quality of lakes, we estimated the cumulative distribution of Secchi depth for the population of lakes in each combined ecoregion from the 2012 NLA data (Fig. 8). Applying our thresholds to these estimates gives an estimate of the percent of lakes in each swimming benefit quality class by combined ecoregion (Fig. 8, inset). Fifty-six (± 10) percent of Mountains lakes, but only 13 ± 5% of Plains lakes had a Secchi depth deeper than 2 m. Despite this large ecoregional difference in Secchi depth, the percent of lakes providing high and low-quality recreation were similar between combined ecoregions (30–40%), reflecting regional variation in the perception of water clarity suitable for recreation. Future iterations of the NLA using the thresholds derived herein may reveal if the quality of the recreational benefits provided by the lakes in U.S. is changing over time.

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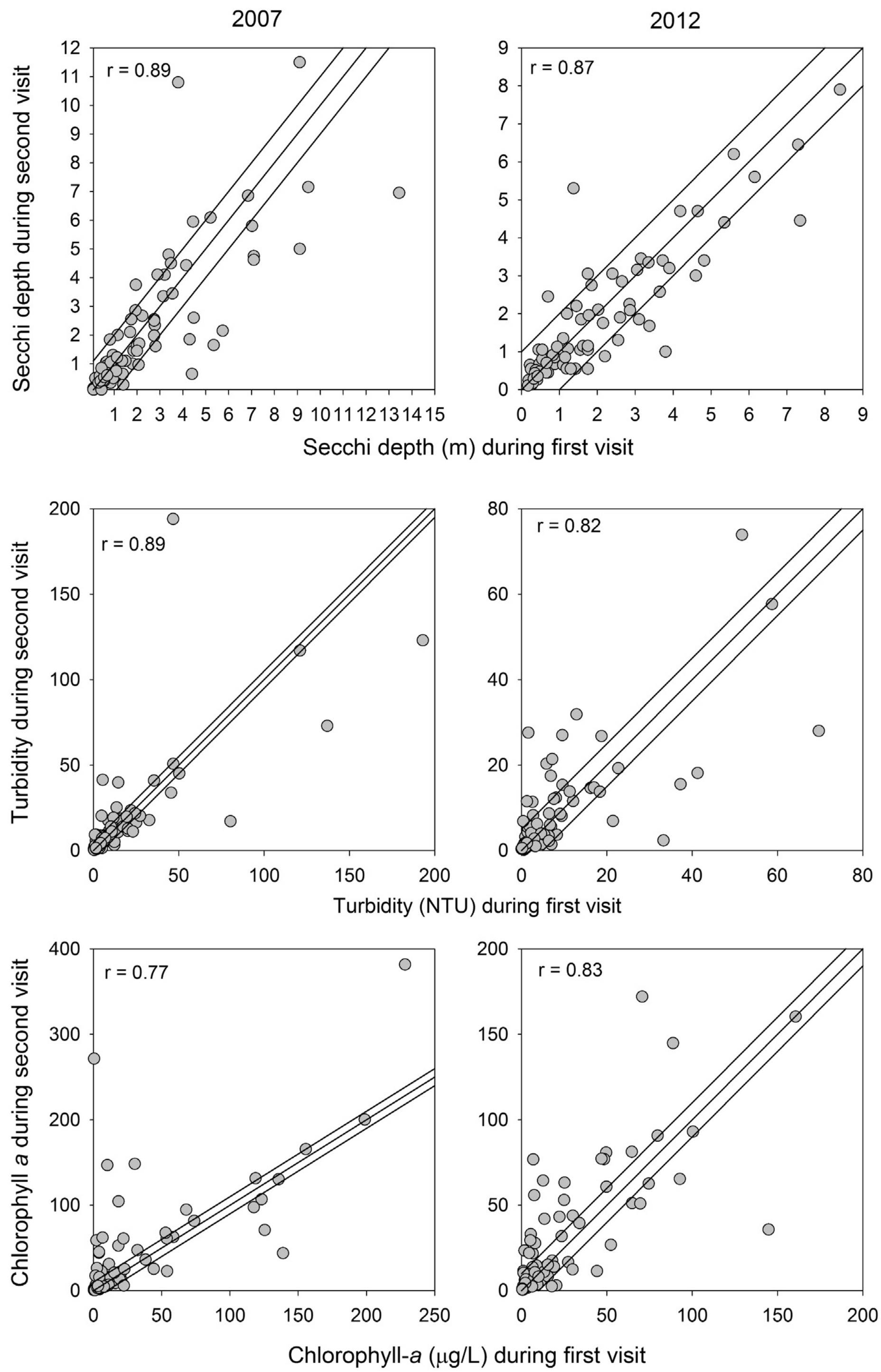
Appendix A

Variation in water clarity metrics between lake visits by year. Values are correlation coefficients for $\log_{10}$-transformed values. Diagonal reference lines show the 1:1 relationship between visits and a ± 1 (Secchi depth), ± 5 (turbidity), or ± 10 (chlorophyll-*a*) unit difference between visits.



Appendix B

Benefit quality thresholds based on water clarity metrics by combined ecoregion. Thresholds apply to lakes > 4 ha in the conterminous U.S.

Benefit	Combined ecoregion	Threshold	Secchi depth (m)	Turbidity (NTU)	Chlorophyll-a (μg/L)
Swimming	Mountains	Exceptional/high	4.8	0.6	1.4
		High/low	2.1	1.5	3.6
		Low/marginal	0.6	3.6	9.2
	Plains	Exceptional/high	1.8	1.6	3.1
		High/low	0.8	4.2	12.7
		Low/marginal	0.2	19.4	39.8

Recreational value	Mountains	Exceptional/high	5.1	0.5	1.3
		High/low	2.1	1.5	3.7
		Low/marginal	0.7	3.7	10.1
	Plains	Exceptional/high	1.8	1.7	3.5
		High/low	0.8	5.1	13.1
		Low/marginal	0.3	19.6	40.9
Aesthetic appeal	Mountains	Exceptional/high	4.5	0.6	1.4
		High/low	1.8	1.8	4.5
		Low/marginal	0.5	4.5	14.6
	Plains	Exceptional/high	1.5	2.1	3.9
		High/low	0.7	5.8	14.7
		Low/marginal	0.2	20.5	39.0

Appendix C

Data source and explanation of Secchi depth and chlorophyll-*a* values discussed in Section 4.4. Secchi depth threshold values for rivers converted from horizontal black disk values after Smith et al. (1995).

Figure reference	Location	Combined US ecoregion	Data source	Secchi depth threshold (m)	Use or benefit	Explanation (Tables and Figures refer to references)	Source
1	Conterminous USA	Plains	Visual assessment	0.2–03	Benefit quality	Threshold between low and marginal benefit quality	This study
2	Conterminous USA	Mountains	Visual assessment	0.5–0.7	Benefit quality	Threshold between low and marginal benefit quality	This study
3	Vermont, USA	Mountains	User survey	0.6	Recreation and aesthetic enjoyment	Fig. 2: mean for "enjoyment nearly impossible"	Smeltzer and Heiskary (1990)
4	Louisiana, USA	Plains	Not specified	0.7	Water quality and fishing	Table 4: Threshold between marginal and acceptable	Burden et al. (1985)
5	Louisiana, USA	Plains	Not specified	0.8	Water quality and fishing	Table 4: Threshold between acceptable and good	Burden et al. (1985)
6	Florida, USA	Plains	User survey	0.8	Recreation and aesthetic enjoyment	Table 4: mean for "enjoyment nearly impossible"	Hoyer et al. (2004)
7	Conterminous USA	Plains	Visual assessment	0.7–0.8	Benefit quality	Threshold between high and low benefit quality	This study
8	Minnesota, USA	Plains	User survey	0.9	Recreation and aesthetic enjoyment	Fig. 2: mean for "minor aesthetic problems"	Smeltzer and Heiskary (1990)
9	Minnesota, USA	Mountains	User survey	1.0	Recreation and aesthetic enjoyment	Fig. 2: mean for "enjoyment nearly impossible"	Smeltzer and Heiskary (1990)
10	Louisiana, USA	Plains	Not specified	1.2	Water quality and fishing	Table 1: Threshold between good and excellent	Burden et al. (1985)
11	Arkansas, USA (rivers)	Mountains	Photo-sorting	1.4	Not specified	Table 4: water quality threshold based on percentiles in responses to images of variable water clarity	West et al. (2016)
12	New York, USA	Mountains	User survey	1.5	Recreation and aesthetic enjoyment	Fig. 2: 68% percent of people perceived that Secchi depth < 1.5 m was impaired	Kishbaugh (1994)
13	New Zealand (rivers)	Not applicable	Questionnaire	1.5	Swimming (bathing)	Fig. 3: perceived as suitable for swimming by 75% of people	Smith et al. (1991)
14	Minnesota, USA	Mountains	User survey	1.5	Recreation and aesthetic enjoyment	Fig. 2: mean for "slightly impaired"	Smeltzer and Heiskary (1990)

15	Florida, USA	Plains	User survey	1.6	Recreation and aesthetic enjoyment	Table 4: mean for “slightly impaired”	Hoyer et al. (2004)
16	Conterminous USA	Plains	Visual assessment	1.5–1.8	Recreational benefit quality	Threshold between exceptional and high benefit quality	This study
17	Florida, USA	Plains	User survey	2.0	Recreation and aesthetic enjoyment	Table 4: mean for “minor aesthetic problems”	Hoyer et al. (2004)
18	Conterminous USA	Mountains	Visual assessment	1.8–2.1	Benefit quality	Threshold between high and low benefit quality	This study
19	Florida, USA	Plains	User survey	2.3	Recreation and aesthetic enjoyment	Table 4: mean value for “could not be any nicer”	Hoyer et al. (2004)
20	Minnesota, USA	Mountains	User survey	2.5	Recreation and aesthetic enjoyment	Fig. 2: mean for “minor aesthetic problems”	Smeltzer and Heiskary (1990)
21	New Zealand (rivers)	Not applicable	Questionnaire	2.8	Swimming (bathing)	Fig. 3: perceived as suitable for swimming by 90% of people	Smith et al. (1991)
22	Vermont, USA	Mountains	User survey	3.1	Recreation and aesthetic enjoyment	Fig. 2: mean for “slightly impaired”	Smeltzer and Heiskary (1990)
23	Minnesota, USA	Mountains	User survey	3.2	Recreation and aesthetic enjoyment	Fig. 2: mean for “could not be any nicer”	Smeltzer and Heiskary (1990)
24	Vermont, USA	Mountains	User survey	4.7	Recreation and aesthetic enjoyment	Fig. 2: mean for “minor aesthetic problems”	Smeltzer and Heiskary (1990)
25	Vermont, USA	Mountains	User survey	5.0	Recreation and aesthetic enjoyment	Fig. 2: mean for “could not be any nicer”	Smeltzer and Heiskary (1990)
26	Conterminous USA	Mountains	Visual assessment	4.5–5.1	Benefit quality	Threshold between exceptional and high benefit quality	This study

Figure reference	Location	Combined US ecoregion	Data source	Chlorophyll-*a* threshold (µg/L)	Use or benefit	Explanation (Tables and Figures refer to references)	Reference
27	Florida, USA	Plains	User survey	80	Recreation and aesthetic enjoyment	Table 4: mean for “enjoyment nearly impossible”	Hoyer et al. (2004)
28	Conterminous USA	Plains	Visual assessment	41.0–39.0	Benefit quality	Threshold between low and marginal benefit quality	This study
29	Louisiana, USA	Plains	User survey	32	Water quality and fishing	Table 3: Threshold between marginal and acceptable	Burden et al. (1985)
30	Louisiana, USA	Plains	User survey	30	Water quality and fishing	Table 3: Threshold between acceptable and good	Burden et al. (1985)
31	Conterminous USA	Plains	Visual assessment	15.0–13.0	Benefit quality	Threshold between high and low benefit quality	This study
32	Conterminous USA	Mountains	Visual assessment	9.2–14.6	Benefit quality	Threshold between low and marginal benefit quality	This study
33	Louisiana, USA	Plains	User survey	14	Water quality and fishing	Table 3: Threshold between good and excellent	Burden et al. (1985)
34	Florida, USA	Plains	User survey	14	Recreation and aesthetic enjoyment	Table 4: mean for “slightly impaired”	Hoyer et al. (2004)
35	Florida, USA	Plains	User survey	12	Recreation and aesthetic enjoyment	Table 4: mean for “minor aesthetic problems”	Hoyer et al. (2004)
36	Lake Champlain, Vermont, USA	Mountains	user survey	8	Recreation and aesthetic enjoyment	Fig. 5: nuisance level	Smeltzer and Heiskary 1990

37	Florida, USA	Plains	User survey	7	Recreation and aesthetic enjoyment	Table 4: mean value for "could not be any nicer"	Hoyer et al. (2004)
38	Conterminous USA	Mountains	Visual assessment	4.5–3.6	Benefit quality	Threshold between high and low benefit quality	This study
39	Conterminous USA	Plains	Visual assessment	3.9–3.1	Recreational benefit quality	Threshold between exceptional and high benefit quality	This study
40	New York, USA (streams)	Mountains	User survey	2.5	Recreational use	Fig. 3: threshold between low and high recreational value.	Smith et al. (2015)
41	Conterminous USA	Mountains	Visual assessment	1.4–1.3	Benefit quality	Threshold between exceptional and high benefit quality	This study

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