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The global abundance and size distribution of lakes, ponds, and impoundments

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Abstract

One of the major impediments to the integration of lentic ecosystems into global environmental analyses has been fragmentary data on the extent and size distribution of lakes, ponds, and impoundments. We use new data sources, enhanced spatial resolution, and new analytical approaches to provide new estimates of the global abundance of surface-water bodies. A global model based on the Pareto distribution shows that the global extent of natural lakes is twice as large as previously known (304 million lakes; 4.2 million km^2 in area) and is dominated in area by millions of water bodies smaller than 1 km^2. Similar analyses of impoundments based on inventories of large, engineered dams show that impounded waters cover approximately 0.26 million km^2. However, construction of low-tech farm impoundments is estimated to be between 0.1% and 6% of farm area worldwide, dependent upon precipitation, and represents >77,000 km^2 globally, at present. Overall, about 4.6 million km^2 of the earth's continental "land" surface (>3%) is covered by water. These analyses underscore the importance of explicitly considering lakes, ponds, and impoundments, especially small ones, in global analyses of rates and processes.

Although lakes are of global importance, most analyses of functional processes in freshwater ecosystems have either emphasized regional similarities (Thienemann 1925; Naumann 1929; Kalff 2001) or have adopted an ecosystem-specific emphasis. The few global analyses of lacustrine processes have been limited because knowledge of the number and size distribution of lakes has been incomplete (Alsdorf et al. 2003; Lehner and Döll 2004). Further, freshwater ecosystems are generally considered to cover only a small portion of the earth's surface. Previous assessments of the global area covered by lakes and ponds are probably underestimates (Kalff 2001) and have ranged from 2–2.8 × 10^6 km^2 (Meybeck 1995; Kalff 2001; Shiklomanov and Rodda 2003). The literature suggests that lakes and ponds constitute only 1.3–1.8% of the earth's non-oceanic area, and that lakes are numerically dominated by small systems, but that global lake area is dominated by a few, large lakes (Schuiling 1977; Wetzel 1990; Meybeck 1995).

Because many consider continental waters to be a minor component of the biosphere, the activity of inland waters is commonly ignored in global estimates of ecosystem processes such as elemental budgets (e.g., IPCC 2001). Recent evidence points to the significant role of freshwater ecosystems in many key processes, for example, carbon dioxide (CO_2) and methane (CH_4) efflux and organic carbon storage in sediments (Cole and Caraco 2001; Sobek et al. 2003; Pace and Prairie 2004). There are two major uncertainties in these global estimates. Both the total area occupied by lakes is poorly known, and the size distribution of lakes is not well described. Because many key processes scale with lake size (Håkanson 2004), both issues create a great deal of uncertainty in global estimates. Hence, there is a need to ascertain the global extent and the size distribution of freshwater lentic ecosystems.

Present estimates of the global extent and size distribution of freshwater ecosystems are subject to great uncertainty (Kalff 2001; Lehner and Döll 2004). Here, we estimate the global extent and size distribution of lakes, ponds, and impoundments by exploring the size-dependence of the abundance of lakes, ponds, and impoundments to formulate scaling laws, which are tested across different regions and scales. These scaling laws are then integrated to provide estimates of the total global extent of freshwater ecosystems.

Methods

Historical analyses and models of natural lake abundance—One of the first attempts to characterize the global abundance and frequency distribution of lentic water bodies was performed by Schuiling (1977). Schuiling inventoried the most complete list of large lakes available (Halbfass 1922), supplementing it with 800 planimetered lake maps, to determine the number of lakes in Europe and the world within size ranges of area. This size–frequency approach significantly undersampled lake areas less than 3 km^2 for the European lakes and 800 km^2 for world lakes. Normalizing data per unit land area, however, enables data from different regions to be plotted together and compared. Such graphical analyses suggest that small lakes are numerically dominant (Fig. 1). In an analysis of land–water interfaces, Wetzel (1990) designed a graphical representation of the relationship between the number of lakes on Earth and their areas and depths, suggesting that the earth contains so many small, shallow lakes that small lacustrine ecosystems may cover more area than large ones. Meybeck (1995) collected data on d_L (the number of lakes in given size categories, per unit area) for lakes in many geographical regions that also indicated consistent decreases in the areal frequency of lakes with increasing size (Fig. 1). Taken together, orthogonal regression of these early data suggests that d_L varies as

$$d_L = 1{,}186\ A^{-0.961} \tag{1}$$

where d_L is the number of lakes per 10^6 km^2 in a size range of one log-unit of width, and A is the area in km^2 (Fig. 1; $r^2 = 0.77$; 95% slope confidence interval is −1.05 to −0.88). The exponent of this relationship indicates that each size category contains approximately the same total surface area of lakes. The relationship postulated by Wetzel (1990) tracks just beneath Eq. 1 for large lakes (>1 km^2) and slightly above it for smaller ones.

There are three important limitations to these data. First, they consider only lake counts and sizes obtained using samples of regional lake densities that do not cover all lakes found in a region. Second, the data underrepresent small waterbodies (e.g., <0.1 km^2) because these do not appear on most printed maps. Third, the regional data cover a limited number of geographic areas. Because of these limitations, we used fine-resolution geographical information systems (GIS) and some modern data to extend the d_L approach to new areas and smaller lakes than have been analyzed elsewhere (e.g., Lehner and Döll 2004).

New data for several geographically dissimilar regions fit well within the range of d_L values observed in past analyses (Fig. 2) and track Eq. 1. This suggests that the relationships between lake densities and lake area are similar among regions and can be extended to smaller lake sizes than were originally analyzed in worldwide data. That is, traditional size–frequency relationships appear to extend to waterbodies as small as 0.001–0.0001 km^2. Inspection suggests, however, that some arid to semi-arid regions (e.g., North Dakota and Oklahoma) may have lower d_L for a given size category of lakes than those in areas with greater run-off (e.g., L'Estrie, Laurentides, regions of Canada; Fig. 2). Multiple regression analysis of the logarithm of d_L (lakes per 10^6 km^2) shows that lake densities within size classes vary predictably as functions of lake area (A; km^2) and average annual run-off (V; mm yr^{-1}) (Fekete et al. 2005):

$$\log d_L = 2.08 - 0.800\ (\log_{10} A) + 0.004\ V - 2.8 \times 10^{-6}\ (V^2) \tag{2}$$

Acknowledgments

This contribution is dedicated to Robert G. Wetzel whose global understanding of aquatic ecosystems has inspired a generation of limnologists. We also acknowledge the many aquatic scientists who have counted, measured, and explored the earth's lakes, ponds, and impoundments. We thank Dan Canfield and Roger Bachmann for sharing data on Florida lakes, Steve Hamilton for sharing data on Amazonian lakes, and Daelyn Woolnough for help with geographical information system analyses.

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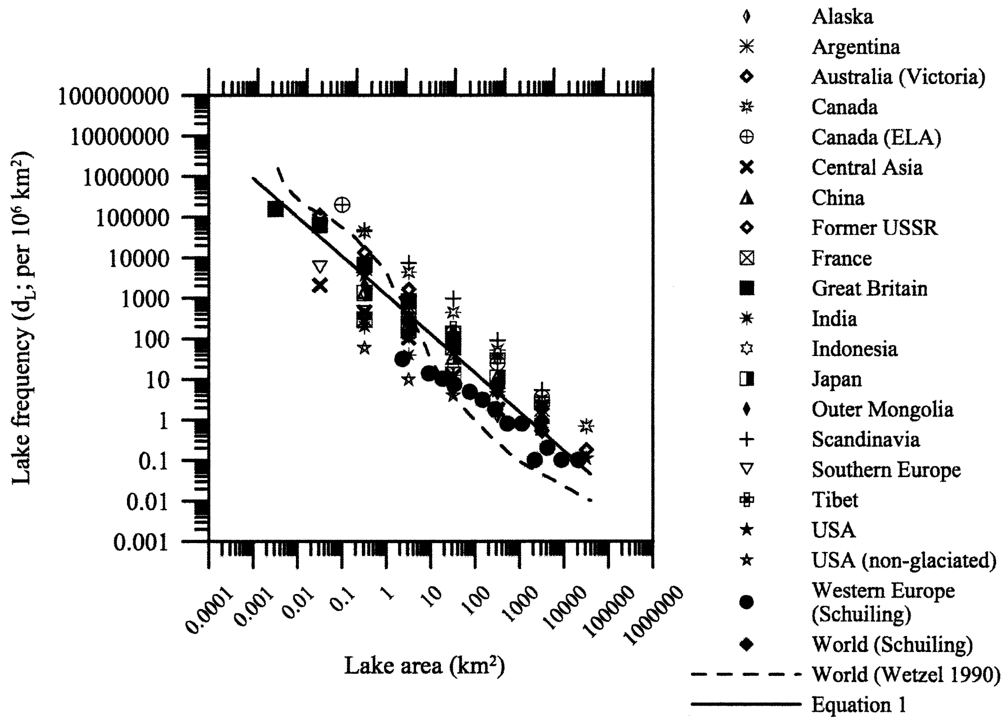

Fig. 1. Relationship between lake surface area and areal frequencies of different sized lakes. The filled circles and open squares indicate the frequencies of lake sizes digitized from Schuiling (1976). The dashed line represents the hypothesis advanced by Wetzel (1990), digitized from his fig. 5. All other data are from Meybeck (1995).

($R^2 = 0.83$, $n = 139$, $p < 0.001$), where d_L is the density of lakes in a $\log_{10}$ bin range with an upper bound of A, and partial effects of all variables are statistically significant ($p < 0.001$). The polynomial effect is highly significant ($p < 0.001$) and indicates that lake density increases with run-off up to about 1,000 mm yr^{-1}, then declines in the erosional landforms that are subject to extremely high run-off. Variation around this relationship is likely the result of differences in regional hypsometry (Strahler 1952) and average landscape slope (Schumm 1956). Application of Eq. 2 using a GIS of global run-off data (Fekete et al. 2005) models many of the world's regions with abundant lakes and ponds (Fig. 3).

The calculation of the global extent of area covered by lakes is complicated by the influence of regional climate on d_L (Eq. 2). The worldwide or "canonical" data of Herdendorf (1984; Fig. 2) consist of counts of all of the world's large lakes. One cannot use d_L data (e.g., Figs. 1 and 2) to accurately estimate the worldwide area of smaller lakes without making some bold assumptions about the influence of climate and hypsometry on d_L for geographically diverse regions of the world. The problem is that we can count the large lakes of the world but understanding the role of small lakes in global budgets and processes requires extrapolation from known, canonical censuses of large lakes to the global extent of lakes of all sizes.

Results and Discussion

The distributional properties of lake number versus size relationships—The power-function fit of the relationship between d_L and A in Eqs. 1 and 2 suggests that lake size distributions share some fundamental distributional properties with other size class data. In fact, lake size data have been recently shown (Lehner and Döll 2004) to have an excellent fit to a size–frequency function of the form

$$N_{a \geq A} = \alpha A^{\beta} \quad (3)$$

where $N_{a \geq A}$ is the number of lakes of greater or equal area (a) than a threshold area (A), and α and β are fitted parameters describing the total number of lakes in the data set that would be of one unit area in size and the logarithmic rate of decline in number of lakes with lake area, respectively. The model above corresponds well to a Pareto distribution (Pareto 1897). The Pareto distribution is particularly versatile and is widely used in fields as disparate as semiotics and engineering (Vidondo et al. 1997). It has also been found useful in describing lake size–frequency distributions (Hamilton et al. 1992), as long as the data are complete and accurate (i.e., not truncated or censored).

The Pareto distribution has a probability density function (*pdf*) described by:

$$pdf(a) = ck^c a^{-(c+1)} \quad (4)$$

where a is the size of the object, and k and c are the location and shape parameters, respectively (Evans et al. 1993). Because lakes cannot be of infinitesimal or infinite sizes, k represents a compound measure of the actual range of lake sizes observed on Earth. The minimum size of lakes and

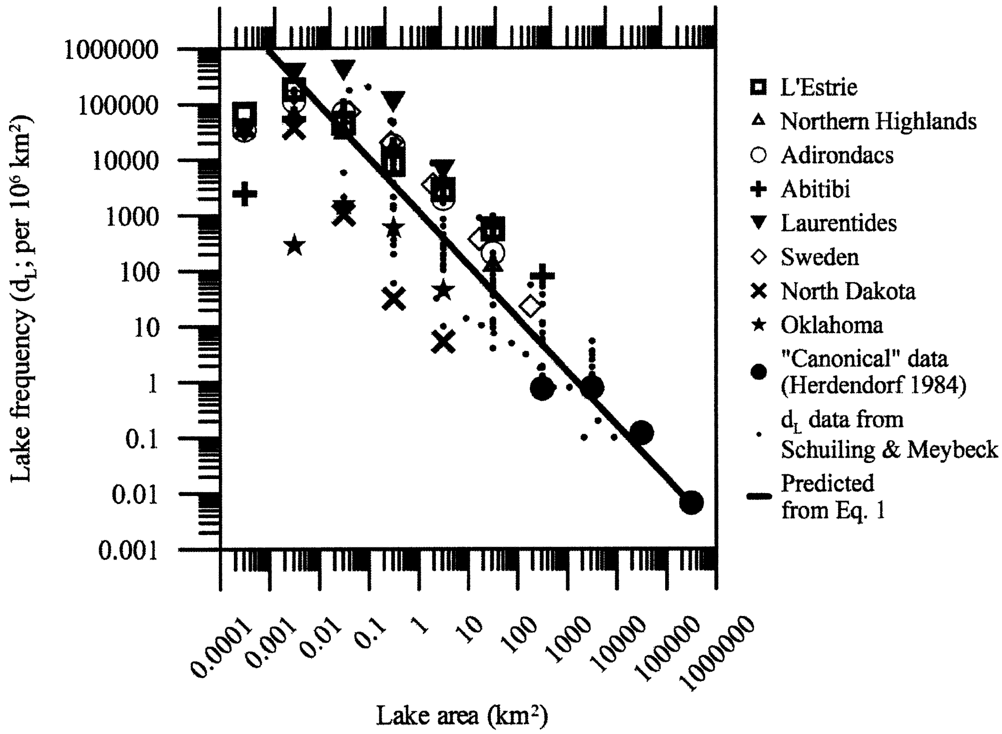

Fig. 2. Relationship between lake surface area and areal frequencies of different sized lakes, determined by detailed GIS analyses (*see sources in Table 1*) and comprehensive counts. The filled dots indicate the frequencies of lake sizes found by Schuiling (1977) and Meybeck (1995). Other regions' lake frequencies are shown by various symbols.

ponds can be considered to be 0.001 km^2 and the maximum lake size that of the Caspian Sea (378,119 km^2). The shape parameter c is the exponent describing the rate at which probability declines with increasing size. Thus, c can be efficiently estimated as the negative slope of the plot of the logarithm of the probability that a lake chosen at random will be of area (a) greater than A as a function of the logarithm of A. In other words, c is equal to $-\beta$ in Eq. 3. If a general Pareto distribution for world lakes can be discovered and shown to have interregional

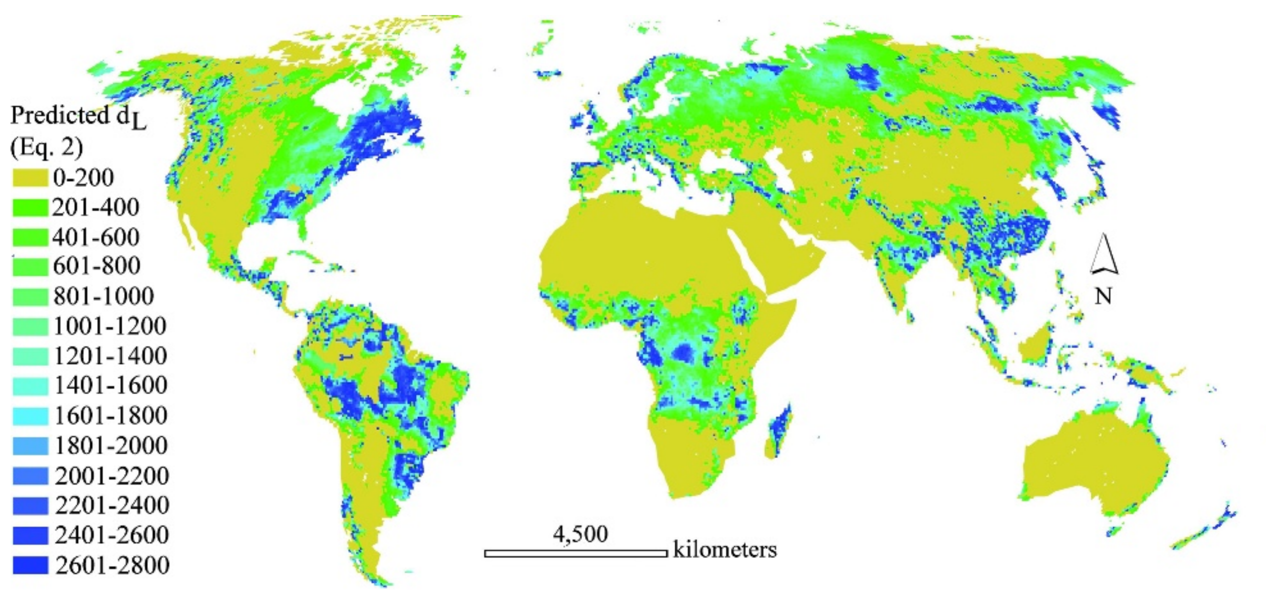

Fig. 3. Geographical analysis of the predicted world distribution of densities (d_L; Eq. 2) of lakes between 1 km^2 and 10 km^2 surface area. Predictions follow a world GIS model of annual run-off (Fekete et al. 2005) with a geographical resolution of 0.5° of latitude and longitude. Lake densities are shown in lakes per 10^6 km^2.

Table 1. Coefficients of Eq. 3 fitted by least squares regression. GIS data were derived from original GIS analyzed by the authors of this study. Data sources for original GIS analyses are noted if the data were not the property of the authors.

Data set	Exponent (β, Eq. 3; c, Eq. 4)	Smallest reliable size (km²)	Number of lakes analyzed (α)	Source
L'Estrie (Québec, Canada)	−0.66	0.001	3,398	GIS (Y. T. Prairie unpubl. data)
Abitibi (Québec, Canada)	−0.67	0.001	1,020	GIS (Y. T. Prairie unpubl. data)
Finland	−0.69	0.009	57,205	(Raatikainen and Kuusisto 1988)
Eastern Lakes Survey (U.S.A.)	−0.76	0.1	1,264	(Linthurst et al. 1986; Landers et al. 1988)
Western Europe	−0.77	5	751	(Schuiling 1977)
Western Lakes Survey (U.S.A.)	−0.78	0.01	752	(Clow et al. 2003)
Amazon basin (South America)	−0.79	0.1	4,482	(Sippel et al. 1992; Hamilton et al. 1992)
Adirondacks (U.S.A.)	−0.79	0.01	2,125	GIS (J. J. Cole unpubl. data)
Median of regional estimates	−0.79			
World's large lakes	−0.83	–	251	(Herdendorf 1984)
Florida (U.S.A.)	−0.88	0.05	5,346	(Shafer et al. 1986)
Mean of regional estimates	−0.89			
Laurentides (Québec, Canada)	−0.90	0.001	562	GIS (Y. T. Prairie unpubl. data)
World's largest lakes	−1.06	10	17,357	(Lehner and Döll 2004)
Oklahoma (U.S.A.)	−1.19	0.1	444	GIS (Oklahoma Center for Geospatial Information 2004)
Orinoco basin (South America)	−1.22	0.1	956	(Hamilton and Lewis 1990; Hamilton et al. 1992)
North Dakota (U.S.A.)	−1.334	0.001	7,239	GIS (North Dakota State Water Commission 2003)

generality, then we can calculate the global extent of all sizes of lakes.

Fit of lake area frequencies to the Pareto distribution—To test lake size distributions for general fit to the Pareto distribution, we collected inventories of all lakes within a variety of geographical settings representing divergent topography and geology. Data not derived from published sources (Table 1) were determined from regional GIS analyses using ARCView (ESRI). Data were scrutinized for evidence of undersampling at small lake sizes to include only untruncated, uncensored data (Hamilton et al. 1992). Figure 4 and Table 1 show strong interregional similarity in the slopes of these distributional curves. Because different regions hold differing total numbers of lakes and their largest lakes differ in size, curves are located at different points along the abscissa. The Pareto distribution shows a similar rate of decline in abundance with increased lake size, regardless of the region of the earth examined.

Given that the size–frequency distributions of lakes follow a Pareto distribution in many regions down to very small lake sizes (Fig. 4), canonical data on the abundance of the world's largest lakes should enable the anchoring of Eq. 3 and the calculation of the worldwide abundance of lakes. Herdendorf (1984) inventoried the world's largest lakes to document the dominance of the 251 largest lakes in the world's freshwater supply (Fig. 4). He concluded that the greatest impediment to this work was the paucity of accurate maps. Lehner and Döll (2004) have recently used GIS analysis to develop and validate a global lake database. They combined analog and digital maps with databases, registers, and inventories of lakes to present a list of >250,000 waterbodies. Considering only the 17,357 natural lakes >10 km² in area included in their analysis, we calculate Eq. 3 by least squares regression:

$$N_{a \geq A} = 195{,}560 A^{-1.06079} \tag{5}$$

($r^2 = 0.998$; $n = 17{,}357$; $SE_\beta = 0.0003$). The exponent of this relationship (β, *Eq. 3*; $-c$, *Eq. 4*) is near the middle of those seen in regional analyses (Table 1) and the two canonical lake area data sets describe an identical lake size distribution (Fig. 4). Orthogonal regression yielded a 99.9% confidence interval of the estimated β from -1.06245 to -1.06056. The accuracy and precision of the estimate of β is very important because calculated lake size distributions and areas are very sensitive to this parameter. Because the shape of Pareto distributions is similar among diverse regions of the earth (Table 1; cf., Lehner and Döll 2004) and the parameters of this distribution are estimable from the canonical data sets, we can thus calculate the global extent of ponds and lakes.

The number of lakes in the world can be calculated following the approach of Vidondo et al. (1997). From Eq. 5, c of the Pareto distribution is 1.06. Given that we define the range of lake sizes as 0.001 to 378,119 km² (the Caspian Sea), integration of Eq. 4 will indicate the fraction of all the world's lakes and ponds that is contained within any range of areas. A good estimate of k is 0.001 km² because this is the smallest size of pond practically recognizable in landscapes. The fraction of all world lakes that are represented by those in the canonical data set (f_c) can be calculated as follows:

$$f_c = -k^c \times \left(A_{c\,\max}^{-c} - A_{c\,\min}^{-c}\right) \tag{6}$$

where $A_{c\ \min}$ and $A_{c\ \max}$ are the minimum and maximum areas of lakes found in the canonical data set (i.e., 10 and 378,119) and c is the negative of the exponent (*Eq. 5*) found

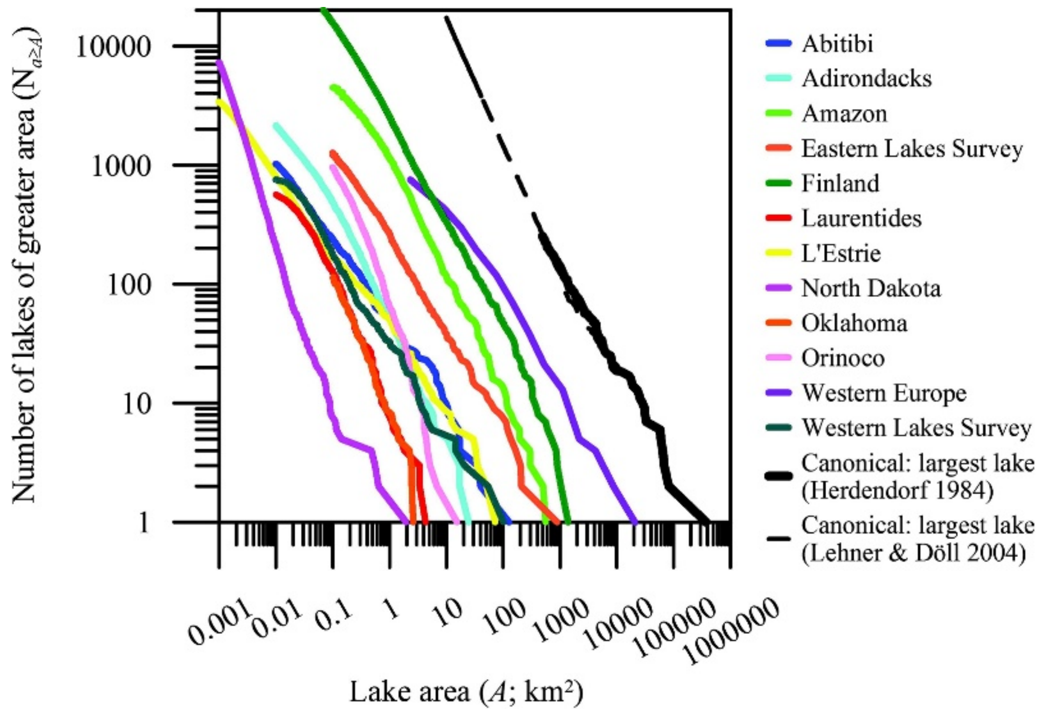

Fig. 4. Plots of data on the axes implied by Eq. 3. Statistical fits of Eq. 3 to these data are shown in Table 1. Data are only plotted throughout the range of lake sizes that could be reasonably expected to be comprehensively censused using the resolution of GIS coverages available (see Table 1). The black lines represent canonical (complete) censuses of world lakes (Herdendorf 1984; Lehner and Döll 2004).

for the canonical data set. Solving Eq. 6 indicates that the canonical lake data set contained a fraction of the world's lakes equal to 5.712×10^{-5}. Division of the number of canonical lakes used to calculate Eq. 5 by this fraction estimates that there are in the neighborhood of 304 million ponds and lakes ($\geq$0.001 km^2) in the world. This total number of world lakes is defined as N_t.

Further, because Eq. 3 fits consistently over a wide range of lake areas (Fig. 4 and Table 1) and because Eq. 5 anchors this canonical frequency distribution to the known sizes of the world's largest lakes, the number of world lakes can be approximated over any size range. If A_{min} and A_{max} are the minimum and maximum sizes of lakes in a given size range, the number of lakes over a size range can be calculated:

$$N_{A_{max} - A_{min}} = -N_t k^c \left(A_{max}^{-c} - A_{min}^{-c}\right) \tag{7}$$

(see Table 2). Because c is greater than unity, Eq. 7 shows that there are many small lakes and few large lakes.

Likewise, the average size and total area covered by lakes in a given size range can be calculated using the Pareto distribution (Vidondo et al. 1997). After simplification, the average area of lakes over a size range of A_{min} to A_{max} can be calculated:

$$\bar{A}_{A_{min} - A_{max}} = c \times \frac{-A_{max}A_{min}^c + A_{max}^c A_{min}}{(c-1)\left(A_{max}^c - A_{min}^c\right)} \tag{8}$$

The total land area covered by lakes of any size range can be calculated as the product of Eqs. 7 and 8.

Analyses of canonical lake data and the exponents of Pareto distributions of lake sizes derived by regional GIS reveal some surprises. Contrary to previous predictions (Schuiling 1977; Wetzel 1990; Meybeck 1995; Kalff 2001), small lakes, not large ones, appear to represent the most lacustrine area. Although lakes $\geq$10,000 km^2 in individual lake area constitute nearly 1×10^6 km^2, these lakes make up only about 25% of the world lake area. Together, the two smallest size categories of lakes in Table 2 comprise more area than the three largest size categories. When converted to d_L units (number per 10^6 km^2 of Earth's surface; Table 2), extension of canonical lake data to small lakes using the Pareto distribution tracks Robert Wetzel's concept (Wetzel 1990) of the likely abundance of small lakes (see Fig. 1).

Undercounting small lakes has led to significant underestimates of the world lake and pond area. World lakes and ponds account for roughly 4.2×10^6 km^2 of the land area of the earth. This more than doubles most quantitative historic estimates (Kalff 2001; Wetzel 2001; Shiklomanov and Rodda 2003). Natural lakes and ponds $\geq$0.001 km^2 comprise roughly 2.8% of the non-oceanic land area; not 1.3–1.8% as previously supposed.

Reservoirs and impoundments—The foregoing analysis made every attempt to exclude consideration of anthropogenic impoundments of water. Artificial waterbodies can, however, be of great importance in many processes (Dean and Gorham 1998; St. Louis et al. 2000) and should be included in global analyses. The size distributions of natural lakes and impoundments are both extensions of

Table 2. The numbers, average sizes, and areas of world lakes calculated from Eqs. 7 and 8. The total area of lakes in the size range is calculated as the product of calculations from Eqs. 7 and 8. Values are inclusive of lower bounds but exclusive of upper bounds.

A_{min} (km²)	A_{max} (km²)	Number of lakes	Average lake area (km²)	Total area of lakes (km²)	d_L (lakes per 10^6 km²)	Source
0.001	0.01	277,400,000	0.0025	692,600	1,849,333	Eqs. 7, 8
0.01	0.1	24,120,000	0.025	602,100	160,800	Eqs. 7, 8
0.1	1	2,097,000	0.25	523,400	13,980	Eqs. 7, 8
1	10	182,300	2.50	455,100	1,215	Eqs. 7, 8
10	100	15,905	24.7	392,362	106	Lehner and Döll (2004)
100	1,000	1,330	248	329,816	9	Lehner and Döll (2004)
1,000	10,000	105	2,456	257,856	0.7	Lehner and Döll (2004)
10,000	100,000	16	37,978	607,650	0.1	Lehner and Döll (2004)
>100,000		1	378,119	378,119	0.007	Lehner and Döll (2004)
All lakes		304,000,000	0.012	4,200,000		

the earth's hypsometry (Strahler 1952), which is fundamentally influenced by the erosional force of the water supply. As landscapes are covered with impounded water, however, small depressions are aggregated into larger lakes. Expressed in terms of an effect on the Pareto distribution, this could lead c (Eq. 4) to be larger.

Because the earth clearly has more small depressions than large ones (both dry and wet), it is likely that a Pareto distribution could fit for impoundments as well as for natural lakes. In fact, Eq. 2 suggests that there are water-rich regions of the earth that are underserved by natural lakes owing to their tilted, erosional, river-dominated topography caused by very high run-off (Fig. 3). As humans install impoundments in more of the depressions that will hold water, impounded waters could cover even more area than natural lakes, while following similar size distributions. If more large impoundments are built than small ones, however, there could be differences in the exponents of the relationships of the type shown in Eq. 3 for natural and impounded waterbodies.

The area impounded by large dams is increasing worldwide. It has been estimated that the volume of water in impoundments increased by an order of magnitude between the 1950s and the present (Shiklomanov and Rodda 2003). As an example, Fig. 5 shows the trend in the area covered by impoundments in the United States. The semi-log trend is approximately linear from 1700 to present, but decelerated around 1960. The annual average rate of increase in impounded area during this term was about 4%. The rate of increase since 1960 has slowed to about 1% per year perhaps because of the increasing rarity of vacant land.

The International Commission on Large Dams (ICOLD; www.icold-cigb.org) tracks data on dams around the world that are of safety, engineering, or resource concern. These data are purposefully biased toward large dams, most notably those >15 m height. The data are thus likely to provide the best estimate of impoundments with the largest impounded areas and progressively less exhaustive coverage of smaller impoundments. Restricting an analysis of Eq. 3 to the 41 largest impoundments from the Inguri impoundment (13,500 km²) down to 1,000 km² yields

$$N_{a \geq A} = 2{,}922{,}123A^{-1.4919} \quad (9)$$

($r^2 = 0.97$; $n = 41$; $SE_\beta = 0.0435$). The strongly negative exponent of this equation indicates that the smallest of the large impoundments comprise more surface area than the

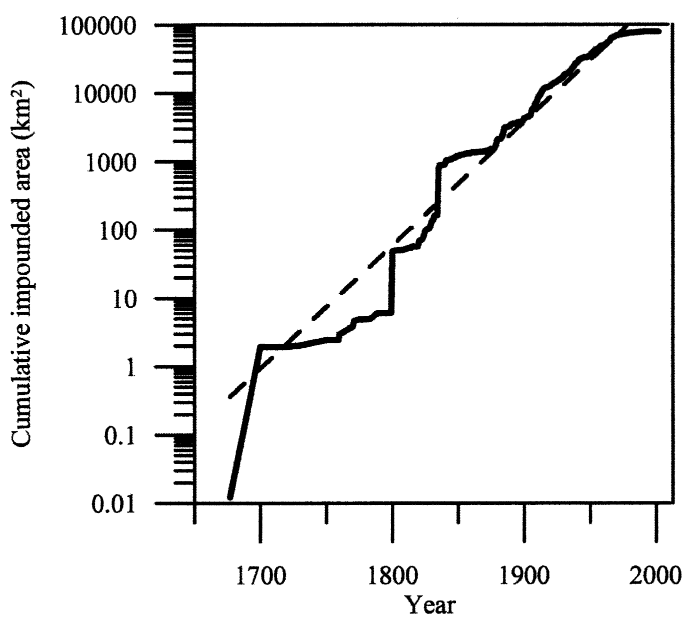

Fig. 5. Rate of change in impounded area in the United States for all water impoundments with dams listed as potential hazards or low hazard dams that are either taller than 8 m, impounding at least 18,500 m³, or taller than 2 m, impounding at least 61,675 m³ of water (USACOE 1999). All data were ignored where the date of dam construction was unknown (ca. 12% of impounded area) or natural lakes (e.g., Lake Superior) were listed as impoundments. The dashed line shows a semi-log regression ($r^2 = 0.95$).

Table 3. The numbers, average sizes, and areas of world water impoundments calculated from Eqs. 7, 8, and 10. The total area of impoundments in the size range is calculated as the product of calculations from Eqs. 7 and 8. Values are inclusive of lower bounds but exclusive of upper bounds.

A_{min} (km^2)	A_{max} (km^2)	Number of impoundments	Average impoundment area (km^2)	Total area of impoundments (km^2)	d_L (impoundments per 10^6 km^2)
0.01	0.1	444,800	0.027	12,040	2,965
0.1	1	60,740	0.271	16,430	405
1	10	8,295	2.71	22,440	55.3
10	100	1,133	27.1	30,640	7.55
100	1,000	157	271	41,850	1.05
1,000	10,000	21	2,706	57,140	0.14
10,000	100,000	3	27,060	78,030	0.02
All impoundments		515,149	0.502	258,570	

largest of them. The intentional bias of this data set toward large dams progressively increases the exponent of this equation as smaller impoundments are included. The average relationship, considering all of the ICOLD impoundments down to 1 km^2, is

$$N_{a \geq A} = 20{,}107A^{-0.8647} \tag{10}$$

($r^2 = 0.97$; $n = 9{,}604$; $SE_\beta = 0.0154$). Integration of this equation certainly results in an underestimate of the area covered by impoundments (cf., Eqs. 9 and 10) because it ignores many impoundments formed by small dams. Calculations following Eqs. 6–8 (Table 3) show, however, that there are at least 0.5 million impoundments $\geq$0.01 km^2 in the world, and they cover >0.25 million km^2 of the earth's land surface. This is a smaller area than estimates based on extrapolation (Dean and Gorham 1998; St. Louis et al. 2000; Shiklomanov and Rodda 2003) but nearly identical to GIS-based estimates (Lehner and Döll 2004). Large impoundment data sets (e.g., Smith et al. 2002) suggest that small impoundments cover less area than large ones (Table 3).

The preceding analysis includes only those impoundments with large, engineered dams and ignores small impoundments created using small-scale technologies. The area covered by small impoundments has largely been a matter of speculation (St. Louis et al. 2000). Farm and agricultural ponds are a growing and globally uninventoried resource. They are constructed as sources of water for livestock, sources of irrigation water, fish culture ponds, recreational activities, sedimentation ponds, and water quality control structures.

Figure 6 shows the area of water impounded by agricultural ponds in several political units. There is climatic regularity in the fraction of farm land that is converted to pond structures. Under dry conditions, farm ponds are rare, owing to the difficulty of collection and conservation of sufficient standing water. Up to about 1,600 mm of annual precipitation, farm ponds are an increasing fraction of the agricultural landscape. In moist climates such as Great Britain, Tennessee, and Mississippi, farm ponds make up 3–4% of agricultural land.

The statistical–climate relationship shown in Fig. 6 was used with data on area under farming practice, pond size, and estimates of annual average precipitation (FAO 2003) to estimate the global area covered by farm pond impoundments. This area sums to 76,830 km^2 worldwide. The accuracy of predictions of farm pond area were verified using published data on farm land areas (USDA 2004) and normal precipitation averages (NOAA 2000) for the United States. This method estimates the area of farm ponds in the contiguous United States to be 21,600 km^2, remarkably close to the 21,000 km^2 estimated by GIS (Smith et al. 2002). The predicted world area of farm ponds is more than six times the area predicted by extrapolation of the large dams database and nearly double the total area covered by impoundments between 100 km^2 and 1,000 km^2 in area (Table 3). Such small impoundments are growing in importance at annual rates of increase from 0.7% in Great Britain, to 1–2% in the agricultural parts of the United

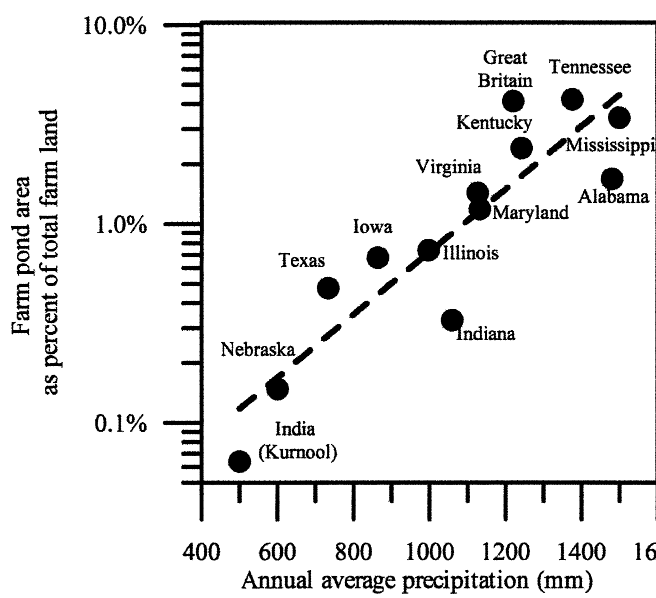

Fig. 6. Relationship between the surface area of farm ponds and the annual average precipitation in several political units. Data sources for farm pond numbers are given in Web Appendix 1. The line is a least squares regression ($r^2 = 0.80$, $n = 13$) where the area of farm ponds expressed as a percentage of the area of farm land (FP) rises with annual average precipitation (P; mm) as $FP = 0.019\ e^{0.0036P}$.

States, to >60% in dry agricultural regions of India (see references in Web Appendix 1, http://www.aslo.org/lo/toc/vol_51/issue_5/2388a1.pdf).

Consistent regional hypsometry permits calculation of the size distribution and area covered by lakes by anchoring a Pareto distribution function to a canonical size distribution of the earth's largest lakes. Natural lakes and ponds are estimated to cover about 4.2 million km^2 of the earth's surface (Table 2), whereas impoundments cover 260,000 km^2 (Table 3), and farm ponds cover about 77,000 km^2. These data, taken together, indicate that lakes, ponds, and impoundments cover >3% of the earth's surface. This is more than twice as much as indicated by previous inventories because small lakes have been undercensused.

On a global scale, rates of material processing (e.g., carbon, nitrogen, water, sediment, nutrients) by aquatic ecosystems are likely to be at least twice as important as had been previously supposed. Since the numerical and areal cover of small waterbodies is much greater than was previously assumed, processes that are most active in small lakes and ponds may assume global significance. On a local scale, previous analyses had indicated that small aquatic systems were spatially unimportant, yet small waterbodies dominate the global area covered by continental waters. Because studies of small aquatic systems have been underemphasized, future work should emphasize the global role and contribution of small waterbodies.

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