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SYNOPSIS: Thermal stratification of five man-made lakes in southern Iowa are studied in relation to basin morphometry. The lakes were Red Haw Lake, Lacey-Keosauqua Lake, Green Valley Lake, Lake Keomah and Lake Darling. Form of the water mass was compared by three mathematical indices including basin slope, area development and volume development. Strongly stratified lakes had the greatest maximum and mean depth, basin slope, area development and volume development. Lakes with unstable and temporary stratification had lower values for basin configuration. Unstratified lakes had the lowest morphometric indices. The use of these indices for predicting the tendency for stratification of a basin prior to dam construction was discussed.
INDEX DESCRIPTORS: Thermal stratification, basin morphometry, mathematical indices.

Thermal stratification occurs quite commonly in man-made lakes of the midwest region and is prevalent in small Iowa impoundments with a maximum depth of 24 ft or more. Closely associated with typical stratified temperate lakes of order two, according to Welsh's (1935) classification, is depletion of dissolved oxygen within the hypolimnion. Where the water surface is sheltered from wind action, low dissolved oxygen concentrations often extend upwards into the metalimnion.

Investigations by Dendy (1945), Sprugel (1951) and Byrd (1951) showed thermal stratification was the principal factor associated with limited vertical distribution and movement of fishes. Studies at Red Haw Lake, Iowa, by Mayhew (1963) revealed stratification had profound influence on both the vertical distribution and seasonal growth of several fish species. Seasonal influence of stratification was so complete in summer months it formed the substructure upon which the whole biological framework rested. Fish biomass was reduced by stratification from crowding of fish into the shallow, oxygenated level and reducing the amount of available habitat. Failure of many fishermen to recognize the lake was stratified and devoid of dissolved oxygen below 12 ft was responsible for a large number of unsuccessful fishing trips.

Moen (1956) found wide variation in the intensity of thermal stratification at man-made lakes in southern Iowa, and classified the impoundments into three different groups. The first group was most characteristic of temperate lakes of order three, nearly homothermous from surface to bottom with high dissolved oxygen concentrations at all depths. The second group stratified temporarily in summer months and seldom had a well defined hypolimnion, although dissolved oxygen concentrations often reached low levels near the lake bottom. The third group exhibited the classical temperature-dissolved oxygen profiles for temperate lakes of order two, having three well defined strata and complete loss of dissolved oxygen in the hypolimnion.

The Red Haw Lake studies by Mayhew (1963) showed slight change in the location of the metalimnion each summer during three years. Atmospheric temperatures during the period of stratification varied insignificantly each year, and higher temperatures appeared most important during initial formation of thermal stratification. The intensity and stability of stratification along with the thickness and location of the metalimnion were functions of basin characteristics and form of the water mass.

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METHODS AND PROCEDURES

Five man-made lakes from widely separated locations in southern Iowa and greatly different in size, depth, topography and intensity of thermal stratification were selected for comparison. Red Haw Lake and Lacey-Keosauqua Lake were thermally stratified and had oxygenless hypolimnions. Green Valley Lake and Lake Keomah stratified temporarily during windless periods with high atmospheric temperatures, and occasionally had low dissolved oxygen levels near the bottom. Lake Darling never stratified and contained high dissolved oxygen concentrations at all depths. All of the lakes were state-owned recreation impoundments located in state parks and were mapped prior to dam construction. Temperature and dissolved oxygen profiles were taken at least twice during the summer months for seven consecutive years.

Thermal stratification and lake basin morphometry were compared through a series of mathematical indices for basin slope, area development and volume development. The indices defined the physical characteristics of the basin as a cone whose height and basal area were identical with the form of the water mass. Area and volume development for individual lake basins were graphically illustrated and slope was computed for each 5-ft contour and for the mean of all contours. Individual lake basins were compared on the uniformity or diversity between one or more of these parameters.

Slope of basin walls described the water mass in two dimensions using the length of each contour and the vertical distance between contours. Slope of basin walls containing each isobath was computed for the generalized function

$$\text{Slope} = \left(\frac{C_1 + C_2}{2}\right)\left(\frac{V}{A}\right)$$

where

C_1 and C_2 = length in ft of the two contours

V = vertical distance or interval in ft between contours

A = surface area of the lake in acres multiplied by .004536.

Mean slope for the basin was mathematically derived from the equation

$$\bar{X}\text{ slope} = \left(\frac{1/2C_0 + C_1 + C_2 + \ldots + (C_n\text{-}1) + 1/2C_n}{N}\right)\left(\frac{D}{A}\right)$$

where

C_0, C_1, C_n = length in ft of each contour

N = number of contours

D = maximum depth of the lake in ft

A = surface area of the lake in acres multiplied by .004356.

Change in basin shape was reflected in both the singular and mean slope associations and was expressed in percent values. As walls of the basin became steeper there were proportional increased values for both slope between contours and the mean slope of the whole basin.

Area development was determined for each impoundment by plotting a percentile hypsographic curve which represented a three dimensional profile of all elements characteristic of the basin form. As area development increased there was an inverse association between the variables, and the slope of the curve was systematically steeper. The reverse occurred with lesser area development.

Volume development was expressed by plotting the Δ-acre ft values between the total basin volume and the volume for each successive contour. The form of the water mass was further defined by an index value from the generalized equation

$$\text{Volume development} = \frac{3 \cdot D_{mean}}{D_{max}}$$

where D_{mean} is mean depth and D_{max} is the maximum depth. This expression represented the ratio of total volume to an infinite cone whose volume development was identical with the lake basin. When the value was equal to unity the form of the basin was a perfect cone; when the basin walls were convex toward the surface, the index was less than unity; and when basin walls were concave toward the surface, the index value was greater than unity.

RESULTS

Red Haw Lake

The lake is located in Red Haw State Park near Chariton in Lucas County. At spillway crest elevation the lake contains 82 surface acres, a maximum depth of 40 ft with a mean depth of nearly 14 ft. The lake was impounded in a very deep valley with an extremely irregular shoreline which is covered with mature woodland. Much of the water surface is sheltered from wind action except during intense storms. Each spring by early May the lake becomes rigidly stratified with the metalimnion located from 9-20 ft and complete absence of dissolved oxygen below 12 ft. Temperature gradients within the upper 4 ft of the metalimnion often exceeded 15°F.

Basin indices showed high values for all parameters, characteristic of a lake basin with steeply sloped walls, small area of shallow depth and systematically increased association between basin development and depth. Slope of contours ranged from 3.6% to 18.6% but averaged 8.6%. The hypsographic curve (Figure 1) showed an inverse association be-

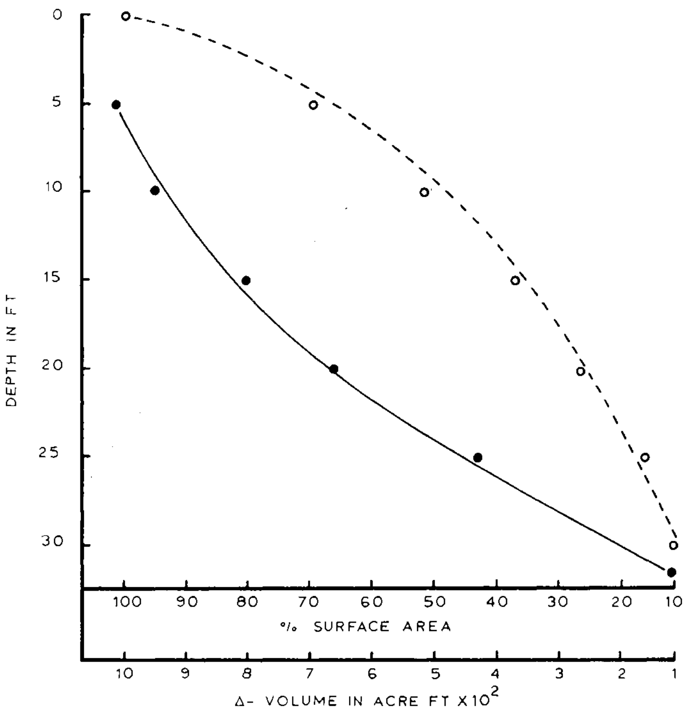

Figure 1. Area and volume development of the Red Haw Lake basin. Dashed line is percent hypsographic curve and solid line is Δ-volume curve. Both lines were fitted by eye.

tween area and depth. At 10 ft more than one-half of the total area at spillway elevation remained and more than 25% of the total area remained at the 20-ft contour. Volume development for the basin was 1.08, indicating the basin walls were slightly concave toward the water surface.

Lacey-Keosauqua Lake

This lake is located in Lacey-Keosauqua State Park near Keosauqua in Van Buren County. Maximum surface area at spillway crest elevation is nearly 35 acres. The lake has a maximum depth of 26 ft and a mean depth of 16 ft. The dam is located in a very deep, heavily wooded valley which affords nearly total protection to the water surface at all times. Intense thermal stratification commenced in early May and persisted through late September. Moen (1956) found the lake stratified on 4 May. Dissolved oxygen is absent at depths greater than 10 ft. On two occasions diminutive stratification occurred within the epilimnion; this usually resulted from abnormally high atmospheric temperature during daylight. When the water surface cooled at night the temperature gradient returned to normal.

Slope of the basin was progressively greater with increased depths. Individual contour slopes ranged from 6.8% to 27.6% with a mean basin slope of 10.7%. Area development (Figure 2) showed a rather unique configuration. Slope of the fitted line was rather oblique at shallow depths, leveling off slightly at intermediate depths and declining sharply at deeper contours. About 90% of the total area at spillway elevation remained at the 5-ft contour, and 60% remained at 15 ft. Below 30 ft nearly 10% of the total surface area was present. Volume development of the basin was 1.02, revealing a nearly cone-shaped basin. Plotting of Δ-volume values in Figure 2 showed typical progressive inverse association between water volume and depth.

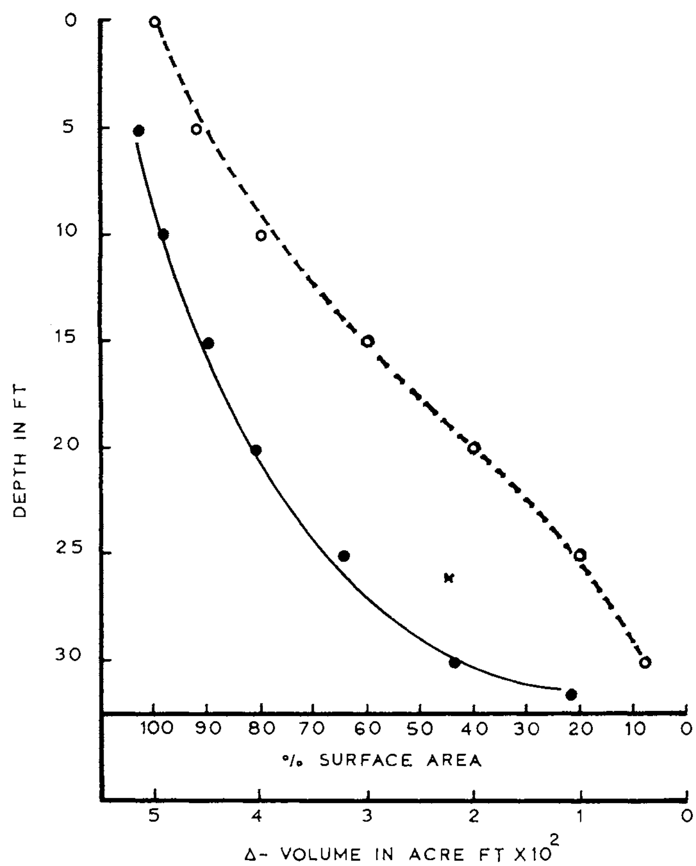

Figure 2. Area and volume development of Lacey-Keosauqua Lake basin. Dashed line is percent hypsographic curve and solid line is Δ-volume curve. Both lines were fitted by eye.

Green Valley Lake

The lake is located in Green Valley State Park near Creston in Union County. Surface area at spillway crest elevation is 398 acres. Maximum depth is 24 ft and mean depth is slightly greater than 10 ft. The impoundment lies in a long, narrow, irregularly Y-shaped valley unprotected from prevailing winds from northwesterly and southwesterly directions. Temporary and unstable thermal stratification occurred commonly in the summer, but a hypolimnion was seldom observed; when present it was usually less than 2 ft in thickness. Dissolved oxygen was found at all depths, but during prolonged stratification accompanied by low wind velocity concentrations often reached critically low levels within 4 ft of the lake bottom.

Slope of the basin walls ranged from 2.7% to 23.1% and had a mean slope of 4.1%. The higher value represented the slope for the 20-24 ft contour and resulted from measurements in much of the original stream course. Hypsographic plots of area development (Figure 3) showed nearly constant and shallow development until the 20-ft contour, followed by a sharp decline. Only 7% of the area at spillway crest elevation remained at the 20-ft level. Volume development was 1.21 for the basin. Plots of Δ-volume values showed similar configuration with area development. Both indices revealed the lake basin was mostly characteristic of a cone with a large base, gently sloped sides which pinched tightly inward near the apex. The sides of the cone were moderately curved toward the base.

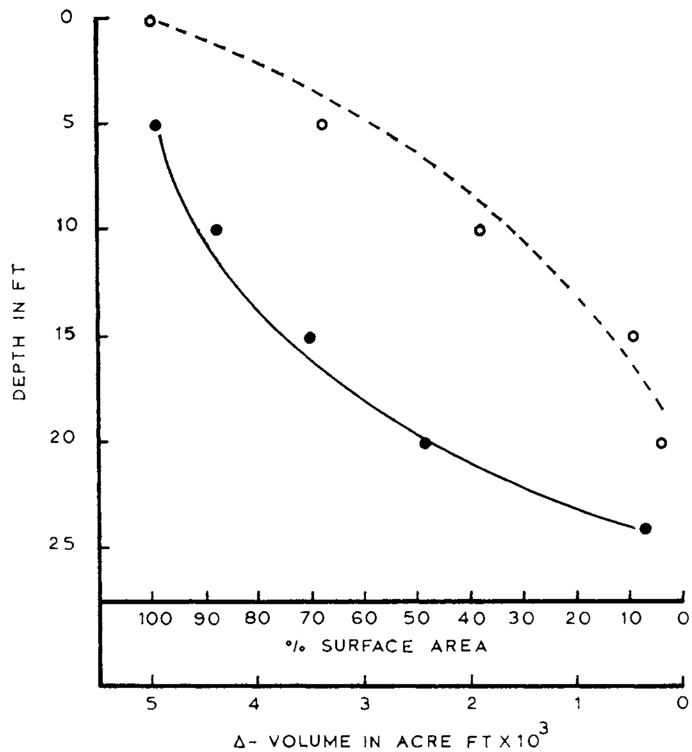

Figure 3. Area and volume development of the Green Valley Lake basin. Dashed line is percent hypsographic curve and solid line is Δ-volume curve. Both lines were fitted by eye.

Lake Keomah

The lake is located in Lake Keomah State Park near Oskaloosa in Mahaska County. Surface area at spillway crest elevation is nearly 83 acres, maximum depth is 22 ft and mean depth is 10 ft. The lake is irregularly Y-shaped with the dam forming the base of the figure. Mature woodland covers the entire perimeter of the lakeshore and much of the watershed. Thermal stratification was present throughout most of the summer, but the hypolimnion was unstable and disappeared frequently from wind-related surface agitation. Dissolved oxygen concentrations within the hypolimnion were usually below the minimum requirements to support aquatic life, but complete absence of dissolved oxygen was never observed.

Basin slope ranged from 2.9% to 14.6% and averaged 3.2% for all contours. Area development was nearly directly proportional at all depths, forming a hypsographic curve with nearly a straight line (Figure 4). Percentile values for area

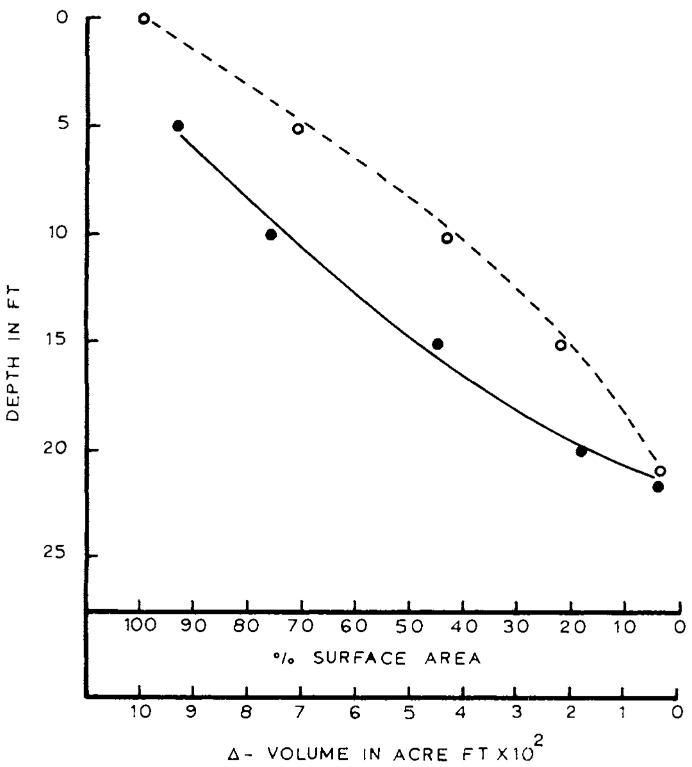

Figure 4. Area and volume development of the Lake Keomah basin. Dashed line is percent hypsographic curve and solid line is Δ-volume curve. Both lines were fitted by eye.

development at 5-ft contour intervals was 5 ft, 71%; 10 ft, 43%; 15 ft, 22% and 20 ft, 17%. Volume development was 1.31 for the basin. The Δ-volume curve also showed nearly direct proportional development curving moderately toward the water surface.

Lake Darling

The lake is located in Lake Darling State Park near Brighton in Washington County. At spillway elevation the surface area contains 404 acres. Maximum depth of the lake is 21 ft and mean depth is 9 ft. The lake is located in a long, narrow valley with several large embayments extending from the main axis. There is little shelter from prevailing winds, particularly from the southwesterly direction. Thermal stratification was never recorded in nearly 15 years of sampling. Surface water temperatures during summer months were usually within 5°F of those near the lake bottom. Moen (1956) reported temporary stratification within 3 ft of the surface during one period of abnormally high atmospheric temperatures. Dissolved oxygen levels usually varied less than 2 ppm from surface to lake bottom.

Slope of the basin walls varied from 1.4% to 6.2% and averaged 1.9% for the whole basin. The hypsographic curve in Figure 5 showed a slight inverse association between area

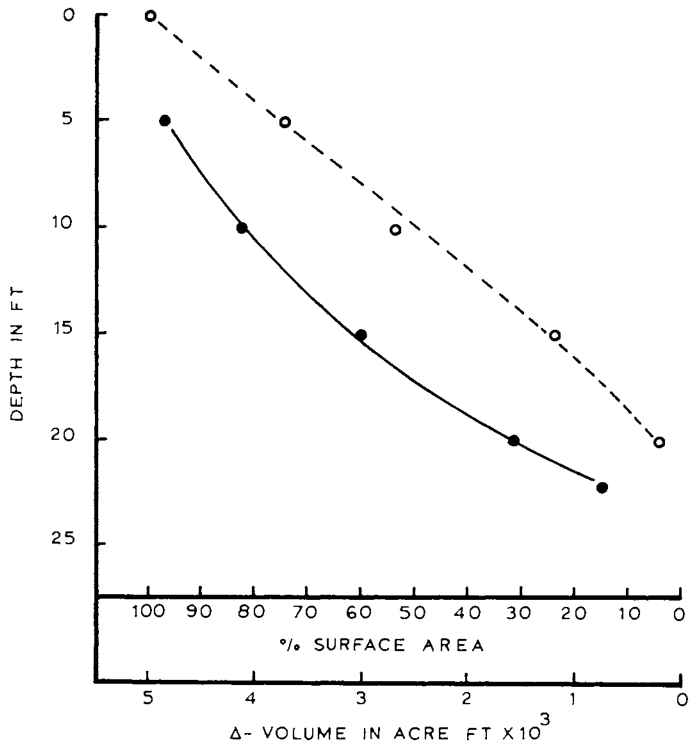

Figure 5. Area and volume development of the Lake Darling basin. Dashed line is percent hypsographic curve and solid line is Δ-volume. Both lines were fitted by eye.

development and depth, particularly at shallow and deep intervals. At the 5-ft depth interval about 75% of the area at spillway elevation remained, and at 10 ft slightly more than 40% remained. But, at the 15-ft and 20-ft intervals the percentile values decreased to 24% and 14%, respectively. Volume development for the basin was 1.46. Δ-volume increased slightly at both the shallow and deep depth intervals because of accelerated curvature in the concave basin walls.

DISCUSSION

The shape of the water mass for stratified lakes was wholly different from lakes with temporary stratification or none at all. Lakes with the greatest maximum and mean depths, steepest basin slope and highest area and volume development were the most strongly stratified. This was usually accompanied by complete loss of dissolved oxygen in the hypolimnion. The stability and intensity of thermal stratification lessened proportionately as index values changed toward shallower basins. Some temporary stratified impoundments had lower dissolved oxygen levels near the lake bottom, but total oxygen depletion was rare. The shallow, gently sloped lake basins with low area and volume development did not stratify and contained high dissolved oxygen concentrations at all depth levels. Longevity of stratification varied greatly between the lakes, but the longest continuous occurrence of a recognizable metalimnion was 139 days at Red Haw Lake.

The impoundments in this study were purposely selected with widely divergent physical and chemical characteristics so the intensity of thermal stratification would be contrasted with basin morphometry. Inclusion of all man-made lakes in southern Iowa into the three categories would certainly contain some lake basins with borderline values which would fit into more than one group. Several indistinct parameters which indirectly influence the intensity of stratification were excluded from this study. These factors included protection of the water surface by shoreline cover, and valley depth which might be measured by a ratio between surface area and maximum depth. Accuracy of predicting the intensity of stratification and location of the metalimnion would be somewhat reduced for lakes in the borderline values, particularly where the latter was desired.

For the most part volume development presented the index value with the greatest potential for classifying lakes by thermal stratification and basin morphometry because it represented the entire basin configuration as an infinite cone having the identical dimensions of the lake. Volume development systematically increased as stratification intensified. The resulting index value, based on the relationship of mean depth with maximum depth, was inversely associated with Δ-volume. Volume development also expressed the affinity between the curvature of the lake basin and the water surface. The basin walls in all of the impoundments curved concavely toward the water surface, but the diversity of the index values clearly separated the basins into distinct groups.

Based on the morphometric indices from the five impoundments, minimum expected values were developed to separate lakes into groups with similar characteristics of thermal stratification and are listed in Table 1.

TABLE 1. MINIMUM EXPECTED VALUES OF THE VARIOUS MORPHOMETRIC PARAMETERS OF STRATIFIED, TEMPORARILY STRATIFIED AND UNSTRATIFIED MAN-MADE LAKES.

	Lake classification		
Parameter	Stratified	Temporarily stratified	Unstratified
Maximum depth	24 ft	16-24 ft	22 ft or less
Mean depth	12 ft	8-12 ft	10 ft or less
Mean basin slope	8%	3-6%	2% or less
Area development at 10 ft	60%	40-60%	40% or less
Volume development	1.15	1.16-1.35	1.40

Most studies imply that thermal stratification is an important factor of environmental stress in man-made lakes because it forms a natural barrier which isolates both the epilimnion and hypolimnion. The hypolimnion is isolated from the atmosphere because each layer is physically incapable of mixing with the other due to thermal resistance, which traps cooler water strata at lower levels for several months. Organic decomposition increases rapidly in the hypolimnion until all dissolved oxygen is utilized. In Red Haw Lake high levels of ammonia nitrogen and hydrogen sulfide also developed in the hypolimnion by late summer (Mayhew, 1963). Even if higher dissolved oxygen levels could be attained the concentrations of other toxic chemical substances would prevent development of a typical biota. A great portion of the epilimnion in all lakes studied is isolated from the lake bottom except for contact between the surface and upper limit of the metalimnion. Fish populations are crowded into this shallow oxygenated stratum and set apart from a vast benthic food supply except in the littoral zone. Often the epilimnion comprised less than 35% of the entire lake volume.

Severe thermal stratification has many attributes of lake level drawdown except the reduction of space occurs at a lower depth instead of at the surface. Population manipulation by drawdown has been a most successful method of fish management (Bennett, 1962). Sport fishery surveys in Iowa recreational impoundments (Mayhew, 1957 and 1963; Mitzner, 1971) revealed stratified lakes rank high in angler harvest and success. Usually they require minimal fish management except for supplemental plantings of fish species which have little chance of self propagation. Stability of fish populations in the stratified lakes presumably results from the natural population manipulation caused by thermal stratification. Temporary stratification apparently has little impact upon fish populations since the structure in these lakes is similar to unstratified lakes.

The probability of thermal stratification is a paramount consideration for selection of sites for small man-made recreational impoundments. Although standing crop is somewhat reduced in stratified lakes, the stability of fish populations gained from stratification far outweighs the suppression. The indices developed in this study are applicable for predicting the intensity of thermal stratification and locating the metalimnion prior to dam construction.

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