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Problems With the Shoreline Development Index—A Widely Used Metric of Lake Shape

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Key Points:

- The shoreline development index is scale dependent and cannot be used to compare the shape of lakes with different surface areas
- Patterns of lake shape reported in global hydrographic studies are artifacts of scale dependence
- Bias-corrections are possible, but introduce additional uncertainties

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Abstract

The shoreline development index—The ratio of a lake's shore length to the circumference of a circle with the lake's area—Is a core metric of lake morphometry used in Earth and planetary sciences. In this paper, we demonstrate that the shoreline development index is scale-dependent and cannot be used to compare lakes with different areas. We show that large lakes will have higher shoreline development index measurements than smaller lakes of the same characteristic shape, even when mapped at the same scale. Specifically, the shoreline development index increases by about 14% for each doubling of lake area. These results call into question previously reported patterns of lake shape. We provide several suggestions to improve the application of this index, including a bias-corrected formulation for comparing lakes with different surface areas.

Plain Language Summary

Lakes vary in shape from nearly perfect circles to the almost comically convoluted. These shapes reflect their geologic (or anthropogenic) origins, and influence within-lake ecological and chemical processes. As a consequence, the shapes of lakes are often compared, both among lakes on Earth and between Earth's lakes and those on other planetary bodies, to provide context when measuring and interpreting other characteristics. In this paper, we show that a widely-used metric of lake shape—The shoreline development index—Is biased and produces false patterns when comparing the shape of lakes with different areas, a common analysis and primary purpose of the metric. When applying the shoreline development index, we suggest: (a) Reporting the scale at which lakes are mapped; (b) when possible, only comparing lakes mapped at the same scale; (c) explicitly considering how bias may impact interpretation of patterns of lake shape; and (d) reporting a bias-corrected or alternative metric.

1. Introduction

The shoreline development index—The ratio of a lake's shore length to the circumference of a circle with the lake's area—Is a core metric of lake morphometry that is presented in the early chapters of both introductory (e.g., Wetzel, 2001; Wetzel & Likens, 2000) and specialist text books (e.g., Håkanson, 1981; Timms, 1992), is widely applied to describe the planar shape of lakes in hydrographic surveys (e.g., Messager et al., 2016; Steele & Heffernan, 2014; Verpoorter et al., 2014), is used as an explanatory factor in statistical analyses (e.g., Casas-Ruiz et al., 2021; Dolson et al., 2009; Seekell, Cael, Norman, & Bystrom, 2021), and is used as a basis for comparing lakes on planetary bodies to Earth analogs (e.g., Fassett & Head, 2008; Sharma & Byrne, 2011). In this paper, we show that the shoreline development index is scale-dependent, such that index values increase when calculated based on progressively higher resolution maps. We demonstrate that this property translates to comparative analyses of lakes—Large lakes have higher index values than small lakes, even when they share the same shape. Hence, the index is biased and produces false patterns when comparing the shape of lakes with different areas, a common analysis and primary purpose of the metric. We present a bias-corrected formulation for comparing lakes with different areas. Finally, we discuss implications of our observations, and provide suggestions to improve the application of the index.

2. Theory

The shoreline development index (D_L) is calculated

$$D_L = \frac{L}{2\sqrt{\pi A}} \tag{1}$$

where L is the shore length and A is the surface area, in the same units (e.g., m and m^2, or km and km^2) (Wetzel, 2001). The minimum value is $D_L = 1$, indicating a perfectly circular lake. Higher values indicate deviation from a circle, for example, due to elongation or shoreline irregularity. The fundamental problem with the shoreline development index is that shore length measurements are scale dependent—Shore length is longer when measured on high resolution maps than when measured on low resolution maps (Goodchild, 1980; Håkanson, 1978; Kent & Wong, 1982). This scale-dependence is demonstrated by estimating shore length repeatedly at different scales (δ):

$$L_\delta \propto \delta^{1-d} \tag{2}$$

where L is the shore length in the same units as δ, and d is the fractal dimension of the shoreline (Mandelbrot, 1967). Shore length measurements are scale-independent if $d = 1$, but empirical measurements always reveal $d > 1$, with a typical value of $d = 1.28$ (Kent & Wong, 1982; Mandelbrot, 1967; Seekell, Cael, Lindmark, & Bystrom, 2021; Sharma & Byrne, 2011). As a consequence, the shoreline development index for an individual lake is also scale dependent such that it increases when calculated based on measurements from progressively higher-resolution maps:

$$D_L \propto \frac{\delta^{1-d}}{2\sqrt{\pi A}} \tag{3}$$

For example, the shore length of Lake Vänern, the largest lake in Sweden ($A = 5{,}893$ km^2), is $L = 1{,}012$ km with the shoreline development index $D_L = 3.72$ when measured on a 1:1,000,00 scale map, but $L = 2{,}007$ km and $D_L = 7.38$ when measured on a 1:10,000 scale map (Håkanson, 1978, 1981). It is clear that shoreline development index cannot be applied to compare, and should not be presented in ways that imply comparison, among lakes mapped at different scales.

Scale-dependence also impacts the shoreline development index when used to compare lakes with different surface areas, even if mapped at the same scale (cf. Cheng, 1995). Consider two hypothetical lakes, Lake 1 and Lake 2, with similar shape, but different surface areas. The shore lengths and surface areas can be estimated by overlaying transparent grids on a map of the lakes (Goodchild, 1980). Specifically, the number of grid cells occupied (N) by the lake is used to estimate area ($A = N\delta^2$) and the number occupied by the shoreline is used to estimate shore length ($L = N\delta$). Enclose Lakes 1 and 2 with the boxes a and b that can subdivided into smaller cells with the same size (δ). The estimated shore lengths and areas for the two lakes are:

$$\begin{aligned} L_1 \propto \left(\frac{\delta}{a}\right)^{-d}\delta; \quad A_1 \propto \left(\frac{\delta}{a}\right)^{-2}\delta^2 \\ L_2 \propto \left(\frac{\delta}{b}\right)^{-d}\delta; \quad A_2 \propto \left(\frac{\delta}{b}\right)^{-2}\delta^2 \end{aligned} \tag{4}$$

It follows that:

$$\frac{L_1}{L_2} \propto \left(\frac{b}{a}\right)^{-d}; \quad \frac{A_1}{A_2} \propto \left(\frac{b}{a}\right)^{-2} \tag{5}$$

Therefore:

$$\frac{L_1}{L_2} \propto \left(\frac{A_1}{A_2}\right)^{d/2} \tag{6}$$

This is equivalent to a power-law regression of shore length by surface area when examining the average pattern for many lakes at once, with $d/2$ being the power exponent and the regression constant describing the characteristic shape of the group of lakes (Seekell, Cael, Lindmark, & Bystrom, 2021). Because $d > 1$, shore length increases with surface area more rapidly than the circumference of a circle increases with the circle's area (i.e., $L_1/L_2 \propto (A_1/A_2)^{0.5}$). As a consequence, large lakes have higher shoreline development index than smaller lakes, even if they have the same characteristic shape and are measured at the same scale:

$$\frac{D_{L1}}{D_{L2}} \propto \left(\frac{A_1}{A_2}\right)^{(d/2)-0.5} \tag{7}$$

Table 1
Morphometry of the Study Lakes

	Scandinavian lakes		Global lakes	
Parameter	Median	Range	Median	Range
Area (km^2)	0.14	0.009–3.78	76	0.02–83,512
Shore length (km)	2.27	0.49–18	53	2.2–5171
Shoreline development index	1.67	1.11–4.54	2.17	1.14–10.24
Bias-corrected shoreline development index	–	–	1.58	1.08–4.08
Fractal dimension	–	–	1.10	1.02–1.37

Equation 7 is equivalent to a power-law relationship with the exponent (d/2) – 0.5, when comparing the averages of many lakes at once. Based on the typical fractal dimension of lake shorelines (d = 1.28), this functional form indicates that the shoreline development index increases by 14% for each doubling of lake area. Our explanation is based on box-counting, but the above reasoning and equations translate directly to other methods of shore length measurement (e.g., opisometer, geographic information system software).

Based on these observations, the shoreline development index can be bias-corrected to improve comparison among lakes with different areas. Specifically,

$$D_{BC} = \frac{L}{2\pi^{0.5} A^{(d/2)}} \quad (8)$$

where D_{BC} is the bias-corrected shoreline development index, A is area, d is the shoreline fractal dimension, and $2\pi^{0.5}$ is a normalization constant that relates area to the perimeter of a circle (Cheng, 1995; Seekell, Cael, Lindmark, & Bystrom, 2021). With this formulation, the shore length (L) and normalization (i.e., the denominator) change at the same rate with area, eliminating the bias.

3. Empirical Analysis

3.1. Data Sources and Analysis

We first tested the relationship between the shoreline development index and area for 106 Scandinavian lakes, primarily from the mountainous border region between Sweden and Norway which is populated by many glacial lakes (Table 1). Specifically, we extracted lake surface areas and perimeters from digitized 1:50,000 scale maps from the Swedish Mapping Agency Lantmäteriet and the Norwegian Water Resource and Energy Directorate (Seekell, Cael, Lindmark, & Bystrom, 2021). We calculated the fractal dimension of the shorelines based on the regression of the logarithm of shore length by the logarithm of area. We then evaluated the relationship between the logarithm of shoreline development index and logarithm of area. Specifically, we tested if the power-exponent was equal to the theoretical expectation (d/2) − 0.5.

We then repeated this analysis for 111 globally distributed lakes of diverse size and origin (Table 1). Morphometric characteristics for these lakes were previously reported by Sharma and Byrne (2011), and were measured based on maps created by the Shuttle Radar Topography Mission. Individually measured fractal dimensions are available for each of these lakes, and we used these values to calculated the bias-corrected shoreline development index. Finally, we evaluated the correlation between the bias-corrected index and area.

The two datasets derive from independent sources that incorporate different advantages and limitations. Collectively, they include almost the full size-spectrum of Earth's freshwater lakes (0.009–83,512 km^2), and represent all common formation mechanisms including glacial, tectonic, impact and volcanic crater, fluvial, inter-dune, and landslide processes (Table 1). Our analysis was conducted using R version 4.0.2 with the "boot" and "CAR" packages (Fox & Weisberg, 2019; Canty & Ripley, 2020; R Core Team, 2020). We report confidence intervals based on bootstrapping (n = 9,999 replications).

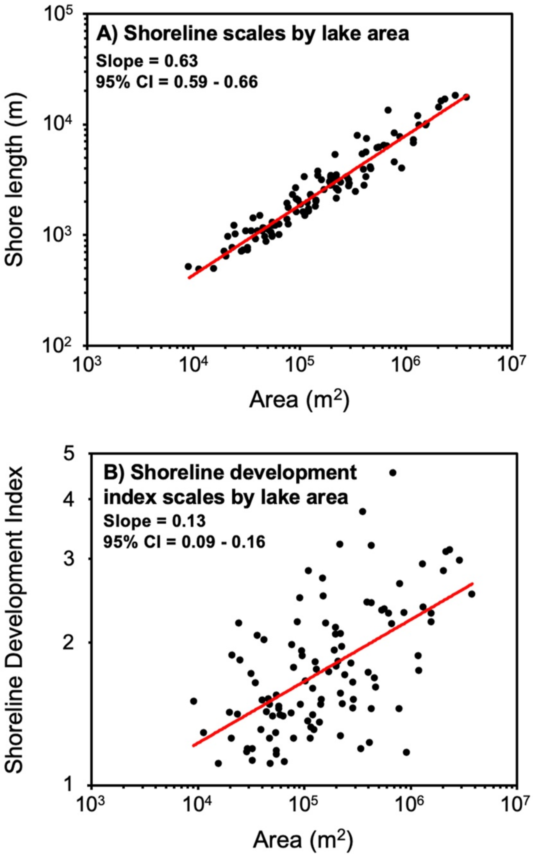

Figure 1. Scaling relationships for 106 Scandinavian lakes. (a) The relationship between shore length and area (b) The relationship between the shoreline development index and area.

3.2. Results

For the Scandinavian lakes, shore length scaled to the $d/2 = 0.63$ power of area (95% CI = 0.59 – 0.66), which is within the theoretical range and similar to reports from other regions (Figure 1a; Seekell, Cael, Lindmark, & Bystrom, 2021). The regression intercept (2.07, 95% CI = 1.98 – 2.15) is typical of glacial lakes (Seekell, Cael, Lindmark, & Bystrom, 2021). There was a significant positive correlation between shoreline development index and area (Kendall's $\tau = 0.37$, 95% CI = 0.25 – 0.48). More specifically, the shoreline development index scaled to the 0.13 power of area (95% CI = 0.09 – 0.16). This value matches our theoretical prediction exactly ($(d/2) - 0.5 = 0.63 - 0.5 = 0.13$; Figure 1b). Hence, the statistically significant relationship between the shoreline development index and area for these lakes is explained by bias originating from the scale-dependence of shore lengths, rather than patterns of shape across the lake size spectrum.

For the globally distributed lakes, shore length scaled to the $d/2 = 0.58$ power of area (95% CI = 0.56 – 0.60; Figure 2a). The regression intercept (1.75, 95% CI = 1.63 – 1.88) falls within a range that can characterize several different formation processes (i.e., glacial, tectonic, crater, karst, inter-dune; Seekell, Cael, Lindmark, & Bystrom, 2021), an observation that is consistent with the diverse formation mechanisms included in the data set. Similar to the Scandinavian lakes, there was a significant positive correlation between shoreline development index and area (Kendall's $\tau = 0.38$, 95% CI = 0.27 – 0.44). For these lakes, the shoreline development index scales to the 0.08 power of area (95% CI = 0.06 – 0.10; Figure 2b), exactly the theoretically specified value (i.e., $(d/2)-0.5 = 0.58 - 0.5 = 0.08$). Hence, the statistically significant statistical relationship between shoreline development index and area for these globally distributed lakes can also be attributed to bias in the shoreline development index. In contrast there is no significant relationship between the bias-corrected index and area (Kendall's $\tau = -0.02$, 95% CI = −0.16 – 0.12; Figure 2b).

4. Discussion

Our analysis demonstrates that the shoreline development index is flawed, and we urge caution when interpreting patterns of lake shape using this metric. Cautionary messages about the shoreline development index have been published several times (e.g., Håkanson, 1981; Hutchinson, 1957; Kent & Wong, 1982; Timms, 1992), however these have been incompletely developed and were focused on variations in index values for individual lakes due to map scale. Our study provides a complete explanation of the implications of scale-dependence for the shoreline development index, including biases related to comparing lakes with different sizes, which is the most common use of the index. Our study highlights the potential for false patterns when comparing the shape of lakes with different areas, but provides a clear path forward through the introduction of a bias-corrected index.

A practical challenge to applying the bias-corrected index is that fractal dimensions are often not known for individual lakes. If necessary, an average value can be substituted for d (i.e., $\bar{d} = 1.28$). This can be easily estimated, for example, by regressing shore length by area for a group of lakes, and the resulting estimate can be expected to accurately produce average patterns for many lakes. However, $D_{BC} < 1$ is possible for sub-circular lakes with relatively smooth shorelines (i.e., if $d < \bar{d}$). In particular $D_{BC} < 1$ for a given lake will occur if its fractal dimension $d < \bar{d}$ and if it is nearly circular (specifically $D_L < A^{\{(\bar{d}-1)/2\}}$). For example, for the 111 lakes in Figure 2, if $\bar{d} = 1.10$, two lakes have $D_{BC} < 1$, both of which are sub-circular karst lakes with. $D_L < 1.18$.

In general, we suggest only applying the bias-corrected shoreline development index to lakes mapped at the same scale. However, when necessary, it is also possible to correct for differences in map scales. Equation 3 specifies that $D_L \propto \delta^{1-d}$, so the effect due to the different map scales δ_1 and δ_2 can be accounted for by rescaling

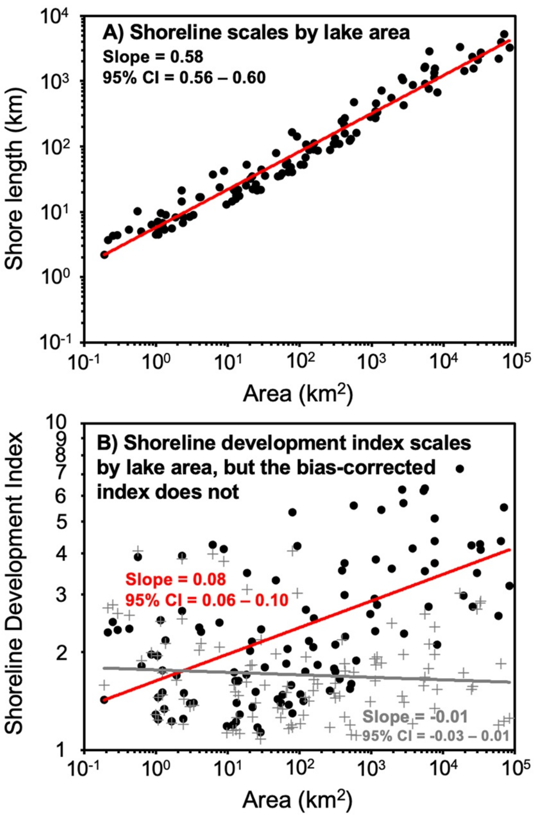

Figure 2. Scaling relationships for 111 globally distributed lakes. (a) The relationship between shore length and area (b) the relationship between the shoreline development index and area (black circles, solid red line). This slope is matches theoretical expectations (the slope from panel A minus 0.5) exactly. The bias-corrected index is not correlated with area (gray crosses, dashed red line).

$D_{L2} = \left(\frac{\delta_2}{\delta_1}\right)^{1-d} D_{L1}$. It is possible to use an average $\bar{d}$ for this correction as well; note however that uncertainty in d, whether lake-specific or an average value, leads to uncertainty in the map-scale-corrected D_L. For example, using $\bar{d} = 1.10$ instead of the individually measured $d = 1.20$ for Lake Winnipeg (53.3°N, 98°W) results in an error of 21% when upscaling or downscaling the map scale by a factor of 10. Hence, while corrections for scale and bias are possible, it is important to recognize that they introduce uncertainties related to the estimation of the fractal dimension. These uncertainties are minimized when using individually measured fractal dimensions to compare lakes measured at the same scale, and maximized when using average fractal dimensions to compare lakes mapped at different scales.

An empirical regularity of large-scale hydrographic studies is that the shoreline development index is, on average, higher for large lakes than small lakes (e.g., Lewis, 2011; Messager et al., 2016; Schiefer & Klinkenberg, 2004; Verpoorter et al., 2014; Xenopoulos et al., 2003). This pattern is typically interpreted to mean that large lakes are either more elongated or otherwise have more irregular shorelines than smaller lakes. This has been taken as evidence that large lakes are, on average, more constrained in shape by structural controls (i.e., those related to large-scale bedrock characteristics), whereas small lakes are more strongly shaped by geomorphic processes (Lewis, 2011; Schiefer & Klinkenberg, 2004). Our analysis demonstrates that, after bias-correction, there is no relationship between lake shape and area. This does not rule out transitions in processes regulating lakes, but it does suggest that such transitions do not manifest themselves in systematic patterns of lake shape across the lake size spectrum.

An accurate characterization of lake morphometry is the foundation to understanding the contributions of lakes to the broader Earth system. Specifically, the question "how many lakes are there and how big are they?" needs to be answered in order to generalize measurements of ecosystem function, such as greenhouse gas evasion to the atmosphere, from individual lakes to the global scale (Downing, 2009; Seekell et al., 2013). Despite the recent development of global lake surveys (e.g., Messager et al., 2016; Verpoorter et al., 2014), there is substantial uncertainty in the characterization of the global lake size-distribution, specifically whether or not lake sizes conform to a power-law distribution (Cael et al., 2022). Our observation that the bias-corrected shoreline development index is not correlated with area contributes to resolving this uncertainty. Essentially, a systematic relationship between shape and area is indicative of topography where the two horizontal axes scale differently (Mandelbrot, 1995). A true power-law lake size-distribution is not expected under these conditions because they imply that shorelines are not statistically self-similar (Mandelbrot, 1995). In contrast, the lack of systematic relationship between the bias-corrected index and area is consistent with the conditions required to observe power-law size-distributions, and is also consistent with previous observations of power-law size-distributions across the range of areas included in our study (Cael et al., 2022; Cael & Seekell, 2016; Mandelbrot, 1995). The application of the bias-corrected index across diverse landscape stands to improve understanding of where and why power-law lake size-distributions form.

Methodological standards have been developed to support the implementation of the Water Framework Directive—A major policy initiative focused on quantifying and improving water quality for European lakes, rivers, and coasts (Boon et al., 2019). The European Standard EN 16039:2011 provides methods for assessing lake morphology and gives the shoreline development index as a metric that should be calculated as part of standard hydromorphological assessments, and also optionally for classifying lakes within typologies meant to ensure fair comparison of water quality among lakes. Annex A of the EN 16039:2011 gives shape as a distinguishing feature for many common lake types, and the shoreline development index the only metric of shape provided in the standards (Annex C), indicating that it should be used to compare lakes with different areas. We recommend that EN 16039:2011 should be revised to include alternate metrics or at least a cautionary message about bias in the shoreline development index.

Despite the limitations outlined in our study, the shoreline development index retains usefulness as an internal control on data quality. Specifically, values $D_L < 1$ are not possible and searching for these values is a simple way to screen for unreliable data to exclude from subsequent analyses. In our experience, these values typically arise for small lakes due to rounding errors. These errors can also occur if shore length and area are measured using different methods, for example, if the shore length is measured with an opisometer but the area was measured with the transparent grid technique, although disparate techniques are rarely applied today due to the accessibility of digital analyses through geographic information system software. While the shoreline development index can be used to screen out erroneous data, we note that passing this screening does not confirm the quality of data.

5. Recommendations

We demonstrated that the shoreline development index is scale dependent and cannot be used to make comparisons among lakes with different areas. We demonstrated that bias from this scale dependence underlies previously reported patterns, casting doubt on their reliability. To enhance comparisons, merging of data sets, and evaluation of data quality, we recommend:

1. Disclosing the scale of measurement when reporting lake morphometrics, including the shoreline development index;
2. When possible, only make comparisons using the shoreline development index for lakes mapped at the same scale;
3. Explicitly consider how bias may impact interpretation of patterns of lake shape; and
4. Report the bias-corrected index or an alternative metric.

Measuring morphometry is so foundational that it is often presented as trivial (i.e., without description of methods or limitations). Our study is exemplary of why morphometrics need to be carefully considered and reported. Additionally, the observation that a widely used metric is biased indicates the need to seek and evaluate new approaches for quantifying lake morphometry.

Data Availability Statement

We use only previously published data, which are available from the original sources. Specifically, the Scandinavian lakes data are in Seekell, Cael, Lindmark, and Bystrom (2021), globally distributed lakes with individually measured fractal dimensions are in Sharma and Byrne (2011).

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