LAKES (FORMATION, DIVERSITY, DISTRIBUTION)

Contents

Abundance and Size Distribution of Lakes, Ponds and Impoundments

J A Downing, Iowa State University, Ames, IA, USA
C M Duarte, IMEDEA (CSIC-UIB), Esporles, Islas Baleares, Spain

Abundance and Size of Lakes Dictated by Climate and Geology

A global understanding of the role of lakes and impoundments in the functioning of any region of the Earth requires quantification of their number and size distribution. Geology, tectonics, and climatic processing have made the Earth's surface an undulating and tilted surface with a hypsometry defined by the amount of relief and the irregularity of the underlying materials. If this undulating surface is cut through by a plane (tilted or not) that represents the groundwater and surface-water table, the water will outcrop in a manner that fills some large depressions and more small ones with water. Depending upon the net rate of replenishment of water by precipitation, the open surface waters of a region may cover much of the land surface or little of it, but the size and shape of depressions in the Earth will determine the regional morphometry or hypsometry. In this way, hypsometry and climate combine to determine the abundance and size distributions of natural lakes and depressions that can be made to hold water through the addition of dams.

Historical Estimates of Limnicity

The 'limnicity' of land surfaces has been speculated upon since the early 1900s. In 1925, August Thienemann[1] concluded from map data summarized in 1914 by Wilhelm Halbfass, that "… around 2.5 million km^2, that is about 1.8% of dry lands, are covered with freshwaters; in Germany, the area of all lakes covers about 5200 km^2, or about 1% of the land surface. The largest lake on Earth is the Caspian Sea which has a surface area of 438 000 km^2." Several modern assessments of the global area covered by lakes and ponds have been made but were probably underestimates. These estimates were also made using similar map-based methods and have ranged from 2×10^6 to 2.8×10^6 km^2. Even 75 years after Thienemann's work, based on sometimes poor and incomplete maps, lakes and ponds were still thought to constitute only 1.3–1.8% of the Earth's non-oceanic area.

---

[1] Text located by Lars Tranvik. Translation supplied by Lars Tranvik and JAD.

The historical stability of estimates of limnicity of land surfaces is due to the prevailing assumption that large lakes make up the majority of Earth's lake area so that map inventories of the world's largest lakes would offer an estimate deficient in only a minor area represented by small water bodies. This idea was substantiated by analyses of the size distribution of lakes. One of the earliest of these was performed by R.D. Schuiling of the Netherlands in 1977. Schuiling plotted the number of lakes found in various size categories of world lakes and European lakes against the surface area of these lakes and found a consistent pattern. These data and others are shown expressed as measures of limnicity (d_L) of different size ranges of lakes in Figure 1. On the basis of such analyses, Schuiling and others concluded that lakes are numerically dominated by small water bodies but globally dominated in area by a small number of large lakes. The only dissenting voice in this dogma was Robert Wetzel who designed a graph of world lake abundance (reportedly, first on the back of a napkin) that showed a disproportionately great density of small lakes in the world, relative to large ones. Although meant to be a conceptual analysis rather than a quantitative one, Wetzel's perceptions concerning the relative abundance of different sizes of lakes in the world were remarkably accurate (Figure 1). He postulated that small lakes dominate the area of land surface covered by water.

The great stability from 1925 to 2002 in the estimate of the cumulative continental area occupied by lakes and other water bodies is due to agreement in the area of the world's largest lakes shown on maps. Table 1 shows some characteristics of world lakes of greatest area, down to a size of 2000 km^2. The Caspian Sea, the lake with the largest area, alone makes up about 15% of the 2.5 million km^2 represented by the largest mapped lakes of the world. Lake Superior, the world's second largest lake, makes up 3.3% of the area of these lakes, while it takes the second through seventh largest lakes (Superior, Victoria, the Aral Sea, Lake Huron, Lake Michigan, and Lake Tanganyika) to have a cumulative area as large as the Caspian Sea. Lakes of progressively smaller sizes are represented by exponentially increasing numbers of lakes. The area distribution thus appears to approximate the Pareto distribution (explained later), which is precisely the type of distribution one would expect for objects created by random or directed processes in fields as diverse as linguistics and astrophysics. In fact, the word-frequency distribution in this Encyclopedia very likely follows a similar distribution.

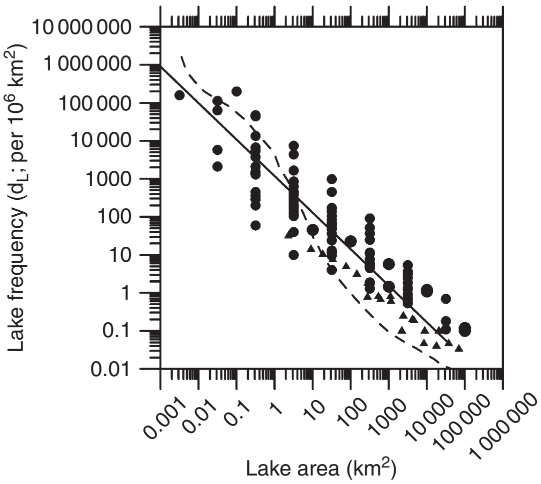

Figure 1 Relationship between lake surface area and areal frequencies of different sized lakes measured as d_L (number of lakes per 10^6 km^2). The filled triangles indicate the frequencies of lake sizes digitized from Schuiling's work. The dashed line represents the hypothesis advanced by Wetzel, digitized from Figure 5 of his 1990 publication. All data represented by filled circles are from Meybeck's publications.

The large area lakes of the world are interesting phenomena in themselves. They are found across a broad range of latitudes and elevations and represent lakes of divergent shape, receiving input from small and large watersheds. Of the world's lakes with greatest area (Table 1), the most northerly is Lake Taymyr at 74.5° N on the Taymyr Peninsula in Krasnoyarsk Krai, Russia. It is ice-covered much of the year, with a brief ice-free season from June to September. The most southerly of the large lakes is Lake Buenos Aires (also known as Lake General Carrera) at 46.5° S in Argentina and Chile, which is large enough to create its own climate in the Patagonia region. The large lake at the highest elevation is Lake Nam Co in Tibet, a holy lake large enough that it takes pilgrims 10 days to walk its circumference. Other well-known high-elevation lakes are Lake Titicaca on the border between Peru and Bolivia and Lake Tahoe in the USA. Some lakes are found below sea level, and many of these are very saline. The Caspian Sea is found at −28 m and several other somewhat smaller large lakes are also found below sea level (e.g., Lake Eyre in Australia, the Dead Sea in Israel and Jordan, the Salton Sea in the USA, and Lake Enriquillo in the Dominican Republic). Although many large lakes have somewhat rounded shapes (Table 1; shoreline development ratios <2), Lake Saimaa, Finland's largest lake, has shores that are extremely convoluted (development ratio >60). Some large lakes of the world have watersheds that are quite small relative to the lake area (i.e., 2–10; Table 1), whereas others such as Lake Chad and Lake Eyre drain areas >100-times their size.

Table 1 The world's lakes >2000 km^2 in area, arranged in decreasing order of lake area

Name	*Latitude*	*Continent*	*Lake area (km^2)*	*WA:LA*	*Elev. (m)*	*Z_{mean} (m)*	*Dev. ratio*
Caspian	42.0	Asia	374 000	10	−28	209	2.8
Superior	47.6	N. America	82 100	2	183	149	4.7
Victoria	−1.0	Africa	68 460	4	1	40	3.7
Aral	45.0	Asia	64 100^{a}	25	53	16	2.6
Huron	45.0	N. America	59 500	2	177	59	5.9
Michigan	44.0	N. America	57 750	2	177	85	3.1
Tanganyika	−6.0	Africa	32 900	8	774	574	3.0
Baikal	54.0	Asia	31 500	21	456	730	3.5
Great Bear	66.0	N. America	31 326	5	156	76	4.3
Great Slave	61.8	N. America	28 568	34	156	73	3.7
Erie	42.2	N. America	25 657	2	171	19	2.4
Winnipeg	52.5	N. America	24 387	40	217	14	2.5
Nyasa	−12.0	Africa	22 490	3	475	273	2.8
Ontario	43.7	N. America	19 000	4	75	86	2.4
Balkhash	46.0	Asia	18 200^{a}	10	343	6	5.0
Ladoga	61.0	Europe	17 700		4	52	2.0
Chad	13.3	Africa	16 600^{a}	151	240	3	2.2
Maracaibo	9.7	S. America	13 010	7	0	22	1.5
Patos	−31.1	S. America	10 140		0	2	2.7
Onega	61.5	Europe	9700		33	30	3.3
Rudolf	3.5	Africa	8660		427	29	1.6
Nicaragua	11.5	N. America	8150		32	13	2.4
Titicaca	−15.8	S. America	8030	8	3809	103	3.5
Athabasca	59.2	N. America	7935	20	213	26	2.8
Eyre	−28.5	Oceania	7690^{a}	146	−12	3	4.5
Reindeer	57.3	N. America	6640	10	337	17	5.3
Issykkul	42.4	Asia	6240		1608	277	2.7
Tungting	29.3	Asia	6000^{a}		11	3	1.5
Urmia	37.7	Asia	5800^{a}	9	1275	8	1.8
Torrens	−31.0	Oceania	5780^{a}	12	30	<1	2.7
Vanern	58.9	Europe	5648	8	44	27	7.3
Albert	1.7	Africa	5590		617	27	1.8
Netilling	66.5	N. America	5530		30		3.8
Winnipegosis	52.6	N. America	5375		3	3	3.7
Bangweulu	−11.1	Africa	4920^{a}	20	1140	1	2.0
Nipigon	49.8	N. America	4848		320	63	2.9
Gairdner	−31.6	Oceania	4770^{a}	2	34	<1	2.3
Manitoba	50.9	N. America	4625		248	3	3.4
Taymyr	74.5	Asia	4560^{a}		3	3	3.7
Koko	37.0	Asia	4460		3197	14	1.5
Kyoga	1.5	Africa	4430		1036	6	7.5
Saimaa	61.3	Europe	4380	14	76	14	63.3
Great Salt	41.2	N. America	4360	12	1280	4	2.1
Mweru	−9.0	Africa	4350		922	7	1.5
Woods	49.3	N. America	4350		323	8	4.9
Peipus	57.3	Europe	4300	11	30	6	2.0
Khanka	45.0	Asia	4190^{a}		69	5	1.5
Dubawnt	63.1	N. America	3833		236		3.5
Mirim	−32.8	S. America	3750	17	1	5	2.7
Van	38.6	Asia	3740	4	1646	55	2.3
Tana	12.2	Africa	3600		1811		1.5
Poyang	29.0	Asia	3350		10	8	6.4
Uvs	50.3	Asia	3350		759	1	1.6
Amadjuak	64.9	N. America	3115		113		3.5
Lop	40.5	Asia	3100		768	2	5.4
Melville	53.8	N. America	3069		0	97	2.7
Rukwa	−8.0	Africa	2716^{a}	28	793	<1	1.9
Hungtze	33.3	Asia	2700		15		1.9
Wollaston	58.2	N. America	2690	9	398	17	5.6
Alakol	46.2	Asia	2650		347	22	1.8

Continued

Table 1 Continued

Name	*Latitude*	*Continent*	*Lake area (km^2)*	*WA:LA*	*Elev. (m)*	*Z_{mean} (m)*	*Dev. ratio*
Hovsgol	51.0	Asia	2620		1624	183	2.1
Iliamna	59.5	N. America	2590		15	123	2.2
Chany	54.8	Asia	2500		105	2	4.1
Nam	30.8	Asia	2500		4627		1.6
Sap	13.0	Asia	2450^a	33	1	4	2.2
From	−30.7	Oceania	2410	35	49	<1	1.5
Kivu	−2.0	Africa	2370		1460	240	3.3
Mistassini	50.9	N. America	2335	8	372	75	4.5
Mai-Ndombe	−2.0	Africa	2325^a		340	5	2.6
Nueltin	60.2	N. America	2279		278		2.5
South Indian	57.1	N. America	2247		254	7	5.7
Buenos Aires	−46.5	S. America	2240		217		1.6
Tai	31.3	Asia	2210		3	2	2.2
Edward	−0.4	Africa	2150		912	35	1.7
Ilmen	58.3	Europe	2100^a	28	18	6	1.5
Helmand	31.0	Asia	2080^a	168	510	4	2.9
Michikamu	54.1	N. America	2030		460	33	3.9

A superscripted ‘a’ indicates that a lake’s area is variable in time and that the area may be nominal. WA:LA is the ratio of watershed to lake area, ‘Elev.’ Is the elevation of the lake above mean sea level, Z_{mean} is the average depth, and ‘Dev. ratio’ is the shoreline development ratio (high numbers mean less circular). Latitudes are expressed in decimal degrees with latitudes in the southern hemisphere expressed as negative numbers. Data are after Herdendorf’s work.

Large lakes have a remarkable range of depths (Table 2), owing to regional hypsometry and the diverse geologic age and composition of their watersheds. The world’s deepest lake is Lake Baikal in southern Siberia, which has a maximum depth of >1700 m. With Lake Tanganyika and the Caspian Sea, it is one of three lakes with a maximum depth >1000 m. In contrast, Lake Patos, a floodplain lake in Brazil the size of which is about 30% of the surface area of Lake Baikal, has a maximum depth of only about 5 m. Shallow lakes often are subject to extreme fluctuations in area owing to flooding or drying during periods of climatic variation. Despite the likelihood that the largest lakes might be expected to cover the greatest range of topography, there is only a weak general relationship between lake size and maximum depth in lakes larger than about 400 km^2 (Figure 2). For lakes >5000 km^2, however, there is a relationship between the minimum size of maximum depth observed in a size class of lakes and their areas. This relationship tells us that very large contiguous areas of the Earth’s surface are unlikely to lack some level of significant relief.

The main problem with analyses of lake size distributions performed prior to the current decade is that small water bodies have been omitted from, or are poorly represented on, many maps. Therefore, the resolution of maps has dictated the perceived relative abundance of small lakes. This can be illustrated using modern satellite imagery by comparing the three panels of Figure 3, all with the same geographic center, but shown at three levels of spatial resolution. In the top panel, we perceive only the largest of the lakes (the North American Great Lakes and a few others). At intermediate resolution, perhaps similar to the resolution seen on maps in the early part of the twentieth century, we see large lakes and many of intermediate size. In the bottom panel, which still has inferior resolution to modern GIS coverages, a myriad of water bodies appear. These likely equal or exceed the area of larger lakes when summed over great land areas. In fact, if one assumes that some random process created pits and bumps in landscapes that were then filled with water, the aspect of lake regions and the size distribution of lakes is very similar to that observed in high-resolution satellite images (Figure 4). Therefore, analyses of limnicity based on maps drew faulty conclusions about the amount of land surface covered by lakes and ponds, as well as the relative areal importance of small and large lakes.

Modern Analyses of Limnicity and Lake Size Distribution

Nearly concurrently, Lehner and Döll and an international team of scientists working with Downing at the US National Center for Ecological Analysis and Synthesis applied modern GIS methods and updated geographic imagery to updating inventories of world lakes. These two efforts used divergent approaches but both had the objective of using new technologies to provide a more accurate estimate of the global

Table 2 Some of the world's large lakes that are of great depth, arranged in decreasing order of maximum depth

Name	*Latitude*	*Continent*	Z_{max} *(m)*	Z_{mean} *(m)*	*Lake area (km^2)*
Baikal	54.0	Asia	1741	730	31 500
Tanganyika	−6.0	Africa	1471	574	32 900
Caspian	42.0	Asia	1025	209	374 000
Nyasa	−12.0	Africa	706	273	22 490
Issykkul	42.4	Asia	702	277	6240
Great Slave	61.8	N. America	625	73	28 568
Toba	2.6	Asia	529	249	1150
Tahoe	39.1	N. America	501	249	500
Kivu	−2.0	Africa	480	240	2370
Great Bear	66.0	N. America	452	76	31 326
Fagnano	−54.6	S. America	449	211	590
Nahuel Huapi	−41.0	S. America	438	206	550
Dead	31.5	Asia	433	184	1020
Superior	47.6	N. America	407	149	82 100
Llanquihue	−41.1	S. America	350	133	800
Geneva	46.4	Europe	310	153	580
Titicaca	−15.8	S. America	304	103	8030
Aregentino	−50.2	S. America	300	120	1410
Iliamna	59.5	N. America	299	123	2590
Atlin	59.5	N. America	283	86	774
Michigan	44.0	N. America	282	85	57 750
Hovsgol	51.0	Asia	270	183	2620
Melville	53.8	N. America	256	97	3069
Constance	47.6	Europe	252	90	540
Ontario	43.7	N. America	245	86	19 000
Ladoga	61.0	Europe	230	52	17 700
Baker	64.2	N. America	230	93	1887
Huron	45.0	N. America	229	59	59 500
Reindeer	57.3	N. America	219	17	6640
Mistassini	50.9	N. America	183	75	2335
San Martin	−48.9	S. America	170	68	1010
Nipigon	49.8	N. America	165	63	4848
Taupo	−38.8	Oceania	165	97	616
Van	38.6	Asia	145	55	3740
Vattern	58.4	Europe	128	40	1856
Onega	61.5	Europe	127	30	9700
Champlain	44.6	N. America	122	49	1100
Athabasca	59.2	N. America	120	26	7935
Edward	−0.4	Africa	117	35	2150
Flathead	47.9	N. America	113	50	500
Sakami	53.3	N. America	110	52	592
Grand	48.9	N. America	110	52	537
Vanern	58.9	Europe	106	27	5648
Biwa	35.3	Asia	103	41	688
Pyramid	40.0	N. America	101	54	510[a]

A superscripted 'a' indicates that a lake's area is variable in time and that the area may be nominal. Z_{max} is the maximum depth and Z_{mean} is the average depth. Latitudes are expressed in decimal degrees with latitudes in the southern hemisphere expressed as negative numbers. Data are after Herdendorf's publications.

extent and distribution of lakes and other water bodies.

The approach used by Lehner and Döll was to combine many data sources to create a global database of lakes and wetlands. This database was created by combining data sources, registers, and inventories focusing on descriptive attributes with analog or digital maps that show the spatial extent and locations of lakes and impoundments. This important step replaced the >13 published, list-based attribute tables with a GIS approach, which allows evaluation of area, shape, and location of lakes and impoundments. These two data sources allow some historical perspective, as well, since modern sources such as satellite images may not include long-term variations that can only be derived using local information. For example, the Aral Sea has decreased in area to less than 30% of its former area. Although the database was compiled to represent lakes $\geq 0.1\,\text{km}^2$ in area, Lehner and Döll judged that even high-resolution

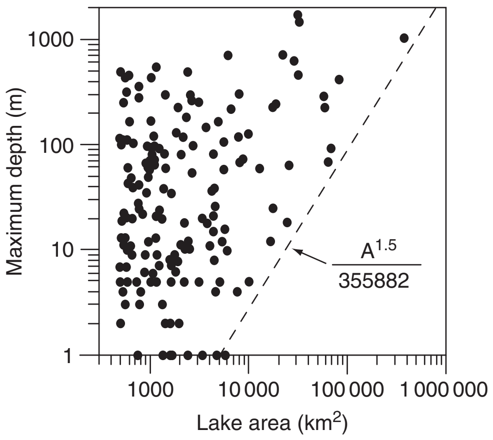

Figure 2 Relationship between lake area and maximum depth taken from data compiled and published by Herdendorf. The dashed line is an empirically derived lower limit to maximum depth (m) for lakes larger than 5000 km^2, where A is the lake area in km^2.

satellite imagery under-samples lakes <1 km^2. Therefore, this approach did not effectively inventory lakes smaller than about 100 ha in surface area but offered the most substantial advance in the inventory of world lakes since Halbfass's compilation of 1914.

Lehner and Döll confirmed previous estimates of both the size distribution (as area) of moderate-to-large lakes as well as the surface area of the Earth they occupy. They showed quantitatively that the number of lakes in a size category increases as a power function of decreasing area. They showed, for example, that although there are 10^5 lakes >1 km^2, there are only about 100 lakes >1000 km^2 in area. They also confirmed the previous estimates of the global area covered by moderate-to-large lakes as being near to 2.5 million km^2. More importantly, however, their use of GIS and satellite imagery allows a greatly improved understanding of how global lake area is distributed geographically (Figure 5) and how lake area is distributed compared with that occupied by rivers and impoundments. In this analysis, rivers were distinguished from lakes and impoundments based on their development ratio so that very long and narrow water bodies were called 'rivers'. Further, this analysis includes only medium-to-large lakes and likely includes only the largest of rivers (i.e., with a breadth of 100 m or more; Strahler order >5). The distribution of lake area is strongly skewed toward the north temperate zone (35–70° N) with a small increase also near the equator (Figure 5). This is consistent with what is known about the distribution of large lakes (North American Great Lakes and the Caspian Sea), the balance of precipitation and evaporation, and agrees well with satellite scans of open water (except where large numbers of small lakes could not be inventoried). This analysis suggested that lakes make up about 1.8% of the land area (2 428 000 km^2), impoundments about 0.2% (251 000 km^2), and rivers about 0.3% (360 000 km^2).

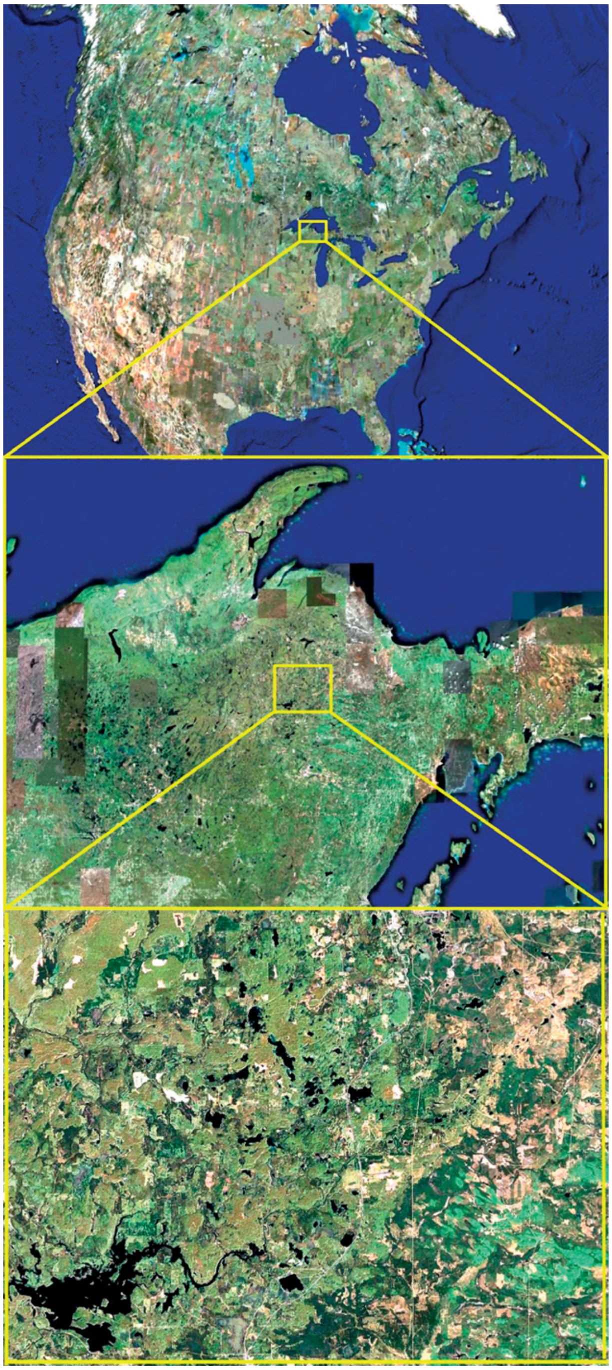

Figure 3 Illustration of the influence of scale of observation on the perceived size distribution of lakes. Source: earth.google.com. The images are centered on the same point but have improved spatial resolution from top to bottom.

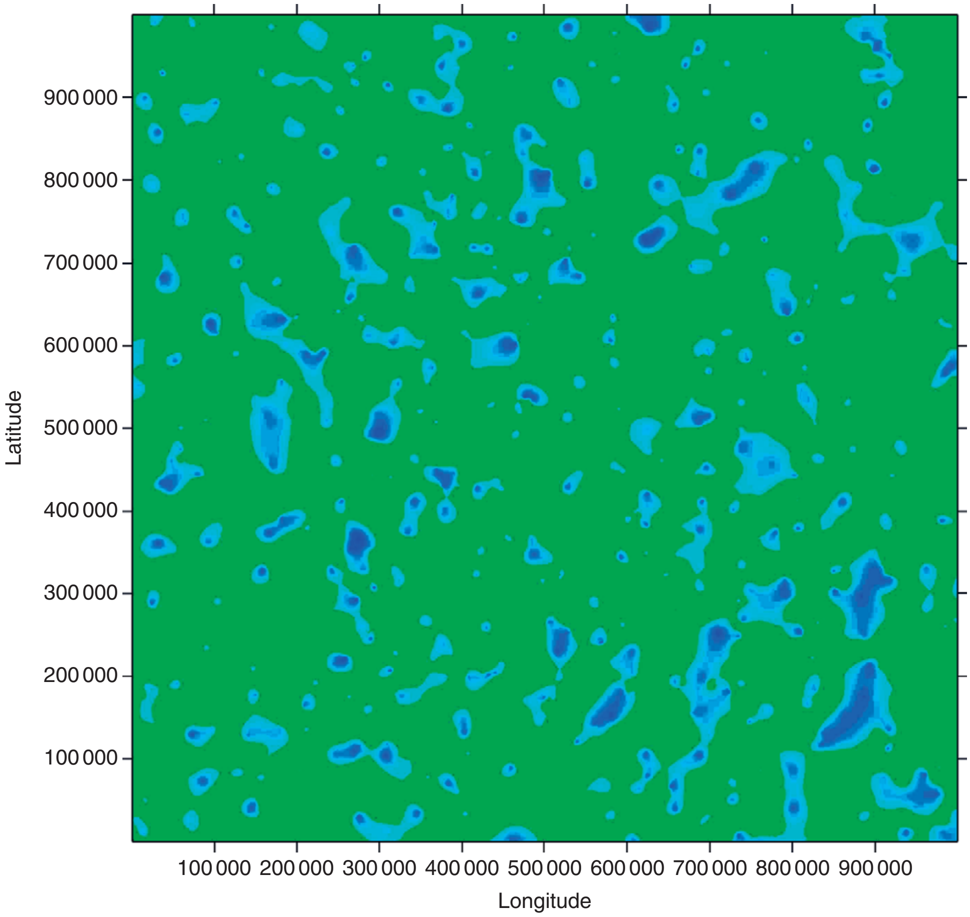

Figure 4 A simulated lake region generated using a random number generator in Microsoft Excel™ to determine 2000 positions of pits and bumps in a $10^6 \times 10^6$ land-unit area. Pit or bump height was determined using the same random number generator to create relief features with an elevation of 0–100 units. The topography of the land surface was created using kriging and the lake shores were arbitrarily set at 27 units of elevation.

The perennial problem in lake inventories has been that small water bodies have gone un-inventoried. This has been assumed, somewhat tautologically, to be of little consequence because small water bodies have been found to be numerically dominant but inconsequential in terms of the area of land surface they cover. On the one hand, as shown by Lehner and Döll, no worldwide GIS coverage exists that has high enough spatial resolution to resolve all of the world's small lakes. On the other hand, we have long-standing information on the size distribution of the world's lakes down to a size of 1–10 km^2 as well as high-resolution GIS coverage on many regions that can be used to examine and characterize the size distribution of lakes down to the smallest sizes.

Downing and coworkers improved estimates of lake abundance and area by working on the small-lake under-sampling problem. They estimated the world abundance of natural lakes by characterizing the size distribution using a nearly universally applicable distribution function, testing its fit to data down to the smallest sizes of lakes, anchoring it in empirical data for large lakes, and solving the distribution function to calculate the world abundance of large and small lakes.

Because the relationship between d_L and lake area (A) in Figure 1 appears to fit a power function, Downing and coworkers and Lehner and Döll suggested that lake-size distributions fit a size–frequency function of the form:

$$N_{a \geq A} = \alpha A^{\beta} \qquad [1]$$

where $N_{a \geq A}$is the number of lakes of great or equal area (a) than a threshold area (A), and α and β are fitted parameters describing the total number of lakes in the dataset that would be of one unit area in size and the logarithmic rate of decline in number of lakes with lake area, respectively. This model corresponds to a Pareto distribution that is particularly versatile and used in fields from linguistics to engineering.

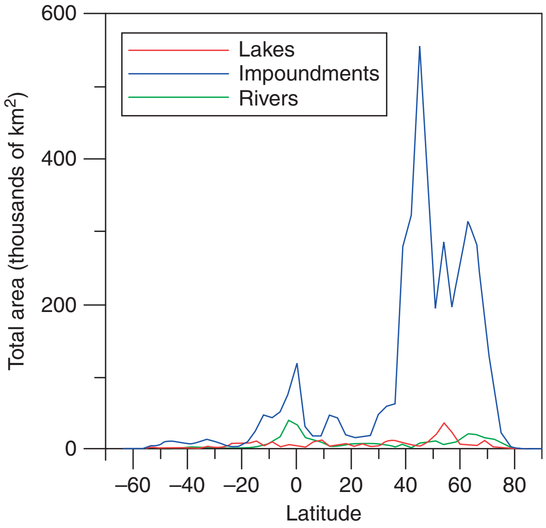

Figure 5 Measured latitudinal distribution of area of lakes, impoundments, and streams redrawn from Lehner and Döll's Figure 3. Areas of water bodies are summed over 3° increments of latitude. Lake areas are corrected following the work of Downing and coworkers by assuming that previous underestimates of lake areas have been distributed evenly across all latitudes. Areas of impoundments are likely to be correct but river areas are probably underestimated.

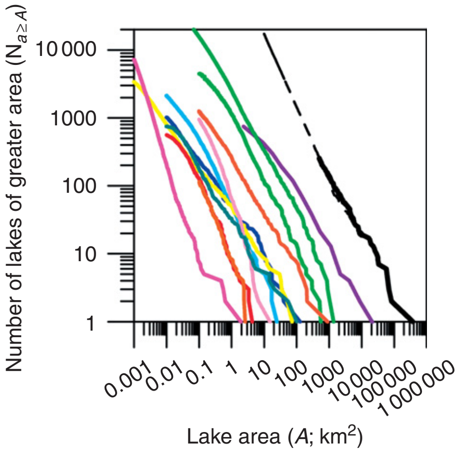

Figure 6 Plots of data on the axes implied by eqn. [1]. Colored lines are high resolution GIS analyses of geographically dissimilar regions. The black lines represent canonical (complete) censuses of world lakes taken from publications by Herdendorf and by Lehner and Döll. This figure is redrawn from a publication by Downing and coworkers.

It has also been found useful in describing lakes' size–frequency distributions, as long as the data are not truncated or censored.

To test lake size distributions for general fit to the Pareto distribution, Downing and coworkers collected exhaustive inventories of all lakes within a variety of geographical settings representing divergent topography and geology. Figure 6 shows that there are interregional similarities among slopes of Pareto curves. These curves show similar rates of decline in abundance with lake size among many regions of the Earth.

Because the size–frequency distributions of lakes follow a Pareto distribution in many regions down to very small lake sizes (Figure 6), exhaustively censused (canonical) data on the abundance of the world's largest lakes allows eqn. [1] to be anchored at the upper end to permit estimation of the world-wide abundance of lakes across the full range of lake sizes. Two collections of exhaustively censused lakes are shown plotted on Figure 6. Considering only the 17 357 natural lakes >10 km^2 in area, eqn. [1] can be fitted by least squares regression as

$$N_{a \geq A} = 195560 A^{-1.06079},\ r^2 = 0.998;\quad n = 17357;\ \mathrm{SE}_\beta = 0.0003 \qquad [2]$$

Since the shape of Pareto distributions is similar among diverse regions of the Earth (Figure 6) and the parameters of this distribution are estimatable from the canonical data sets, Downing and coworkers provided a means of estimating the global extent of ponds and lakes down to very small sizes.

Analyses of lake-size distributions based on the Pareto distribution (Table 3) reveal that, contrary to others' predictions, small lakes represent a greater lacustrine area than do large ones. The large lakes ≥10 000 km^2 in individual lake area make up only about 25% of the world's lake area. Together, the two smallest size categories of lakes in Table 3 make up more area than the three top size categories. Thus, undercounting small lakes has resulted in the significant underestimation of the world's lake and pond area over the last century. World lakes and ponds account for roughly 4.2×10^6 km^2 of the land area of the Earth. This is more than double the historical estimates. Natural lakes and ponds ≥0.001 km^2 make up roughly 2.8% of the non-oceanic land area; not 1.3–1.8% as assumed since the early 1900s.

Impoundments

Parallel with the analysis of natural lakes above, one can fit the Pareto distribution to the sizes of large impoundments. Downing and coworkers did this using data from the International Commission on Large Dams who publish data on dams around the world that are of safety, engineering or resource concern (e.g., Figure 7). These data are purposefully biased toward large dams so the data provide the

Table 3 The frequency of lakes and impoundments of different sizes worldwide, estimated following Downing and coworkers' method employing the Pareto distribution

Area range (km^2)	*Number of lakes*	*Total area of lakes (km^2)*	*Number of impoundments*	*Total area of impoundments (km^2)*
0.001–0.01	277 400 000	692 600	76 830 000^a	76 830^b
0.01–0.1	24 120 000	602 100	444 800	12 040
0.1–1	2 097 000	523 400	60 740	16 430
1–10	182 300	455 100	8 295	22 440
10–100	15 905	392 362	1 133	30 640
100–1000	1 330	329 816	157	41 850
1000–10000	105	257 856	21	57 140
10000–100000	16	607 650	3	78 030
>100000	1	378 119		
All water bodies	304 000 000	4 200 000	77 345 000	335 400
Percent of land area	2.80%		0.22%	

Superscript 'a' indicates that the calculation was based on an average farm pond size of 0.001 km^2. 'b' indicates an estimate of the global area of farm ponds.

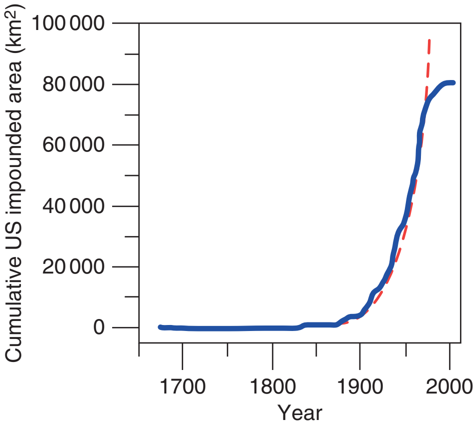

Figure 7 Rate of change in impounded area in the United States for all impoundments listed by the United States Army Corps of Engineers with dams listed as potential hazards, or low hazard dams that are either taller than 8 m, impounding at least 18 500 m^3, or taller than 2 m, impounding at least 61 675 m^3 of water (after Downing and coworkers). 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 ($r^2 = 0.95$) based on the exponential phase of impoundment construction.

most accurate estimate of impoundments with the largest impounded areas, and progressively less complete coverage of small ones. Fitting eqn. [1] to data on the 41 largest impoundments from the largest impoundment (13 500 km^2) down to 1000 km^2 yields:

$$N_{a \geq A} = 2922123A^{-1.4919}, r^2 = 0.97, n = 41 \quad [3]$$

This equation implies that the smallest of the large impoundments make up more surface area than the largest of them because the exponent is strongly negative. This dataset is intentionally biased to large dams so the exponent increases if small impoundments are included. If one considers all of the ICOLD impoundments down to 1 km^2, the result will be biased toward underestimation of impoundment area, but is

$$N_{a \geq A} = 20107A^{-0.8647}, r^2 = 0.97, n = 9604 \quad [4]$$

This equation results in an underestimate of the area covered by impoundments because it ignores many impoundments formed by small dams. Calculations using this function and the Pareto distribution, however, show that there are at least 0.5 million impoundments ≥ 0.01 km^2 in the world and they cover >0.25 million km^2 of the Earth's land surface (Table 3). This calculation using the Pareto distribution yields a smaller area than estimates based on extrapolation but nearly identical to GIS-based estimates. Large impoundment data suggest that small impoundments cover less area than large ones (Table 3).

Most analyses of impoundment size distributions have ignored small, low-tech impoundments created using small-scale technologies. Farm and agricultural ponds are growing in abundance, world-wide, and are built as sources of water for livestock, irrigation, fish culture, recreation, sedimentation, and water quality control.

Figure 8 shows that the area of water impounded by agricultural ponds in several political units expressed as a fraction of farm land varies systematically with climate. In dry regions, farm ponds are rare, but up to about 1600 mm of annual precipitation, farm ponds are a rapidly increasing fraction of the agricultural landscape. In moist climates, farm ponds make up 3–4% of agricultural land. Downing and coworkers used this relationship (Figure 8) with data on area under farming practice, pond size, and estimates of annual average precipitation to estimate the global area covered by farm pond impoundments.

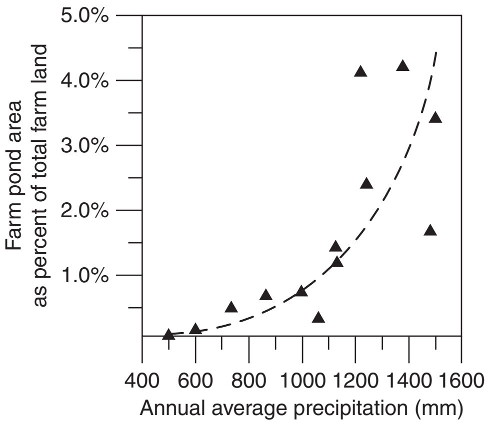

Figure 8 Relationship between the surface area of farm ponds and the annual average precipitation in several political units (after Downing and coworkers). The line is a least squares regression ($r^2 = 0.80$, $n = 13$) where the area of farm ponds expressed as a percentage of the area of farm land (FP) rises with annual average precipitation (P; mm) as $\text{FP} = 0.019\,\text{e}^{0.0036P}$.

They found that 76 830 km^2, worldwide, is covered with farm ponds. These small impoundments are growing in importance at annual rates of from 0.7% per year in Great Britain, to 1–2% per year in the agricultural parts of the United States, to >60% per year in dry agricultural regions of India.

Conclusions

Although data have been available on the world's largest and most spectacular lakes since the early 1900s, global estimates of the abundance and size distribution have underestimated the abundance and area of small natural lakes. When appropriate GIS methods and mathematical models are used, the area of land surface covered by lakes has been found to be 2.8% of the terrestrial surface area of the Earth, nearly double some historical estimates. There are 304 million natural lakes in the world that cover 4.2 million km^2. More than 207 million lakes are <0.01 km^2 in individual area and the area covered by lakes of different sizes is greater for small lake size-classes than for large ones. Inventories of natural lakes consider only lakes with permanent open water, including lakes, ponds, and bogs, but other systems, including flood lakes, temporary water bodies, and wetlands, would add substantially to the area occupied by continental aquatic systems. The land area covered by constructed lakes and impoundments is smaller than that of natural lakes but 77 million world impoundments cover 335 000 km^2 or about 0.22% of the land surface. The area covered by small, low-tech farm ponds is about the same as that covered by the world's three largest impoundments. Impoundment area is generally underestimated, however, by poor availability of data on small and moderately sized basins and the number of such low-tech structures is increasing rapidly where agricultural needs are great.

See also: Aesthetic Values of Lakes and Rivers; Aquatic Ecosystem Services; Ecology of Wetlands; Geomorphology of Lake Basins; Mixing Dynamics in Lakes Across Climatic Zones; Origins of Types of Lake Basins; Streams.

Further Reading

Dean WE and Gorham E (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology* 26: 535–538.

Downing JA, *et al.* (2006) The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography* 51: 2388–2397.

Hamilton SK, Melack JM, Goodchild MF, and Lewis WM Jr. (1992) Estimation of the fractal dimension of terrain from lake size distributions. In: Petts GE and Carling PA (eds.) *Lowland Floodplain Rivers: A Geomorphological Perspective*, pp. 145–164. John Wiley.

Herdendorf CE (1984) *Inventory of the Morphopmetric and Limnologic Characteristics of the Large Lakes of the World. Technical Bulletin*, pp. 1–54. The Ohio State University Sea Grant Program.

Kalff J (2001) *Limnology: Inland Water Ecosystems*. Prentice Hall.

Lehner B and Döll P (2004) Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* 296: 1–22.

Meybeck M (1995) Global distribution of lakes. In: Lerman A, Imboden DM, and Gat JR (eds.) *Physics and Chemistry of Lakes*, pp. 1–35. Springer-Verlag.

Schuiling RD (1977) Source and composition of lake sediments. In: Golterman HL (ed.) *Interaction Between Sediments and Fresh Water*, pp. 12–18. Dr. W. Junk B.V. Proceedings of an international symposium held at Amsterdam, the Netherlands, September 6–10, 1976.

Shiklomanov IA and Rodda JC (2003) *World Water Resources at the Beginning of the Twenty-First Century.* Cambridge University Press.

Smith SV, Renwick WH, Bartley JD, and Buddemeier RW (2002) Distribution and significance of small, artificial water bodies across the United States landscape. *Science of the Total Environment* 299: 21–36.

St. Louis VL, Kelly CA, Duchemin E, Rudd JW, and Rosenberg DM (2000) Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. *BioScience* 50: 766–775.

Tilzer MM and Serruya C (eds.) (1990) *Large Lakes: Ecological Structure and Function*. Springer-Verlag.

Wetzel RW (1990) Land-water interfaces: Metabolic and limnological regulators. *Verhandlungen der Internationale Vereinigung der Limnologie* 24: 6–24.

Wetzel RW (2001) *Limnology: Lake and River Ecosystems*. Academic Press.