Geomorphology of Lake Basins

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Introduction

Mapping is basic human activity, born in antiquity and developed today to embrace complex, multilayered geographic information systems. Maps of lakes are of more intrinsic value than terrestrial maps, because they show features below the water surface the eye cannot see. Moreover, they can be used to compute various parameters of value in understanding the structure and functioning of lakes. This chapter is devoted to explaining these parameters and to expand upon the role of lake geomorphology in limnology.

Morphometric Parameters

In the past, mapping lakes was a laborious task. Lake shorelines had to be established by such methods as transverse, stadia or plane table surveys, all time consuming, and spot depths by lead lines at fixed positions. Today, outlines of shores are easily obtained from aerial or satellite images and depth profiling done by echosounders. Exceptions include shallow ephemeral lakes, like many in Australia, which are best mapped when dry using modern terrestrial surveying equipment. Once, the basic data had to be processed by hand to produce a map, but nowadays almost all stages can be computerized. In all cases scale is important, the finer the scale, the more accurate the map. The parameters derived from these maps can be divided into those taken directly or indirectly from the map and those that are derived by computation from the primary parameters.

(a) Primary Parameters

(i) *Lake length*. This is the length of the line connecting the two most remote points on the shoreline. It should not cross land (so in an oxbow lake the line is curved), but it may cross islands. Such measurements are of intrinsic geomorphic value only. Of more use limnologically is the *maximum effective length*, which is defined by the longest straight line over water on which wind and waves can act. While the two values are similar in large deep lakes like Africa's Lake Victoria, in island-studded lakes like Sweden's L. Vänern, the maximum effective length is 69% of the maximum length. Knowledge of this parameter is important in geomorphic studies on shorelines and in studies on seiches and stratification in physical limnology.

(ii) *Lake width* is defined by a straight line at right angles to the maximum length and connecting the two most remote shorelines. Again, of more value is the maximum effective width, which does not cross land. This, and the mean width are of use mainly in hydromechanical studies.

(iii) *Lake depth* is the maximum known depth of a lake, and is the single most important geomorphic parameter of a lake. The world's deepest lake is Lake Baikal in Siberia (1620 m deep) and many large glacial, volcanic, and tectonic lakes exceed 200 m in depth. By contrast, most lakes on flood plains or formed by wind are shallow, rarely exceeding 5 m in depth. The limnological consequences of this are paramount and discussed later. *Mean depth* (lake volume/lake area) is also worth noting and has been used many times to explain varying productivities between lakes (e.g., the deeper the lake the less productive it is). Of the various other depth-related parameters, *relative depth*, which is the ratio of the maximum depth to the mean diameter of the lake, is useful in explaining stability of stratification in lakes. For large shallow lakes like the wind-stirred Lake Corangamite in Victoria, Australia, the value is 0.09%, while the nearby meromictic West Basin Lake in a volcanic crater, the relative depth is 3.0%.

(iv) *Direction of major axis*. It is important to know this in geomorphic and hydrodynamic studies as lakes may be aligned to dominant wind direction and hence be more subject to wind than others. For instance, in the eastern inland Australia, only those lakes with an axis near N-S grow spits under the influence of winds from the NW that close off the southeast corner (see later).

(v) *Shoreline length* is easy enough to measure by a map measurer, but is very much influenced by map scale. It is used to calculate shoreline development, a parameter used in littoral studies.

(vi) *Lake area*, once determined by planimetry, but now easily done with a computer, and hardly affected by map scale, is another of the most basic lake parameters. The world's largest lakes are of tectonic and of glacial erosion origin. At the individual country scale, lakes are often listed by area with an explanation for any pattern based on geomorphic distinctiveness of the district/mode of origin. For instance in New Zealand, geology and climate explain the dominance of large piedmont glacial lakes on the South Island, and many somewhat smaller volcanic lakes on the North Island. If the area occupied by a lake fluctuates (because it is terminal or used for water supply) then it is useful to know the area at any depth and this is visualized in a *hypsographic curve* (Figure 1(a, c)).

(vii) *Lake volume* is calculated from summing the volumes between each contour, though for increased accuracy different formulae are used according to lake form. This is another parameter often quoted for lakes, particularly if they are large. Most impressive in this instance is Lake Baikal's massive volume of 23 000 km^3, representing one-fifth of the world's fresh water. Visualization of volume at any depth, particularly useful in lakes and reservoirs that fluctuate in depth, is achieved by a *volume/depth curve* (Figure 1(b, d)). In this respect, volume percentages derived from cumulative curves for reservoirs are widely quoted in the media in dry countries like Australia, where water reserves are precarious and precious.

(viii) *Insulosity* is the percentage of the lake area occupied by islands. Though some lakes have minor islands, like subsidiary cones in crater lakes, their insulosity values are of no consequence. It is mainly in glacial ice scour lakes and other lakes with highly irregular shorelines where there are many islands that this parameter exceeds ca. 10% and assumes importance. While its worth is intrinsically geomorphic, it is sometimes equated to the value of a lake for recreation, where humans

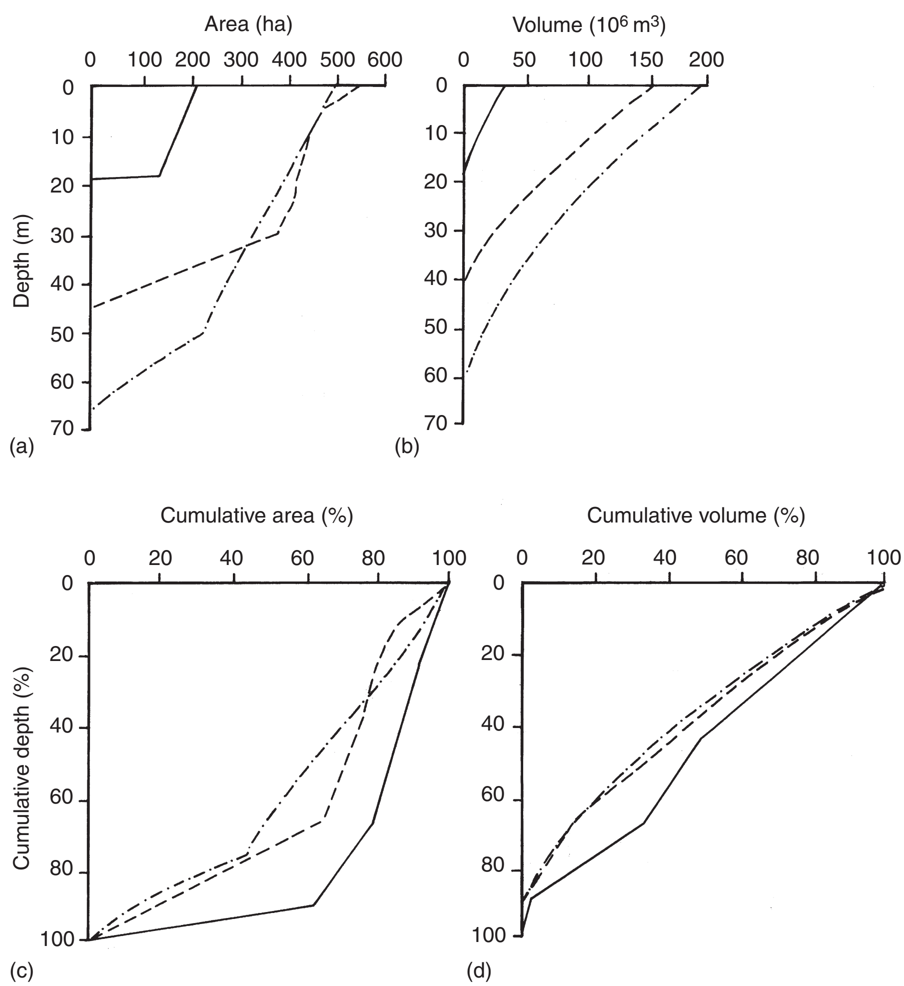

Figure 1 Absolute hypsographic (a) and volume curves (b), and relative hypsographic (c) and volume curves (d) for three maar lakes in Victoria, Australia.

require high shoreline–waterway interaction, as in Swedish lakes Vänern and Mälaren. On the other hand, sailors and waterskiers require open water for their recreation activities, so small, lakes without islands are favored. Thus, there is no relationship between insulosity and recreational use of a lake!

(ix) *Watershed to lake area/volume*. This is easy to calculate from maps and is used as an estimate of terrestrial inputs as in eutrophication studies and also as water renewal ratios for some in-lake processes.

(b) Common Derived Parameters

(i) *Shoreline development* (D_s) is a measure of the irregularity of the shoreline; its accuracy is dependent on map scale. Essentially, it is the ratio of the length of the shoreline to the length of the circumference of a circle of area equal to that of the lake. It is an index of the potential importance of littoral influences on a lake. Perfectly circular lakes have a D_s of 1.0, average lakes have values between 1.5 and 2.5, while lakes and reservoirs with much indented shorelines have values exceeding 3 (Figure 2). Expressed in relation to lake types, volcanic vent lakes have minimal D_ss, and lakes in dammed valleys and in ice-scoured terrain have the highest values.

(ii) *Volume development*. This index (D_v) is used to express the form of a basin, and is defined as the ratio of the volume of a lake to that of a cone of basal area equal to the area of the lake and depth equal to the maximum depth of the lake. Lakes with a D_v of 1.0 are perfectly cone-shaped and uncommon. Values <1.0 indicate a trumpted-shaped lake and are rare and values >ca. 2.5 indicate a beaker-shaped lake and are also uncommon (Figure 2). Most lakes have values somewhat greater than unity. The unusual values may be related to lake type, e.g., doline lakes usually have D_vs near 1 and claypans and maar lakes may have D_vs near 3, but sometimes D_vs may be the result of peat growth/marl deposition/shoreline slumping/erosion in the littoral, leading to values near 1. In all cases the index is a surrogate for the role of the sublittoral in a lake's limnological processes, the lower the value the greater the sublittoral influence.

(iii) *Slope* is the angle, usually expressed as a percentage of repose of the bottom sediments and can be determined directly from an echogram or from a contour map using appropriate measurements and formulae. Slopes of near 0% (profundal areas) to 20% (sublittoral slopes) are common, but occasionally values approach the maximum of 90% in a steep-shored crater, glacial erosion and lakes due to earth movements. This parameter is used mainly in sedimentological studies and to lesser extent in benthic studies in choosing suitable stations. *Mean slope* is an average for a whole lake and is derived from a contour map and application of formulae. Not surprisingly, mean values are much more subdued than slopes at designated contours and commonly range from <1% to 10%, but may exceed 25% in some lakes, e.g., Lake Barrine, a small maar in north Queensland, Australia, has a mean slope of 30%. Perhaps in interlake comparisons, visual inspections of comparative hypsographic curves (Figure 1) are just as instructive as are figures for mean slope, and far less troublesome to prepare.

(iv) Sometimes a derived parameter can be established for a special need. For example *Ratio of epilimnion sediment area to epilimnion volume* has been used more effectively than parameters based on whole lake volume in eutrophication studies because it more accurately accounts for nutrient recycling in a lake.

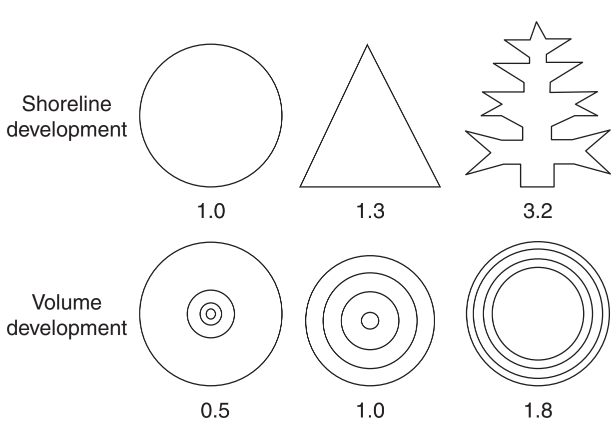

Figure 2 Graphical representation of shoreline development for three lakes of different shape, and of volume development for another three lakes of different volume distribution. In the latter, concentric lines represent depth contours.

Lake Shapes

Many lakes have characteristic shapes determined by their mode of origin that are only partly described by their parameters. The ratio of length over width can give information on whether a lake is rectangular, circular or ellipitical and high D_ss can indicate a dendritic lake, but a simple descriptive word is usually better. *Circular* lakes (D_s near 1) are uncommon, but can be found in volcanic vents, in some deflation basins and in lakes due to meteoric impact. *Subcircular* lakes are more common and are associated with a variety of origins: volcanic craters, deflation basins, dolines, cirques, kettle-holes to name the more common ones. *Ellipitical* lakes are a special subgroup of these and are generally associated with wind deflation. *Subrectangular* elongate lakes generally are of structural origin or result for glacial erosion in valleys (piedmont lakes). Markedly *dendritic* lakes result from flooding of dissected valleys as in some coastal lagoons, some landside lakes and in many reservoirs. It is these in which D_s is high (>3). *Triangular* lakes also usually arise from flooding, usually either on floodplains or along coasts. These may be confused with circular lakes on length/width ratios, but not by their descriptor. *Lunate* (or new-moon shaped) lakes result from river meandering to form oxbows, and sometimes from asymmetrical placed subcones in volcanic craters. Highly *irregular* lakes are possible from the fusion of lake basins and in glacially scoured areas. These also may have high D_ss.

Changes with Time

Over geological time, lakes are temporary landscape features (but see later), filling with sediment and/or eroding at the outlet. Consequently lake morphometry changes with time, imperceptibly in well-watered areas, but at the other extreme, oscillating widely in terminal lakes in arid areas. The most obvious changes are lake level fluctuations and their concomittent shoreline changes. Sedimentation is less obvious, except for delta construction.

Lowered lake levels, of whatever cause, result in stranded beaches, spits and deltas. Worldwide, piedmont glacial lakes provide many examples, perhaps none better than New Zealand's Lake Wakatipu with its 10 strandlines cut into a major bench and deltaic fronts at 50 m above present lake level The terminal lakes of Tibet have numerous elevated shorelines attesting to a more fluvial past, as do most of the world's large lakes in endorheic regions. Interesting as these landforms may be, and useful in aging a lake, it is the changes with decreasing depth in physicochemical processes in the lake such as thermal and chemical stratification, that are important limnologically.

In some lakes, levels have been elevated since initial formation, drowning shoreline features and river channels. Coastal marine lagoons, tied to changing sea levels, provide many examples including Lake Macquarie near Sydney, Australia, where drowned river channels and spits are clearly discernable (Figure 3). As in lakes with lowered levels, raised levels may change physicochemical processes, and in addition, there may be hydrodynamic changes associated with changed inflows.

All lakes accumulate sediment, either mainly from stream inflows, or biological production in the lake itself, or occasionally from overland flows and rarely by showering ash from volcanic eruptions (as in lakes around Taupo and Rotorua in New Zealand). Rates

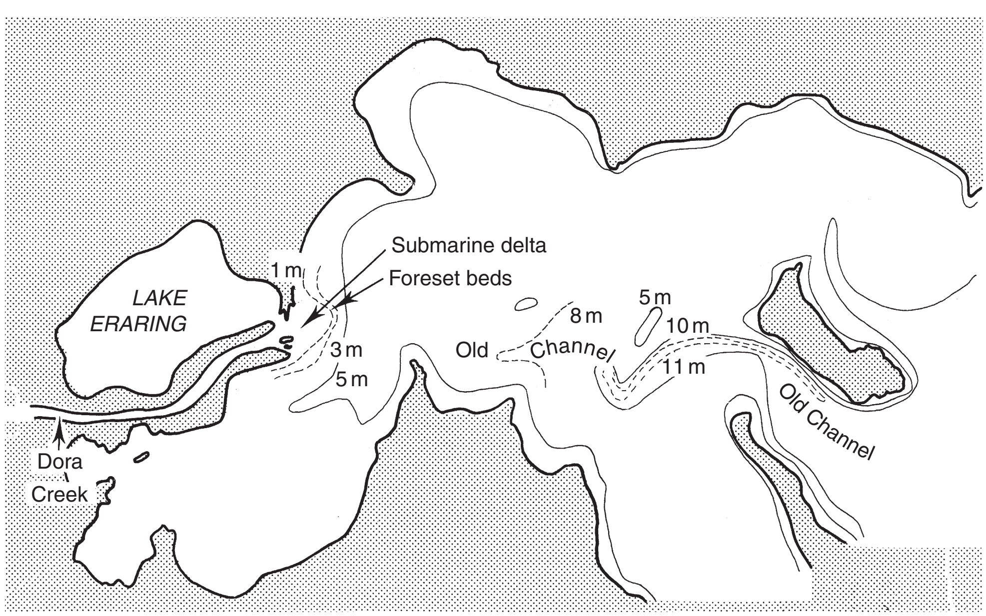

Figure 3 The western bay of Lake Macquarie, near Sydney, Australia, a drowned coastal valley, showing the former river course and a lobate delta.

are highly variable and depend on geomorphic type, catchment size and erodability, and trophic status (and proximity to a volcano!). The most rapid accumulation is by delta building in lakes with large inflows in mountainous areas. Well-known examples include the deltaic plain at the head of Lake Geneva and the surficial sediments that divide Thuner See and Brienzer See at Interlaken, both in Switzerland. Deltaic form depends on the relative densities of lake and river water and lake currents. Arcuate Gilbert deltas due to homopycnal flows are perhaps the most common type in piedmont glacial lakes, lobate deltas associated with hypopycnal inflows in coastal marine lagoons (Figure 3), and alluvial fans in shallow desert lakes. No matter the deltaic form, lake surface area and volume are reduced, but probably with minimal influence on limnological processes in large lakes.

On the other hand, lake floor sedimentation due to submarine delta building by hyperpycnal inflows (as in Lake Pukaki in New Zealand) and by chemical or biological deposition decrease lake depth and hence may influence physicochemical processes, particularly if the sediments of productive lakes consume oxygen during stratification. Rearrangement of bottom sediments due to slumping or bioturbidation are of little geomorphic consequence, but may upset layering and hence interpretations of lake/catchment history recorded in sediment cores.

Ancient Time plus Size

While differing geomorphology, as measured by the above parameters, influences lake ecology, there are many other factors involved, one of which is geological time. Most lakes exist for hundreds to thousands of years, perhaps even a few hundred thousand years, but some persist for many millions of years, and cognisance of this, together with their size (volume, perhaps area), allows greater understanding. Scale is indeed important in limnology.

By considering a new coefficient, Touchart divides lakes into four broad groups. He estimates the scale of a lake, by taking the logarithm of the product of the age (expressed in millennia) by its volume (in cubic kilometres). Lakes with values 4–8 are almost exclusively large old structural lakes such as Baikal, Caspian, Tanganyika (values of 8), Victoria (7), Issyl-Kul, Aral, Titicaca (6), Balkhash, Tahoe (5), and Biwa, Toba, Taupo (4), among others. Most of these are largely independent of morphoclimatic hazards and have high biological endemism. For instance in Lake Baikal there are 255 species of gammarid amphipods in 35 genera, 34 of which are endemic. New Zealand's Lake Taupo is an exception, going back perhaps only a million years, but subject to many catastrophic reincarnations as recent as 1800 years ago). Biodiversity is low as a consequence of this Recent age, and also it small size (623 km^2) and being on an isolated island.

The next group usually have values 1–4 and are medium sized, largely of morphoclimatic heritage, i.e., shaped largely by the Würm glaciation. Examples include, Lakes Superior, Great Bear (4), Ontario, Winnipeg (3), Constance, Geneva (2), Te Anau, Wakatipu (both NZ)(1) among a host of others. They are often large ($>10\,000\ km^2$) and deep (200–500 m), and formed by glacial erosion. Life expectancy is in the order of only thousands/tens of thousands of years. Biodiversity is lower and morphodynmaic processes (delta-building, sedimentation) in their basin are relative important in limnological processes. These are the lakes most common in the Temperate Zone of the Northern Hemisphere where limnology developed, so they are the 'standard' lakes of text books. To a large degree both of these classes of lakes are dominated by their shear size, so that morphometric parameters other than area and depth are generally unimportant in influencing limnological processes.

A third group of lakes are small (Touchart coefficients of 1 or less) and largely influenced by current morphodynamic processes or recently inherited ones. These include fluviatile lakes, karstic lakes, aeolian lakes, and landside lakes in the first subgroup and many small glacial and volcanic lakes in the second. All are subject to changing shape and dimensions and many have a particularly precarious existence (e.g., landslide lakes). It is in these lakes where key abiotic variables (e.g., Secchi depth) are related in varying degrees to lake morphology and catchment area.

Touchart's fourth group of lakes also have coefficients of 1 or less; they are the lakes (reservoirs) of human origin. They are of variable size (in area, some challenge lakes with coefficients of 4), but are recent in origin and have a short life span. Moreover, their morphometry is forever changing and their catchments dominate their limnological processes.

Touchart largely omits consideration of short-term changing morphology, partly seen in reservoirs, but absolutely characteristic of intermittent lakes. Such lakes are uncommon where most limnologists live in Europe and North America, but prevalent in the drier parts of Asia, Africa, South America and especially Australia. Some are of very ancient lineage, e.g., Lake Chad, Lake Eyre, but lack ancient/endemic biodiversity because intermittent lakes are useless evolutionary loci. Others (e.g., seasonal lakes due to flooding; shallow lakes due to wind deflation) are temporary landscape features and if they lie in a distinct basin, are best depicted with inverse contours (i.e., bottom at 0 m, highest level at x metres/centimetres to account for their fluctuations in water level (Figure 5). Most abound in geomorphic expressions of their shallowness and variability, so that a consideration of their geomorphic parameters together with their hydrologic variability can explain some ecological features.

Parameters of the Geomorphic Lake Types

Structural (Tectonic) Lakes

As shown above, many of these like Lakes Baikal and Tanganyika, are especially large, deep and old, so that they have special limnological features, that are expressed most meaningfully by their Touchart coefficients. Such lakes have D_vs a little above unity (1.2–1.5) and moderate D_s (1.3–3.4). Many older tectonic lakes of moderate depth (e.g., Caspain Sea, Aral Sea) have D_v s <1, while the shallow intermittent ones vary according to hydrological condition. For instance in Lake Eyre D_v decreases from 1.68 when 'full'(=5.7 m deep) to 1.55 at 4 m deep to 1.43 at 1 m deep, while D_s decreases from 4.7 when full (it spreads up entering creeks to give a highly indented shoreline) to much lower values when contained well within the vast salt flats. The limnology of Lake Eyre is different when full to when near empty, largely because of differing water salinities but the consequences of its differing geomorphic parameters contribute too. Lake Chad also has differing geomorphologies at different water levels, and probably so do many other shallow arid zone lakes. In addition, tectonic lakes in terminal basins have many stranded beach features useful in deducting past histories, as in many Tibetan lakes to give one set of numerous possible examples.

Meteoritic Impact Lakes

These are rare, but impressive because of their roundness ($D_s = 1$). Depths vary, but Lake Ungava (=Chubb) in Quebec Province, Canada, is 251 m deep and diameter about 3 km. Intermittent Lake Acraman in South Australia, although not quite round is notable because of its huge size (diameter 22 km).

Volcanic Lakes

Like structural lakes, there is no one set of parameters which characterize all volcanic lakes, though some subtypes have characteristic features. One group are the maars and calderas; generally these have low D_ss (near 1), high D_vs (near 2), high littoral slopes and low profundal slopes. In an analysis of 15 Australian maars, D_s averaged 1.14 (lowest 1.01) and D_v 1.91 (highest 2.8) (Figure 4). Such lakes are

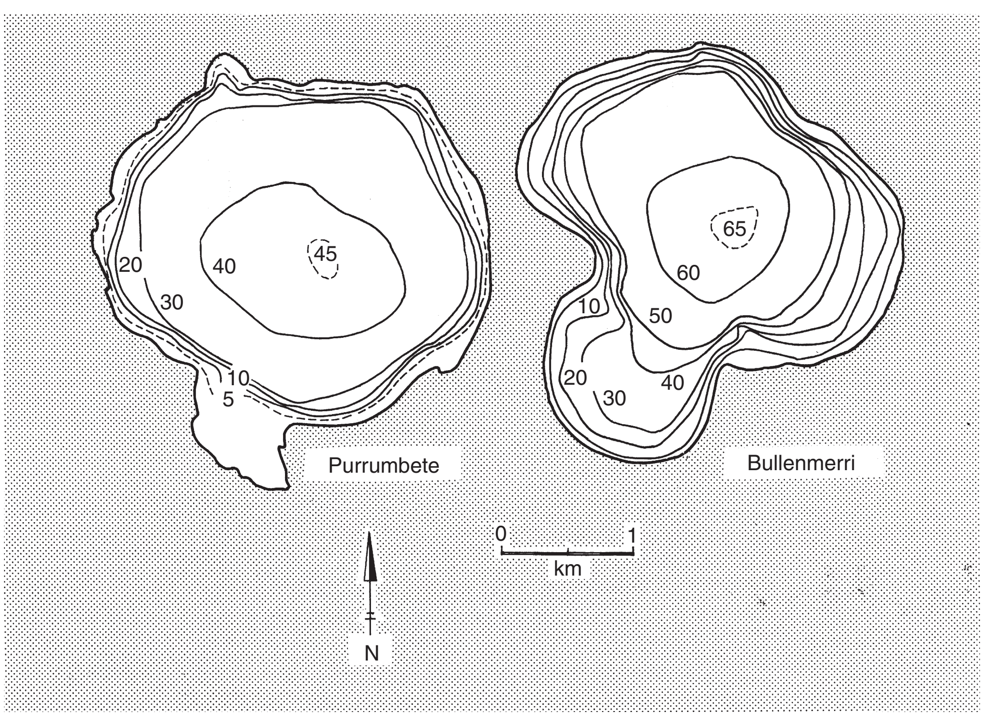

Figure 4 Bathymetric map of two maar lakes in western Victoria, Australia. Lake Purrumbete lies almost wholly within its crater, while Lake Bullenmerri lies within three adjoining craters. Both have a D_s a little >1 and a D_v near 2.

typically dominated by their limnetic zone and have physicochemical processes not too dissimilar to the classic large lakes of limnological literature. On the other hand shallower lakes on Victorian lava fields are not that different (except for their saline waters) to shallower lakes elsewhere. These are dominated by shallow water and littoral processes due to low maximum and mean depths, low littoral slopes and often high shoreline developments. Again, the basic geomorphic differences between the various types of lakes are expressed in depth and size, and perhaps there is scope in the Touchart system to differentiate lakes with coefficients <1 within his third type.

Glacial Lakes

Again there is a wide variety of limnologies better explained by the size-age coefficient of Touchart (group 2, see above) than by geomorphic parameters alone. Nevertheless for the piedmont lakes due to glacial erosion, waters are deep, and D_vs are high. For 10 such large lakes on the South Island of New Zealand, 7 are deeper than 200 m and the average D_v is 1.75. Shore and littoral features are unimportant compared with the contribution of large and deep limnetic region. Cirque lakes for another group, but their geomorphic parameters are hardly unique and influencial. The smaller kettles and the like are dominated by their small overall size and hence littoral processes.

Fluviatile Lakes

Almost all of these are small, and even if >10 km^2 are still shallow and hence belong to Touchart's group 3 and so littoral dominated. Two common types have some characteristic parameters: most oxbows are lunate-shaped with a curving maximum length and moderate D_ss (<2.5), while most blocked valley lakes are dendritic with higher D_ss (2–4). Some, e.g., the bog lakes of the Waikato, New Zealand have shorelines much smoothed by growth of littoral vegetation so that D_ss are low, as are D_vs.

Solution Lakes

As for fluviatile lakes most of these, especially dolines, are small and shallow, and though uvalas and poljes may be larger in area, they are still shallow. Perhaps the parameter of most interest is their D_v – this is often 1 or less, indicating a cone or trumpet-shaped basin. Unlike the previous fluviatile lakes, but like kettles, they may have multiple deeper subbasins.

Aeolian Lakes

Lakes formed, or largely moulded by wind action, are generally shallow (<5 m, often <1 m deep), relatively small (<100 km^2, often <1 km^2) and have sandy shores, so that shore processes are most important in their limnology. Hence spits, beaches, islands, and deltas feature in their evolution and their basin orientation is both a consequence of their development and/or a causal driver in their further evolution. Orientation to wind and effective maximum lengths for wave generation are basic controllers of their geomorphology. Many lakes in southwestern Western Australia and elsewhere are rounded or ellipitical and difference in orientation and size between areas is related to different wind directions and/or rainfall distribution. On the other side of Australia, only those lakes orientated with their major axis N-S, develop spits in the southeastern corner in an attempt at lake compartmentalization (see later) (Figure 5). These spits increase D_s, which increases the habitat for shorebirds. Under unidirectional or bidirectional winds, shallow lakes may completely segment (i.e., form separate compartments), creating smaller lakes with more shorelines and increasing the important of littoral processes.

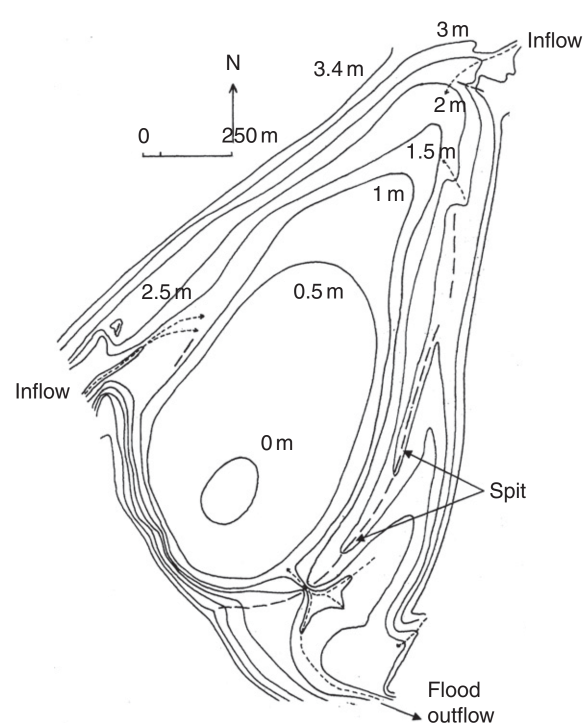

Figure 5 Bathymetric map of Lake Yumberarra, Outback Queensland, Australia. Key: beach ridges long dashes; creek channels, short dashes. Depth contours inverted from normal pattern, as this is more convenient in shallow intermittent lakes with highly variable water levels.

Coastal Lakes

Although most coastal lakes are due to sea-level rise, their geomorphology is variable due to different inherited features. A few are in fjords, so may be deep and steep-sided, while most are in drowned valleys, so dendritic or triangular, and those on low coasts may be elliptical. Australia's southeast coast has numerous coastal lakes of many subtypes, as does the Landes coast of France, the Cape Cod coast of North America, the Baltic coast to name a few others. Their active depositional environment encourages delta and spit formation, and lake compartmentilization in low coasts, so that shorelines are longer than those inherited. Given most lie in windy environs, basin orientation, and effective lengths are particularly important for those lake processes dependent on wave generation.

Glossary

Arcuate Gilbert delta – A delta arched in plan and composed of a wide block of sediments up to the water surface.

Homopycnal inflows – Incoming water and lake water of same density, so thorough mixing of the two.

Hyperpycnal inflows – Incoming water more dense than lake water, so it flows along the bottom of the lake.

Hypopycnal inflows – Incoming water less dense than lake water, so it flows on the surface.

See also: Abundance and Size Distribution of Lakes, Ponds and Impoundments; Lakes and Reservoirs of Australia and New Zealand; Lakes of Antarctica; Origins of Types of Lake Basins.

Further Reading

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