

THERMAL STRATIFICATION OF WISCONSIN LAKES

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Abstract

A model predicting summer temperature stratification in lakes utilizing lake surface area and maximum depth information was developed from vertical profile temperature and dissolved oxygen data collected on approximately 500 Wisconsin lakes. From the model, the number of stratified versus non-stratified lakes (natural and impoundments) was estimated for the 3,000 plus Wisconsin lakes with surface areas 25 acres (10 hectares) or greater. Statewide, about one-half of the lakes are predicted to be non-stratified. Impoundments, which represent about 16 percent of the state's lakes, are about 86 percent non-stratified. Potential uses for the lake stratification model are noted.

INTRODUCTION

Thermal stratification in moderately deep temperate latitude lakes is a well documented phenomenon. Hutchinson (1957) provides a thorough discussion of the contributions of earlier researchers. Thermal stratification results from density differences in lake water of varying temperatures (Birge, 1916). After the winter ice melts, water temperatures increase above the point of maximum density of 4°C until maximum Wisconsin lake surface temperatures, generally between 21°-27°C (Wisconsin DNR, Bureau of Research lake data files), are reached by mid-summer. The wind provides energy during the spring to circulate the warming surface waters throughout the entire water column (spring overturn) maintaining homiothermal (uniform) lake temperatures. As water temperatures increase above 4°C, water density decreases, with each successive degree of rising water temperature resulting in a greater decrease in water density. Consequently, more wind energy is required to completely circulate the warmer lake surface waters with the cooler, more dense bottom waters.

In deeper lakes, as surface temperatures increase on calm, warm spring days, the den-

sity differences between surface and bottom waters become too great for the wind to maintain complete homiothermy. Thermal stratification results with the establishment of an *epilimnion* (upper warm water, freely circulating), *hypolimnion* (deep, cold, relatively undisturbed water), and a zone of steep thermal gradient called the *metalimnion* (or *thermocline*). These regions exist throughout the summer months until fall, when the lake surface water cools sufficiently to again equalize water density differences between top and bottom, thereby initiating fall overturn.

Shallow lakes exhibit complete mixing regularly throughout the summer as the wind provides enough energy to destabilize the minor density differences that develop between the surface and bottom as a result of surface warming on hot, calm summer days. Certain lakes have sufficient depth to allow for temporary thermal stratification, which persists until major weather systems with high winds again cause complete mixing. These weather systems occur frequently enough during the summer months in Wisconsin (Stauffer, 1974) that these weakly stratified lakes can be considered as non-stratified. Stratified lakes do not exhibit

complete mixing during the summer, although metalimnetic deepening, as a result of these strong weather fronts, does occur (Stauffer, 1974).

Rigorous mathematical expressions have been developed to describe the heat flux processes of lakes that ultimately result in thermal stratification (see Hutchinson, 1957). Calculations based on various physical lake characteristics can describe the *stability* of a lake, or the amount of work needed to cause a lake to destratify to a uniform temperature. Lake depth is an important variable in the calculation. However, the lake depth required before thermal stratification develops varies greatly between individual lakes as a function of lake surface area, basin orientation relative to prevailing winds, lake depth-volume relations, protection by surrounding topography and vegetation, and other factors (Wetzel, 1975).

Few generalizations about stratification have been attempted for diverse groups of lakes. Hutchinson (1957) noted that the eddy diffusivity (related to the process of turbulent mixing) is greatest in the wind-swept epilimnion of large, exposed lakes. Consequently, lakes of similar maximum depths may be either stratified or non-stratified, depending on their surface area.

Ragotzkie (1978), using data from Wisconsin and central Canadian lakes, developed one of the first simple lake stratification models. Lake fetch (F) was used to predict the depth of the summer thermocline (D_{th}) for lakes having fetches from 0.1 to over 20 km:

$$D_{th} = 4\sqrt{F}$$

Summer stratification of a lake has a tremendous impact on the chemical constituent concentrations of each lake and a great influence on the lake's biological community structure. Although Wisconsin lakes are very diverse in their geochemical characteristics (Poff, 1961) and watershed nutrient loadings, particularly between northern and

southern Wisconsin, they are also greatly affected by thermal stratification (Lillie and Mason, in press). In general, southern Wisconsin lakes are more fertile, and those that stratify usually exhibit dissolved oxygen depletion throughout the hypolimnion as a result of respiration and bacterial decomposition of organic matter. The lack of oxygen in the colder hypolimnion precludes the survival of cold-water-adapted fish such as trout since surface water temperatures are high where dissolved oxygen concentrations are adequate. Other aquatic life such as bottom feeding insects and zooplankton are restricted from the anoxic hypolimnion except for brief periods when certain species migrate into the hypolimnion. Northern Wisconsin lakes are generally less fertile and therefore in many cases do not undergo complete hypolimnetic oxygen depletion. Cold-water-adapted fish do well in the hypolimnion of these lakes during the summer months when surface waters are too warm.

The lack of oxygen in the hypolimnion of fertile lakes causes the hypolimnetic lake sediments to release such dissolved constituents as inorganic phosphorus, ammonia, and hydrogen sulfide into the overlying water throughout the summer stratification period (Mortimer, 1941-1942). In shallow, fertile lakes a significant amount of dissolved nutrients released from the lake sediments during periods of brief stratification can be transported by subsequent mixing to the surface waters where high levels of algal production are maintained.

Resuspension of sediments is another important effect of lake mixing. Shallow lakes continually resuspend nutrient rich sediments that contribute to increased nutrient concentrations for algal growth.

The combined result of sediment resuspension and frequent stratification followed by lake mixing in shallow lakes results in potentially high rates of internal nutrient recycling during the summer months. As a result, surface waters of non-stratified lakes

in Wisconsin generally show a net increase in total phosphorus concentration from spring to summer, while deep stratified lakes usually exhibit a net decrease in total phosphorus concentration (Lillie and Mason, in press). Thermal stratification effectively creates a temporary nutrient barrier between the epilimnion and the hypolimnion, while nutrients are being removed from the epilimnion by sedimenting algae. The importance of this barrier varies between lakes as a function of lake basin morphometry.

The classification and inventory of lakes in relation to their trophic status has been emphasized increasingly in recent years by state and federal agencies. Since thermal stratification can significantly affect lake water quality and concomitant recreational potential of a lake, a model capable of predicting stratification in Wisconsin lakes from

limited data could provide useful information for the classification process.

METHODS

Data used in this report came from two sources: (1) vertical profile temperature and dissolved oxygen data on approximately 500 lakes 25 acres (10 hectares) or greater in surface area, collected by the Wisconsin DNR, Bureau of Research; and (2) lake surface area and maximum depth information on Wisconsin lakes 25 acres or greater (data compiled by DNR Bureau of Fish Management). The lake inventory data was subdivided into natural lakes and impoundments.

Decisions about the establishment of thermal stratification are based on inspection of the temperature and dissolved oxygen vertical profiles. Three main types of tem-

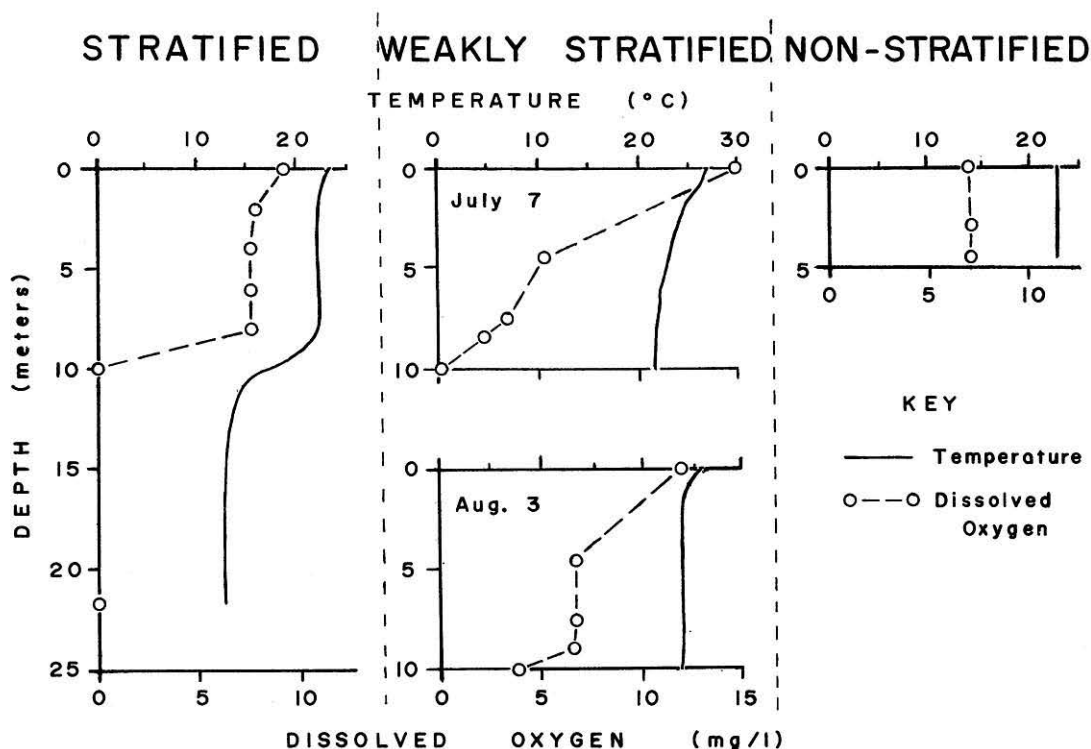


Fig. 1. Temperature stratification patterns found in Wisconsin lakes. (Stratified = Lake Monona, Dane Co., Aug. 1, 1978; Weakly Stratified = Lake Waubesa, Dane Co., July 7 and Aug. 3, 1976; Non-stratified = Round Lake, Chippewa Co., July 15, 1975).

perature profiles are found in Wisconsin lakes (Fig. 1). The stratified lake has a distinct epilimnion, metalimnion, and hypolimnion. The hypolimnion in the example is completely anoxic, indicating the absence of mixing with the epilimnion. The non-stratified lake is homiothermal; dissolved oxygen concentrations demonstrate well-mixed conditions.

The weakly-stratified lake (Fig. 1) demonstrates the difficulty in deciding whether or not the lake is capable of developing permanent stratification throughout the summer season (late June, July, and August). On July 7, the lake appears to be stratified and dissolved oxygen depleted near the lake bottom. However, on August 3, the temperature gradient is not as steep (with bottom temperatures being more than 2°C higher) and dissolved oxygen concentrations are higher in deeper waters, indicating that some recent mixing has occurred. The July 7 data provides a clue to the lake's ability to destratify; bottom water temperatures are almost 22°C. Any cooling and/or mixing of the lake's surface waters as a result of a weather front

would reduce the density differences between the top and bottom waters sufficiently to allow complete vertical mixing.

Consequently, any lakes with mid-summer bottom water temperatures above 20°C were generally considered to be weakly stratified and were combined with the more obvious non-stratified lakes for the purposes of this study. For the few lakes where stratification or lack of it was even more difficult to determine, the authors assigned lakes to the appropriate category based on their judgment about the influence of other factors affecting stratification, such as lake shape and surrounding topography.

RESULTS AND DISCUSSION

Lake surface area and maximum depth information were plotted for all natural lakes that could be classified as either stratified or non-stratified based on interpretation of the temperature and dissolved oxygen vertical profile information (Fig. 2). A generally linear separation between the stratified and non-stratified lakes resulted from a logarithmic presentation of lake area. Those lakes

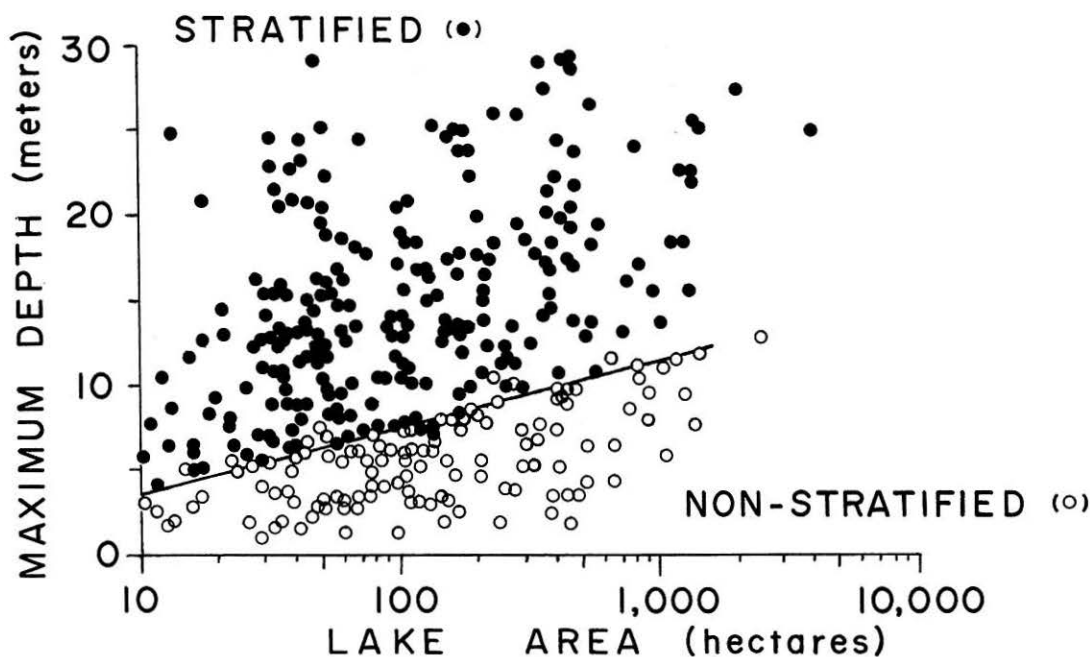


Fig. 2. Lake stratification model for Wisconsin lakes.

lying close to the stratification/non-stratification interface (Fig. 2) represented borderline cases, with stratified lakes having less stability when in close proximity to the interface. Many of the non-stratified lakes near the interface were weakly stratified.

Impoundments plotted in this same manner showed somewhat similar results, however a few anomalies were noted. In some cases stable temperature stratification occurred in small, relatively shallow depressions near the spillways of dams where there was no circulation and warmer surface waters were passing over the spillway. A number of impoundments (and a few natural lakes) receive large river discharges in relation to their volume and thereby experience a physical flushing which precludes the establishment of thermal stratification. Lack of stratification in Wisconsin impoundments with high flushing rates was found in depths up to 22 meters. Because of these abnormal stratification characteristics impoundments were excluded from the development of the final stratification model (Fig. 2). However, the model should be applicable to most impoundments.

Color, caused by dissolved humic substances, is one important variable affecting the depth of thermocline development in all lakes. The increased absorptive capacity of colored water restricts penetration of radiant energy. Consequently, colored lakes frequently have shallower epilimnions and narrower thermoclines than clear-water lakes (Wisconsin DNR, Bureau of Research lake data files).

Because of the linear separation between stratified and non-stratified lakes, a simple mathematical model was developed to predict lake stratification based on maximum depth and lake area:

$$\frac{\text{Maximum Depth (meters)} - 0.1}{\text{Log}_{10} \text{ Lake Area (hectares)}}$$

> 3.8 - Lake should be stratified

This model allowed for the prediction of the number of stratified versus non-stratified lakes for Wisconsin from surface water inventory data. As the model was based only on lakes with surface areas 25 acres (10 hectares) or greater and because smaller lakes may be heavily influenced by surrounding topography, the model was only applied to the 3,000 plus Wisconsin lakes in this size range. Impoundments and also lakes with high color were included in the data set. The number of poor predictions was relatively small.

Since the mathematical expression was developed using a data set from Wisconsin lakes, application of the model to other areas of the country may result in inaccurate stratification predictions because of differences in basin configuration, climate, or other factors. However, lakes in the upper Midwest should be reliably predicted by the model.

The lake stratification model, when compared to the model developed by Ragotzkie (1978), produced corresponding results.

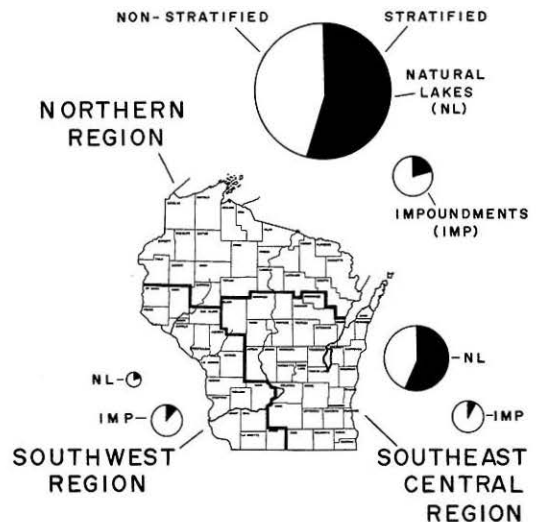


Fig. 3. Regional stratification characteristics of Wisconsin natural lakes and impoundments. (Number of lakes proportional to area of circle; Stratified lakes = solid area, Non-stratified lakes = open area).

His equation predicted the top of the thermocline, whereas the line drawn in Figure 2 would correspond approximately to the bottom of the thermocline. Consequently, Ragozkie's equation for lakes between 10 and 20,000 hectares (after fetch was converted to circular lake area) when plotted was somewhat parallel to our line in Figure 2, but at shallower depths for corresponding lake areas. As lake area increased, the two models predicted a more extensive thermocline; this is consistent with observational data on Wisconsin lakes (Wisconsin DNR, Bureau of Research lake data files).

For identification of lake stratification characteristics Wisconsin is divided into three regions (Fig. 3). The southwest region generally coincides with the Western Upland Geographical Province of Martin (1965), part of which includes the Driftless or unglaciated area. The topography is highly dissected with few natural lakes present. The northern region includes a majority of the state's lakes; these are characterized by low alkalinity (Lillie and Mason, in press) as a result of the igneous bedrock geology (Hanson, 1971; Poff, 1961). The southeast central area of the state generally has lakes of higher alkalinity and poorer water quality than northern lakes; this is particularly true in the southern part of the southeast central region (Lillie and Mason, in press). Separation of the state into distinct regions based on county lines is arbitrary, but lake inventory information was available on a county basis. The bedrock and surficial geology each indicate much more complex regional distinctions.

Natural lakes and impoundments are unevenly distributed throughout the three state regions (Fig. 3). Approximately 75 percent of Wisconsin's 3,000 plus lakes of 25 acres (10 hectares) or greater surface area are located in the northern region of the state. The southeast central region has roughly 20 percent of Wisconsin lakes in this size range, and the remaining 5 percent are located in

the southwest region. Impoundments comprise less than 16 percent of the total number of Wisconsin lakes 25 acres or greater. The number of impoundments is similar in all three regions. Most lakes in the northern region are natural; impoundments represent only about 8 percent of the total number. Impoundments constitute about 75 percent of all lakes found in the southwest region. There are few natural lakes in southwestern Wisconsin since that area was not covered by the Wisconsinian ice (Martin, 1965).

Slightly more than one-half of Wisconsin's lakes with surface areas of 25 acres or greater are predicted by the lake stratification model to be non-stratified throughout the summer (Fig. 3). About 26 percent of the impoundments are predicted to be non-stratified, compared to only 45 percent of the natural lakes.

Impoundments are 80, 93, and 84 percent non-stratified in the northern, southeast central and southwest regions, respectively. The high percentage of non-stratified impoundments is not surprising since they represent shallow lakes on dammed rivers. Natural lakes are predicted to be 55 and 58 percent stratified in the northern and southeast central regions, but only 22 percent stratified in the unglaciated southwestern region.

Striking water quality differences have been noted between stratified and non-stratified lakes. From data collected on approximately 500 lakes throughout the state, average summer secchi disc (water transparency) readings were 2.8 and 1.5 meters for stratified and non-stratified lakes, respectively (Wisconsin DNR, Bureau of Research, unpublished data). Differences in water transparency were related to greater concentrations of chlorophyll (algal biomass) and higher turbidity in nonstratified lakes.

The lake stratification model has potentially important applications for the classification of Wisconsin lakes. The combined effect of generally poorer water quality in non-stratified lakes resulting from greater

efficiencies in internal nutrient recycling, coupled with the large number of non-stratified lakes in Wisconsin, necessitates careful selection of lakes as candidates for limited non-point pollution control efforts. Lakes that are chosen for programs designed to restrict nutrient inputs, which are often expensive, should possess characteristics that would indicate a high probability of water quality response (improvement or long-term protection), thereby ensuring a high benefit to cost ratio. Temperature stratification would seem to be a very important characteristic in lake selection.

The thermal stratification model has other potential uses in water resource management activities. The model may be useful for the initial selection of lakes capable of supporting cold water fisheries, particularly in northern regions where hypolimnetic dissolved oxygen concentrations are likely to be adequate. The model can also serve as a guide to lake managers conducting dredging projects. By predicting lake depths needed for the development of thermal stratification, dredging can be planned to reduce internal nutrient recycling in fertile lakes. The stratification model could also be used in the design of impoundments for the above reasons or to maximize sediment trap efficiency.

Other more theoretical uses of the temperature stratification model may have management implications. The sediments contain a history of the lake's development, and lakes of certain depths may have accumulated sufficient bottom sediments over time to convert the lake from stratified to non-stratified. Probable trophic changes in the lake may be deduced by interpretation of differences in the physical and chemical sediment characteristics. Differences in the biological remains present, above and below the sediment depth where the lake should no longer be stratified, also provide clues. Such interpretation might allow the prediction of projected water quality changes in stratified

lakes that are currently experiencing a high rate of in-filling and sediment deposition.

Finally, a stratification model similar to the one presented here may be developed to predict the depth of the epilimnetic/metalimnetic boundary. This depth could be used to calculate the lake bottom area exposed to wind mixing, thus providing an index of potential internal nutrient recycling, as well as information useful for calculating total lake sedimentation rates. This model, coupled with other lake morphometric data, may also help to refine existing lake eutrophication models that relate external phosphorus loadings to in-lake water quality.

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