# A Revised Classification of Lakes Based on Mixing[1]

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Deficiencies in the Hutchinson–Löffler classification of lakes based on mixing are reviewed and organized under the following headings: (1) exclusion of shallow lakes, (2) unsatisfactory relationship between meromixis and the six basic lake types, (3) excessively complex treatment of tropical lakes, and (4) difficulties in classification of cold lakes due to the 4°C boundary on cold monomixis. A revision remedies these deficiencies with minimal changes in terminology and conceptual foundation of the original classification. The revision incorporates the following features: (1) the meromixis/holomixis dichotomy is combined with the six lake types based on seasonal mixing in such a way that the two systems are hierarchical and universal; meromictic lakes are assigned to a seasonal type on the basis of the behavior of the upper water column, (2) oligomixis is eliminated, (3) shallow lakes are brought under the classification by definition of four polymictic types based on ice cover and frequency of mixing. Dependence of the eight mixing types of the revised classification on latitude, elevation, and depth is estimated from existing data, and examples are given of each type.

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L'article qui suit contient une analyse des lacunes dont souffre la classification de Hutchinson–Löffler des lacs, fondée sur le mélange. Ces lacunes ont été organisées comme suit : (1) exclusion des lacs peu profonds, (2) relation inadéquate entre la méromixie et les six types de lacs fondamentaux, (3) traitement excessivement compliqué des lacs tropicaux et (4) difficultés à classifier les lacs froids à cause de la limite imposée par la température de 4°C à la monomixie froide. Je propose de rémédier à ces lacunes par des changements minimes de terminologie et de fondement conceptuel à la classification originelle. Ma révision introduit les caractéristiques suivantes : (1) la dichotomie méromixie/holomixie est combinée avec les six types de lacs fondés sur le mélange saisonnier de façon que les deux systèmes soient hiérarchiques et universels; les lacs méromictiques sont placés dans un type saisonnier en se fondant sur le comportement de la partie supérieure de la colonne d'eau, (2) l'oligomixie est éliminée, (3) les lacs peu profonds sont introduits dans la classification en définissant quatre types polymictiques reposant sur la couverture de glace et la fréquence du mélange. Des données existantes servent à illustrer la façon dont les huit types de mélanges de la classification révisée dépendent de la latitude, de l'altitude et de la profondeur, avec exemples de chaque type.

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MANY lake classification schemes have been proposed, but only the trophic classification of Naumann (1919; Hutchinson 1973) and the mixing classification of Hutchinson and Löffler (1956) are today in common use. These two classifications have probably persisted because of their simplicity, and because they are based on two of the most fundamental means for comparing lakes — nutrition and temporal variation. Classification schemes are never wholly satisfactory, but the trophic classification seems to have found broad

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acceptance. The Hutchinson–Löffler mixing classification is also both reasonable and useful, as shown by its inclusion in most limnology textbooks (Ruttner 1963; Dussart 1966; Bayly and Williams 1973; Wetzel 1975; Maitland 1978; Cole 1979). Despite its wide appeal, however, the mixing classification continues to be the target of ad hoc revision, suggesting that it might be improved by some comprehensive changes.

As explained by Hutchinson and Löffler (1956), their mixing classification is successor to Forel's (1895) even simpler classification (and its modification by Yoshimura 1936), which was nomenclaturally misleading and did not adequately separate the major lake types. The Hutchinson–Löffler classification is much better in these respects but should be revised for several reasons, especially to make it conform better to extensive thermal data taken outside the middle temperate latitudes over the last 25 yr. Numerous attempts, many of which will be cited below, have been made to change the Hutchinson–Löffler classification. These have been mostly unsuccessful. Attempts at revision may have failed because they were either too drastic or because they focused too specifically on one particular point. The revisions I suggest attempt to deal comprehensively with the problems raised by the classification. At the same time, terminology and conceptual boundaries between lake types are kept as near to the traditional as possible. To a large extent my revision is merely an integration of many separate suggestions made by those who have used the classification and noted some deficiency in it.

## The Present Classification System and Its Deficiencies

The Hutchinson–Löffler classification recognizes six lake types as follows:

1) Amictic: always ice-covered;
2) Cold monomictic: ice-covered most of the year and warming sufficiently to thaw but not to exceed 4°C;
3) Dimictic: ice-covered part of the year, stably stratified part of year, and mixing in spring and fall;
4) Warm monomictic: never ice-covered, mixing once per year, and stably stratified the rest of the year;
5) Oligomictic: never ice-covered, stratified most of the time but cooling enough to mix at irregular intervals longer than 1 yr;
6) Polymictic: never ice-covered, stratified, but with several episodes of complete mixing per year.

These types are only for "lakes deep enough to stratify," i.e. shallow lakes are not included in the typology. Hutchinson and Löffler predicted the approximate distributions of the six lake types, and Hutchinson (1957) elaborated on the distributions and on the variations of each type.

The amictic type is rare, as it is limited to the highest latitudes and the highest elevations outside the polar regions. Walker and Likens (1975) have pointed out that the nomenclature might suggest that amictic lakes are completely stagnant, which is not the case. For classification purposes, however, "mixing" as used by Hutchinson and Löffler refers specifically to homogenization of the entire water column. Deep turbulence or thickening of the mixed layer are not sufficient.

Hutchinson and Löffler also pointed out that the cold monomictic type is rare, as it occurs only at extreme latitudes or high elevations. The temperate zone is dominated by dimictic and warm monomictic lakes, which together outnumber all other types in the classification.

The Hutchinson–Löffler typology is most speculative in its treatment of tropical lakes. Hutchinson and Löffler predicted that in the Tropics polymixis would be dominant at high elevations, warm monomixis would be dominant at middle elevations, and oligomixis would be dominant at low elevations. They reasoned that all elevations would share a muted seasonality, but that the base temperatures would differ according to elevation. As the rate of density change increases with the base temperature, the muted seasonality of the Tropics would, they believed, result in persistent stratification at low elevations and emphemeral stratification at high elevations. Thus polymictic lakes would be found at high elevations, oligomictic lakes at low elevations, and warm monomictic lakes between these. These conclusions were reached, however, before the availability of extended thermal records for tropical lakes. Complications appeared even in the original publication, which gave Lake Victoria and several other lakes at low to moderate elevations in the Tropics as examples of the polymictic type, in apparent contradiction to the predicted restriction of this type to higher elevations. Hutchinson (1957) also indicated that lakes with daily mixing are to be called polymictic if they are tropical, although shallow temperate lakes that might mix daily were clearly excluded from the original version of classification.

The concept of meromixis, although usually treated separately, is closely related to the Hutchinson–Löffler classification. Hutchinson (1957), following Findenegg (1935), defined a meromictic lake as "a lake in which some water remains partly or wholly unmixed with the main water mass at the circulation periods." A lake that is not meromictic is holomictic. A holomictic lake belongs to one of the six mixing types, unless it is shallow.

Löffler (1957, 1958, 1964, 1968) was first to begin modifying the Hutchinson–Löffler classification. He split the polymictic category into two types, warm and cold polymictic, both of which are tropical. The basis of separation is an arbitrary boundary on maximum temperature (10°C) for lakes that do not stratify stably. Löffler (1968) defended the exclusion of shallow lakes from the classification, since he believed that inclusion of these lakes would make the classification too complex.

Paschalski (1964) suggested subtypes for the Hutchinson–Löffler classification and showed that there is historical precedent for an alternate system, which he called "European" (the origins of both Hutchinson and Löffler notwithstanding). The "European" system has not been widely accepted, probably because it is somewhat more complex, and, as pointed out by Paschalski, is more parochial to the temperate zone. Other suggested revisions of more limited scope are very numerous. Dussart (1966) used the Hutchinson–Löffler classification but modified the distribution diagram in order to show that polymictic lakes could occur outside the Tropics, as suggested by Paschalski (1964). Walker and Likens (1975) broadened the polymictic category in a similar way, as have a number of others who have studied shallow lakes (e.g. Harvey and Coombs 1971).

In surveying the lakes of Australia, New Zealand, and Tasmania, Bayly and Williams (1973) found it necessary to introduce a new lake type in order to have an appropriate niche for lakes that develop ice cover in the winter, and rise well above 4°C in the summer, but fail to stratify stably. Berg (1963) noted similar inadequacies in coverage of North American lakes that warm above 4°C but do not stratify. Cole (1979) pointed out that some deep lakes of the temperate zone (Ohrid, Tahoe, Maggiore) must logically be called oligomictic, as they mix completely only at intervals of several years. Walker and Likens (1975) suggested complete elimination of the oligomictic category because of its ambiguity: the distinction between oligomictic and meromictic lakes is difficult. They also suggested that the meromictic/holomictic dichotomy be formally combined with the Hutchinson–Löffler classification.

Features of the Hutchinson–Löffler classification that have stimulated the above-mentioned changes in usage can be grouped under four headings:

1) Exclusion of shallow lakes from the classification;
2) Unsatisfactory relationship between meromixis and the six basic lake types;
3) Excessively complex treatment of tropical lakes;
4) Difficulties in the classification of cold lakes resulting from the 4°C temperature boundary on cold monomixis.

The exclusion of shallow lakes was not an oversight but is probably unnecessary and produces considerable difficulties. Shallow lakes are common or even dominant in some lake districts. Limnologically significant examples are numerous, including Lake George in Uganda, Lake Wingra in Wisconsin, Loch Leven in Scotland, Lough Neagh in Ireland, Lake Suwa in Japan, Lake Sibaya in South Africa, Lake Balaton in Hungary, and others. The minimum depth required to bring a lake under the classification is not constant; it varies as a function of lake size, latitude, elevation, and a number of other factors. Thus a small temperate lake 15 m deep may be clearly dimictic, whereas a large windswept lake of the same depth might never achieve stable stratification.

Hutchinson (1957) recognized the interaction between depth and mixing by creating a separate classification that combines the older depth classifications of Whipple and Birge (see Hutchinson 1957). According to Hutchinson's depth classification, lakes would be first, second, or third class depending on whether their bottom temperatures varied none, some, or much from the annual minimum. The basis of this classification is different enough from that of the mixing classification that the two do not blend easily. The general trend has been to ignore the depth classes.

Confusion between meromixis and Hutchinson–Löffler lake types can occur when meromixis is not maintained by a permanent density gradient. In the most distinctive cases of meromixis, the mixolimnion is separated from the monimolimnion by a chemocline, below which high concentrations of dissolved solids cause a density increase. Not all lakes that fit the definition of meromixis have this characteristic. For example, Åberg and Rodhe (1942), Hutchinson (1957), and Wetzel (1975) describe a meromictic phenomenon that occurs in small temperate lakes during years with rapid spring warming. Under such circumstances, a lake may enter stable stratification without having become completely homogeneous under the influence of the wind. In years without complete mixing, normally dimictic lakes are properly classified as meromictic. One is left with the impression that the classification is forcing an inappropriate application of terminology in such cases.

A similar situation arises in a different way when a deep or well-sheltered lake with strong warm monomictic or dimictic tendencies fails to achieve chemical homogeneity during the seasonal period of deep mixing but does mix enough to prevent dissolved solids accumulation in deep water. For example, Lake Malawi mixes deeply each year (Talling 1969). Because of its great depth the lake does not achieve chemical uniformity during the seasonal mixing, yet it lacks density stratification maintained by dissolved solids. Thus, although it shows clear affinities with the warm monomictic type, Lake Malawi must be classified as meromictic, because it does not achieve complete chemical uniformity at the time of mixing. Among lakes that freeze, Lake Baikal does not mix completely, despite pronounced mixing seasons (Hutchinson 1957). Confusion is added by the possibility that even such a deep lake may mix completely at long intervals, which would change the classification from meromictic to oligomictic. Classification of such lakes either as meromictic or oligomictic would obscure the fact that there is a regular seasonal deep mixing that is functionally of great importance.

Walker and Likens (1975) suggested that meromixis be combined with the other lake types. This seems reasonable insofar as a meromictic lake can be viewed as one extreme of a spectrum of mixing frequencies. Paschalski's (1964) "European" system in fact incorporates this concept and thus provides a precedent. This approach has some disadvantages, however. First, meromixis is not usually subject to direct climatic control, as are the seasonal mixing regimes. In fact a meromictic lake will typically show in its upper water column (mixolimnion) the characteristics of one of the Hutchinson–Löffler lake types. Climate and elevation impose a set of seasonal mixing phenomena in the upper water column, while some combination of geochemical, morphometric and biotic factors impose meromixis simultaneously. Thus it does not seem correct to consider meromixis simply as a parallel category to dimixis or warm monomixis.

For tropical lakes, some classification difficulties can be traced to an underestimation of the importance of seasonality. Although the amplitude of seasonality is comparatively low in the Tropics, definite annual cycles affecting insolation, air temperature, wind strength, humidity, and rainfall are the rule rather than the exception. That regular meteorological cycles of such low amplitude could induce annual patterns in lakes has now been amply demonstrated, especially over the last 20 yr. The broadest coverage of tropical lakes has been in Africa. In the single most important publication relevant to lake classification in the Tropics, Talling (1969) reviews thermal data for a great variety of lakes extending from the northern limit to the southern limit of the African Tropics and including a great range of elevations. Talling's review gives examples of lakes that, because of great depth or a combination of effective sheltering and high relative depth, do not become chemically homogeneous on an annual basis (see also Wood et al. 1976). More importantly, he also shows that such lakes as well as lakes that do become chemically homogeneous annually are united by a common tendency to show deep mixing and minimal stability at a particular time of year, i.e. there is a universal tendency to warm monomixis. Furthermore, he shows that there is a strong tendency for the mixing season to coincide with the hemispheric winter, suggesting that minimum air temperature is of key importance. Lakes just on the equator may have an annual regime influenced by other aspects of weather, but nevertheless tend to mix at a particular time of year.

The strong trend for African tropical lakes to show warm monomixis has also been found outside Africa. Lake Lanao in the Philippines (Lewis 1973) and Lake Valencia in Venezuela (Lewis 1983) are both warm monomictic. Lake Valencia, which was studied for 5 consecutive years, has an annual overturn whose occurrence is predictable within an interval of 20–30 d. The thermal data of Richerson et al. (1977) on Lake Titicaca also suggest that this very high tropical lake has a predictible annual deep mixing season, as do Amatitlân and Atitlân in Guatemala (Weiss 1971a, b). Green et al. (1976) found that the small Indonesian Lake Lamongan (7°S) showed overturn in July, in accord with the general trend toward winter mixing. This is an especially significant example, as data for Lamongan and other Indonesian lakes visited by Ruttner (1931) during the warm season were apparently responsible for the importance attached to oligomixis among lowland tropical lakes in the Hutchinson–Löffler classification. Although high volume development and small size may well prevent Lamongan and other similar lakes from achieving complete homogeneity every year, deep mixing probably is a predictable annual occurrence.

Detailed studies of thermal structure in tropical lakes of moderate to large size have revealed some peculiarities about the behavior of these lakes during the stratification season. Frequent thermal profiles for Lake Lanao, Lake Valencia, and Lake Titicaca have shown that the thickness of the mixed layer varies much more between weeks in these lakes than would be expected in temperate lakes of similar size. For example, in Lake Valencia the average thickness of the mixed layer during stratification is 13 m, which is not significantly different from what one would expect for a lake of similar size in the temperate zone. However, during the stratification season, short periods of cool, windy weather can increase the thickness of the mixed layer temporarily to as much as 25 or 30 m, yet without completely disrupting stratification. When warm, calm weather returns, a secondary thermocline develops in the former mixed layer, again restricting mixing to a much thinner layer. This secondary layering may persist for a period of days or weeks, after which it is typically disrupted again by cool or windy weather.

A major increase in the thickness of the mixed layer in response to nonseasonal weather changes while the lake is stratified has been called atelomixis by Lewis (1973), who proposed that such a mechanism is very important in increasing the productivity of tropical lakes by bringing up nutrients from deep water to offset nutrient depletion during the stratification season. It is not clear whether all tropical lakes will show a tendency toward extreme variation in the thickness of the mixed layer during stratification, or whether the phenomenon is restricted to lakes of certain sizes or certain locations. Lakes of moderate to large size will be most likely to show the phenomenon simply because size is directly related to the range of variation in wind stress.

Large changes in mixing depth during stratification are identified particularly with tropical lakes because their stability is typically lower than that of temperate lakes, and possibly also because of differences in the Coriolis effect on currents in temperate and tropical lakes. Ruttner's work (1931, 1937) has often been cited in support of the notion that stability can be as high in tropical lakes as in temperate ones. However, Ruttner's comparisons were between Lunzer Untersee and various Indonesian lakes. As indicated by Ruttner in his comparisons, Lunzer Untersee has low stability due to its high elevation, which limits surface temperatures to about 19°C. As the majority of dimictic lakes become warmer than this, Lunzer Untersee understates the stability of temperate lakes. The upper limit on density difference between layers in tropical lakes is below what would be expected during stratification in most temperate lakes; the stability of tropical lakes during stratification thus tends to be less. In addition, the Coriolis effect on water currents is much smaller at low latitudes than at high latitudes. For this reason, winds over tropical lakes may be more effective agents of mixing (Lewis 1973). Lower stability and smaller Coriolis effect probably account for the sensitivity of the mixed layer thickness of tropical lakes to changes in wind strength.

Although atelomixis is a very important phenomenon biologically, it does not change the fundamental classification of a deep warm monomictic lake because it does not result in complete disruption of thermal stratification. However, it is obvious that the same phenomenon could produce complete mixing at irregular intervals in tropical lakes having depths between 10 and 50 m. This will be considered further in connection with the revised classification incorporating shallow lakes.

Lakes that are frozen most of the year and thaw during the summer present special problems because the Hutchinson–Löffler classification specifies a 4°C boundary for cold monomictic lakes. It is not unusual for perennially cold lakes to rise well above 4°C even though they do not stratify. If so they are not cold monomictic, although they obviously have great affinities with cold monomictic lakes.

## A Revised Classification

A better combination should be made of meromixis and the holomictic lake types. This can be accomplished most simply, and without any major rearrangement of concepts or terminology, by making the two classifications hierarchical and universal: any lake can first be classified as either meromictic or holomictic and, regardless which of these categories is correct, can also be classified according to a typology based on seasonal patterns. Thus whereas the Hutchinson–Löffler typology has applied only to holomictic lakes, its revised form can apply both to holomictic and meromictic lakes. For meromictic lakes, a mixing type can be assigned according to the behavior of the upper water column (i.e. the mixolimnion).

Integration of the meromixis/holomixis dichotomy with the seasonal mixing types as suggested here solves many problems. In a given year, a lake can correctly be called meromictic if it does not become completely homogeneous chemically at the time of minimum stability. At the same time, it can be assigned to an appropriate seasonal mixing category. In classifying the lake, one is not forced to ignore the seasonal behavior of the lake if it should fail to homogenize completely. This system also does away with oligomixis, thus achieving the effect suggested by Walker and Likens (1975) based on their survey of meromixis. Lakes that have been called oligomictic will be meromictic in most years, and will have a seasonal classification corresponding to temperature and mixing behavior in the mixing portion of the water column. In certain years such lakes will be holomictic, but with the same seasonal classification.

The number of lake types is reduced by elimination of oligomixis, but must in turn be increased slightly to take in shallow lakes. Shallow lakes are first divided into two large categories: those that develop seasonal ice cover (i.e. for more than a few hours) and those that do not. The former are identified by the prefix "cold" and the latter by the prefix "warm." Although it could be argued that this choice of prefixes is not ideal, insofar as a "warm" lake may be quite cold to human touch, the convention is already firmly established by the Hutchinson–Löffler categories and is succinct if not fully explanatory. In either the warm or cold category, two possibilities are recognized: (1) the lake may achieve stratification for periods of days to weeks but not for entire seasons, or (2) the lake may mix daily, either in response to variations in wind or at night when heat is lost. Although some might argue that these two categories should not be separated, there are important functional differences in the two types. Stratification lasting days to weeks will span an interval significantly longer than the generation time of many plankton organisms, whereas daily stratification will not. Lakes that mix at intervals of days to weeks can be called *discontinuous polymictic* and those that mix daily or without interruption can be called *continuous polymictic*. Since there is a warm and cold type for each of these, we have a total of four possible polymictic lake types. These types include many shallow lakes, although they are not restricted merely to lakes of a certain depth. In the spirit of the original classification, the emphasis is on mixing rather than depth. Broadening of the concept of polymixis in this way to cover shallow lakes at any latitude, is actually a reversion to the first use of the term in an overlooked publication by Wiszniewski (1953: Paschalski 1964).

The two types of cold polymictic lakes could be allowed to include the traditionally defined cold monomictic lakes. It seems advisable to retain the cold monomictic category as a separate type, however, to avoid confusion with traditional usage and to recognize the special properties of a lake that will, regardless of depth, show no direct stratification whenever it is ice-free. Thus any lake that does not reach 4°C will be classified here as cold monomictic. Lakes that pass from ice cover to some temperature above 4°C will be dimictic if they stratify for the whole season, discontinuous cold polymictic if they stratify for days or weeks but not the whole season, and continuous cold polymictic if they do not stratify or stratify only for hours at a time.

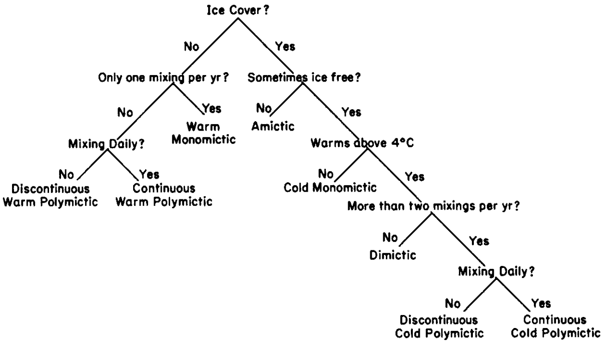

FIG. 1. The revised classification.

With the incorporation of the new types, the complete classification is as follows:

1) amictic: always ice-covered;
2) cold monomictic: ice-covered most of the year, ice-free during the warm season, but not warming above 4°C;
3) continuous cold polymictic: ice-covered part of the year, ice-free above 4°C during the warm season, and stratified at most on a daily basis during the warm season;
4) discontinuous cold polymictic: ice-covered part of the year, ice-free above 4°C and stratified during the warm season for periods of several days to weeks, but with irregular interruption by mixing;
5) dimictic: ice-covered part of the year and stably stratified part of the year with mixing at the transitions between these two states;
6) warm monomictic: no seasonal ice cover, stably stratified part of the year, and mixing once each year;
7) discontinuous warm polymictic: no seasonal ice cover, stratifying for days or weeks at a time, but mixing more than once per year;
8) continuous warm polymictic: no seasonal ice cover, stratifying at most for a few hours at a time.

Figure 1 shows the revised classification in diagrammatic form. The amictic, dimictic, warm monomictic, and cold monomictic categories are unchanged from the original classification.

In regions where deep lakes are cold monomictic, shallow lakes will be continuous or discontinuous cold polymictic. Whereas a deep lake can take up considerable heat without exceeding 4°C, a shallow lake with less water to be heated is more likely to exceed the 4° mark, which will place it with one of the two cold polymictic categories. For similar reasons, shallow lakes will often be cold polymictic in a region where deep lakes are dimictic. Thus middle to high latitudes will be rich in cold polymictic lakes wherever there are numerous shallow lakes. Much of the Arctic is in fact characterized by shallow lakes (Hobbie 1973), as are large portions of glaciated temperate areas. In view of their numerical importance, these shallow cold polymictic lakes are underrepresented in the literature. The abundance and variety of such lakes is well illustrated by the work of Harvey and Coombs (1971) on Manitoulin Island, Lake Huron. In this area deep lakes should

TABLE 1. Latitude adjustment per 100 m of elevation required to bring a lake to zero elevation for lake classification purposes.

| Latitude (Degrees) | Latitude adjustment (Degrees per 100 m elev.) |
|---|---|
| 0 | 0.27 |
| 10 | 0.31 |
| 20 | 0.34 |
| 30 | 0.39 |
| 40 | 0.46 |
| 50 | 0.54 |
| 60 | 0.68 |
| 70 | 0.89 |
| 80 | 1.3 |
| 90 | 2.4 |

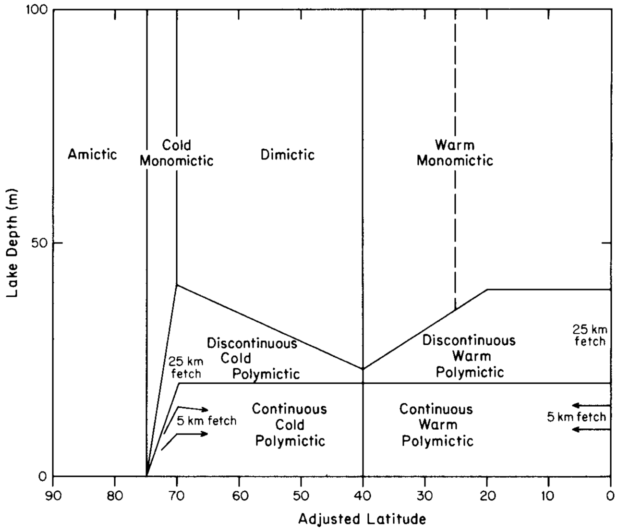

FIG. 2. Estimated distribution of the eight lake types of the revised mixing classification in relation to latitude (adjusted for elevation, see text) and water depth.

be dimictic, yet of the 51 lakes they studied, Harvey and Coombs found that 41 were polymictic. Of these, two were discontinuous cold polymictic, showing stratification during calm weather, and the rest were continuous cold polymictic. Summertime temperatures are as high as 25°C in some of these lakes.

A lake that would be warm monomictic except that it is too shallow to sustain stratification for an entire season will be either discontinuous or continuous warm polymictic. A discontinuous warm polymictic lake stratifies stably for periods of days or weeks during the warm season, but cool and windy weather can mix the entire water column, temporarily disrupting stratification. A similar but even shallower lake will mix continuously or at least nightly and will thus be continuous warm polymictic.

Following the precedent of Hutchinson and Löffler (1956), it would be instructive to depict the approximate distributions of the lake types. However, expansion of the classification to include shallow lakes necessitates consideration not only of elevation and latitude, but also of depth. The three factors cannot conveniently be presented on the same graph, but elevation and latitude can be brought together under a single factor called "adjusted latitude." Adjustment of latitude merely involves adding degrees of latitude equivalent to the elevation of the lake, thus adjusting all locations to an elevation of 0 m.

Adjustment of latitude for differences in elevation is not a perfectly straightforward procedure. The effect of elevation is a function of latitude, as indicated by the different slopes of the boundary lines between lake types. The slopes of the boundary lines in the original Hutchinson–Löffler diagram were plotted against latitude, and the plot was used in defining the elevation correction for any given latitude. The corrections obtained by this method are given in Table 1. As a rough rule of thumb, for purposes of lake typology, a 200-m increment of elevation is equivalent to 1° of latitude. More exact estimates can be obtained from Table 1, but the adjustment is only approximate in any case. It is easy to see from the table that elevation is relatively unimportant to lake typology except at the highest elevations. The lake types are shown in relation to corrected latitude, depth, and fetch in Fig. 2. Of course the predicted boundaries between the categories cannot be taken too literally, as latitude, elevation, and depth are not the only factors affecting lake mixing.

Figure 2 indicates a broader distribution for the amictic type than was originally suggested by Hutchinson and Löffler (1956). Antarctic lakes in Victoria Valley at 77°S are unequivocally amictic (Table 2). Char Lake, at 74°N, is usually cold monomictic but is sometimes amictic (Schindler et al. 1974a). The lower boundary for amictic lakes is thus set at 75°.

The upper boundary for dimictic lakes is higher in Fig. 2 than shown by Hutchinson and Löffler (1956). The valuable 6-yr study of Lake Latnjajaure by Nauwerck (1980) shows that this low-elevation lake at 68°N in Lappland is just on the border between dimictic and cold monomictic, and the detailed studies of Vorderer Finstertalersee (Pechlaner et al. 1972) show that this lake with adjusted latitude of 69° is just dimictic. The upper boundary for dimixis is thus set at 70° rather than 60° as it was by Hutchinson and Löffler. This and the lowering of the amictic boundary to 75° suggest, as indicated by present evidence, that cold monomixis occurs under a very narrow range of conditions (approximately 70–75° adjusted latitude).

Shallow lakes in the range of 70–75° may warm past 4°C and thus be either continuous or discontinuous cold polymictic. The boundaries between these and cold monomictic lakes will depend on depth and fetch. Figure 2 shows boundary lines for a fetch of 25 km. For comparison, the figure also indicates where the boundary would be for a fetch of 5 km (lines with arrows). The tendency for a shallow lake to be polymictic as opposed to monomictic obviously increases toward lower adjusted latitudes, because of greater warming. This is shown in Fig. 2 as a sloped boundary line separating monomictic from polymictic types between 75° and 70° adjusted latitude.

Deep lakes between 40° and 70° adjusted latitude will generally be dimictic, although some important variations attributable to continentality of climate are not represented in the

TABLE 2. Examples of the eight lake mixing types. Lakes marked "m" show the characteristic seasonal pattern only in the upper water column (i.e. they are always or usually meromictic).

| Lake type | Name | Location, Elevation (m) | Reference |
|---|---|---|---|
| Amictic | Vanda | 77S, 161E, 68 | Goldman et al. (1967) |
| | Fryxell | 77S, 163E, 22 | Vincent (1981) |
| Cold monomictic | Char | 74N, 95W, 120 | Schindler et al. (1974a) |
| | Meretta | 75N, 95W, <100 | Schindler et al. (1974b) |
| Continuous cold polymictic | Heywood | 60S, 45W, <100 | Light et al. (1981) |
| | Smokey Hollow | 46N, 82W, 190 | Harvey and Coombs (1971) |
| | Joseph | 53N, 113W, 670 | Hickman (1979) |
| Discontinuous cold polymictic | Tobacco | 46N, 82W, 228 | Harvey and Coombs (1971) |
| Dimictic | Mendota | 43N, 88W, 259 | Stewart and Hasler (1972) |
| | Erken | 59N, 18W, 11 | Nauwerck (1963) |
| | Baikal (m) | 53N, 108E, 453 | Hutchinson (1957) |
| | Fayetteville Green (m) | 43N, 76W, 278 | Brunskill and Ludlam (1969) |
| Warm monomictic | Lanao | 8N, 124E, 702 | Lewis (1973) |
| | Windermere | 54N, 3W, 39 | Jenkins (1942) |
| | Malawi (m) | 12S, 34E, 475 | Talling (1969) |
| | Ohrid (m) | 41N, 20E, 695 | Hadžišče (1966) |
| Discontinuous warm polymictic | Rotorua | 38S, 176E, 280 | Cassie (1969) |
| | Leven | 56N, 3W, 107 | Bindloss et al. (1972) |
| | Mahinerangi | 45S, 170E, 391 | Mitchell and Galland (1981) |
| Continuous warm polymictic | George | 0N, 30E, 913 | Ganf and Viner (1973) |
| | Sonachi (m) | 0N, 36E, 1889 | MacIntyre and Melack (1982) |

figure (Hutchinson 1957). Very shallow lakes in this range will be continuous cold polymictic. The depth boundary for this condition, as shown in Fig. 2, is determined largely by fetch. The fetch effect has been approximated according to the empirical relationship $D = 4\ F^{0.5}$, where $D$ is mixed layer thickness (m) and $F$ is fetch (km) (Ragotskie 1978). The figure shows the boundary for $F = 25$ km, but also indicates, by means of the short lines with arrows, where the boundaries would be for $F = 5$ km.

Below about 40° adjusted latitude, deep lakes will be warm monomictic. If they are very deep or very well sheltered, they may in addition be meromictic in most years, but this does not affect the seasonal mixing classification according to the present scheme. These lakes will show a single predictable annual period of deep mixing or complete overturn. A vertical dashed line in Fig. 2 separates the tropical from the temperate warm monomictic lakes. This dashed line is an indication that warm monomictic lakes at lower latitudes show greater fluctuations in the thickness of the mixed layer at irregular intervals during the stratification season (i.e. atelomixis). The greater irregularity of mixed layer thickness is explained by a convergence of the surface and deepwater densities and the reduced Coriolis effect along the spectrum from temperate to tropical warm monomictic lakes. This tendency will be most pronounced in lakes of moderate to large size; it will not be so noticeable in small lakes.

The shallowest lakes between 0° and 40° adjusted latitude will be continuous warm polymictic, typically losing stratification at night. Lake George, Uganda, can be considered archetypal for this category, but such lakes will also be found at high elevations in the Tropics. The type reaches its high-elevation extreme with shallow tropical lakes that are near the snowline. Such lakes may freeze at night and thaw in the daytime (Löffler 1960). Since they do not develop a seasonal ice cover, they are a peculiar sort of continuous warm polymictic lake.

As with the lakes between 40° and 70° adjusted latitude, the boundary for continuous polymixis is set by the empirical relationship between depth of thermocline and fetch. As there is presently little indication that the mean thickness of the mixed layer is significantly greater at low latitudes than at high latitudes, the same boundary is used for a given fetch as in the higher latitude ranges. However, the irregular thickening of the mixed layer at lower latitudes is more pronounced and this broadens the depth range covered by discontinuous warm polymictic lakes. The placement of the upper critical depth for the discontinuous warm polymictic category is based principally on detailed studies of Lake Lanao and Lake Valencia (Lewis 1973, 1983). Below 20° adjusted latitude, the depth range of lakes in this category is essentially constant because the difference in density between the upper and lower water column is very nearly stable between 0 and 20° latitude. From 40° to 20°, the depth range of the discontinuous warm polymictic category increases because the density difference between upper and lower water column during stratification decreases, thus increasing the likelihood that strong winds will change the mixing depth during the season of stratification.

Table 2 illustrates the application of the revised classification scheme to a diverse group of lakes. Shallow cold lakes that rise well above 4°C but mix daily when ice-free include Heywood, Smokey Hollow, and Joseph lakes. These would have been of uncertain classification by the Hutchinson–Löffler typology, but with the revised scheme they have an appropriate niche in the continuous cold polymictic category. Tobacco Lake, which is even more distant from any of the traditional categories, shows the usefulness of the discontinuous cold polymictic category. Inclusion of Lake Baikal and Fayetteville Green Lake with the dimictic category and Lake Malawi and Lake Ohrid with the warm monomictic category shows that these lakes have pronounced seasonal cycles in addition to meromictic properties. The two warm polymictic categories appropriately separate lakes Rotorua, Leven, and Mahinerangi, which mix part of each year at odd intervals longer than one day, from lakes George and Sonachi, which mix daily.

The revised classification, like the original, separates lakes according to three criteria: ice cover, mixing, and direct stratification. As shown by Table 2, however, the revised classification not only accepts shallow lakes, but also recognizes that shallow lakes diversify the range of seasonal behavior beyond what would be expected for deep lakes only. The awkward choice between meromixis and seasonal behavior of the upper water column is avoided, but without discarding the concept of meromixis, which can be applied across the entire spectrum of seasonal mixing types. The mixing behavior of tropical lakes is recognized as simple in principle, encompassing only three basic seasonal patterns, any one of which may be superimposed on meromixis. In general the revised classification takes into account the existence at any latitude and elevation of a graded series of mixing behaviors based mainly on depth and fetch. In view of the direct connection between these gradations in mixing behavior and biological processes, the revised classification may better complement the study of lakes as dynamic ecological systems.

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