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THERMAL VARIATION AND HEAT UPTAKE IN A STRATIFIED STRIP MINE LAKE IN SOUTHERN ILLINOIS

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ABSTRACT

Thermal variation and heat uptake in a stratified strip mine lake were analyzed using data collected during the heating periods of 1978 and 1979. Temperatures increased throughout the water column until the date of maximum mean temperature, after which the meta- and hypolimnion continued to gain heat while the epilimnion cooled. Heating rates were higher in 1978 with the largest differences at 4 (0.183 vs. 0.078 Δ°C/day) and 5 m (0.104 vs. 0.028 Δ°C/day). Birgean summer heat budgets (9,990.1 and 9,621.8 cal/cm^2) accounted for only 6.8% and 6.6% of total solar input. Both the amount and rate of heat uptake decreased after the summer solstice. Simpson's formula was as accurate as planimetry for calculating heat budgets.

INTRODUCTION

Many impoundments have been created in Illinois and throughout the Midwest as the result of past reclamation practices on lands surface mined for coal. Lakes on mined land are often quite distinct from other comparable lentic systems with respect to physico-chemical, morphometric, and edaphic characteristics. Although strip mine lakes have been the subject of numerous investigations, especially with reference to their management potential (Konik 1980), the limnology of these aquatic ecosystems has not been thoroughly documented.

For example, there is little information in the literature regarding the thermal properties of strip mine lakes other than, at most, monthly surface/bottom temperatures or vertical profiles (e.g. Gibb and Evans 1978, Konik 1980, and Lewis and Peters 1954). An accurate characterization of the thermal regime in a temperate impoundment requires that data be recorded at short time intervals, especially during the summer months (Hutchinson 1957). No previous study of strip mine lakes could be found that met this requirement.

Vertical thermal profiles of a circumneutral, final-cut strip mine lake, located in southern Illinois, were recorded regularly during the heating periods of 1978 and

1979 (Chimney 1980). In light of our limited understanding of the thermal characteristics of strip mine lakes, it was felt appropriate that such an analysis be conducted using these data. This paper will report on thermal variation and heat uptake.

STUDY AREA

This study was conducted on Moroni's Big Lake (MBL), a circumneutral, final-cut strip mine impoundment located approximately 2 km north of DeSoto, in Jackson County (T8S-R2W-Sec.8,17), Illinois (Fig. 1, Table 1). MBL was a second-order lake according to Hutchinson's (1957) criteria; it exhibited strong thermal stratification (April through October) and had hypolimnetic temperatures well above 4°C. MBL lacked a natural inlet and only had an outlet during periods of high water. The only significant recharge originated from immediate surface runoff and/or groundwater. The lake was long and narrow and well protected from wind action along its entire length by high spoil banks and the exposed highwall. Additional information on MBL can be found in Chimney (1980, 1981), Larson (1974), Rickett (1968), and Stahl (1979).

MATERIALS AND METHODS

Data were collected during the heating periods of 1978 and 1979 at a single, open-water station located in the deepest portion of MBL (Fig. 1). Water temperatures were measured at 1 m intervals (0-13m) to the nearest 0.1°C using the thermistor on a YSI 57 oxygen meter. The amount of error introduced into calculations by excluding data from 14 m was insignificant due to the small relative volume of the 13-14 m stratum (only 0.68% of total lake volume). Temperature profiles were recorded weekly June to September and at less regular intervals March to June and September to December during both years. There were 16 sampling dates in all during 1978 and 24 dates in 1979.

The mean temperature of MBL was calculated for each date as a weighted average (Cole 1979, Hutchinson 1957, Stewart 1973):

$$\overline{\theta} = \left[\frac{\theta_1+\theta_2}{2}\left(\frac{V_1}{V}\right)\right]+\left[\frac{\theta_2+\theta_3}{2}\left(\frac{V_2}{V}\right)\right]+\ .\ \ .\ \ .+\left[\frac{\theta_{x-1}+\theta_x}{2}\left(\frac{V_n}{V}\right)\right] \quad (1)$$

where

$\overline{\theta}$ = mean temperature of lake (°C)

$\theta_1, \theta_2, \theta_3, \theta_{x-1}, \theta_x$ = water temperature at specified depths (°C)

V_1, V_2, V_n = volume of stratum defined by depths of water temperature (°C)

V = volume of lake (m^3)

Heat uptake was calculated as Birgean heat budgets (Birge 1915, as in Hutchinson 1957) relative to the heat content of MBL when 4°C isothermal:

$$\theta_b = \frac{1}{A_o} \int_o^{z_m} [A_z(\theta_{sz}-4)]dz \qquad (2)$$

where

θ_b = heat budget, heat uptake relative to 4 °C isothermal condition (cal/cm^2)

A_o = surface area of lake (cm^2)

A_z = area at depth z (cm^2)

z_m = maximum depth (cm)

$(\theta_{sz}-4)$ = difference between measured temperature at depth z and 4 °C (°C)

Heat budgets were computed for each date during June to September in order to establish the maximum heat uptake (= Birgean summer heat budget) for both years.

Equation 2 was evaluated using the Simpson's discrete approximation program contained in a Texas Instruments Solid State Software® Master Library module and a TI 59 programmable calculator. Simpson's formula, a widely used algebraic integration procedure, is highly reliable (Adams 1963). The accuracy of this algorithm is enhanced as the number of values of f(x) used is increased. For this reason, estimates of $[A_z(\theta_{sz}-4)]$ at each half-meter depth (0.5,1.5,2.5,etc.) were interpolated and used in all heat budget calculations.

Heat budgets for a number of randomly selected dates were also obtained by plainmetric integration, the method usually employed by limnologists (Cole 1979, Hutchinson 1957). These values were used to evaluate the utility of Simpson's formula in this application.

All statistics were calculated using a TI 59 programable calculator and appropriate programs contained in a Texas Instruments Solid State Software® Applied Statistics module. Reference was also made to Sokal and Rohlf (1969). The critical level of significance (α) used in all cases was 0.01.

RESULTS AND DISCUSSION

Temperature changes June to September were plotted to examine the influence of depth on heat uptake (Fig. 2). Temperatures at 1 m were very similar to those at the surface ($r = 0.9828$ in 1978 and $r = 0.9916$ in 1979) and were excluded from the figure. The dates of the summer solstice (22 June, the day receiving the most solar radiation during the year) and the maximum mean temperature (20.2 °C on 3 August 1978 and 19.5 °C on 31 July 1979) were included for reference.

The dates of maximum mean temperature separated the heating and cooling periods in MBL. In general, temperatures increased throughout the water column up until this date, even though daily solar radiation had been declining for more than a month (Fig. 2). This is not unusual in temperate lakes, although both the amount and rate of heat gain is often substantially less after the solstice than before

(Hutchinson 1957). The steep thermal gradient which persisted after the date of maximum mean temperature promoted the continued mixing of heat into the meta- and hypolimnion (4-5 m and 6-13 m respectively) long after the epilimnion (0-3 m) had begun to cool. Because the epilimnion represented 52.9% of total lake volume, the mean temperature more closely reflected temperature changes within this stratum than those of deeper waters.

Temperature increase June to Stepember was approximately linear at most depths (Fig. 2). The slope of each line represented the heating rate (Δ°C/day) at that depth. The shape of the heating rate-depth curves were characteristic of a transport process through a stratified fluid medium (Fig. 3). Overall, heating rates were higher in 1978 and 1979. The most substantial between-year differences occurred within the metalimnion (0.183 vs. 0.078 Δ°C/day at 4 m and 0.104 vs 0.028 Δ°C/day at 5 m in 1978 and 1979 respectively) and were attributed primarily to steeper temperature gradients in 1978. An assumption of significantly greater wind-induced turbulence during 1978 was not substantiated by inspection of local weather records (unpub. data).

The largest heat budgets (9,990.1 cal/cm^2 in 1978 and 9,621.8 cal/cm^2 in 1979) coincided with the dates of maximum mean temperature (Fig. 4). By the summer solstice, MBL had acquired 78.6% and 81.2% of that year's summer heat budget which was comparable with other temperate lakes (Hutchinson 1957). The average rate of heat uptake after the solstice (based on a 42 and 39 day heating period) was 50.8 and 46.4 Δcal/cm^2/day in 1978 and 1979 respectively. The rate of heat uptake prior to the solstice (based on an approximate 116 day heating period in both years) was 67.7 and 67.3Δcal/cm^2/day. Clearly, both the absolute amount and rate of heat uptake were less as daily solar radiation declined. The amount of solar radiation received at this latitude (37°50′) during the study period was estimated by planimetric integration of the appropriate section of the solar flux curves given in Gates (1962, Figure 2). The calculated summer heat budgets accounted for only 6.8% and 6.6% of total radiation input. The rest of the solar flux would have been lost through reflection and reradiation back to the atmosphere, absorption by the sediments, and evaporative cooling (Hutchinson 1957, Wetzel 1975).

A matched-pair t test using data from six dates indicated that no significant differences existed between heat budgets calculated by Simpson's formula or planimetry (t = 0.151, df = 4). There was, on average, only a 0.37% difference between the results of each method on any date. Simpson's formula proved to be a reliable procedure for computing heat budgets. It had the added advantages of eliminating both experimenter and instrument error associated with using a planimeter and required considerably less time to obtain the final result.

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Table 1. Morphometric characteristics of Moroni's Big Lake. Terminology followed Wetzel (1975) and Håkanson (1981).

Maximum Depth (z_m)	14.0 m
Maximum Length (l)	538 m
Maximum Width (b)	100 m
Mean Depth ($\bar{z}$)	6.1 m
Mean Width ($\bar{b}$)	102 m
Quartile Depths (D_{25})	10.8 m
(D_{50})	4.9 m
(D_{75})	1.9 m
Relative Depth (z_r)	5.3 %
Shoreline Length (L)	
with islands	2,362 m
without islands	2,312 m
Shoreline Development (D_L)	
with islands	2.85
without islands	2.79
Surface Area (A)	54,747 m^2
Volume (V)	336,559 m^3
Volume Development (D_V)	1.31

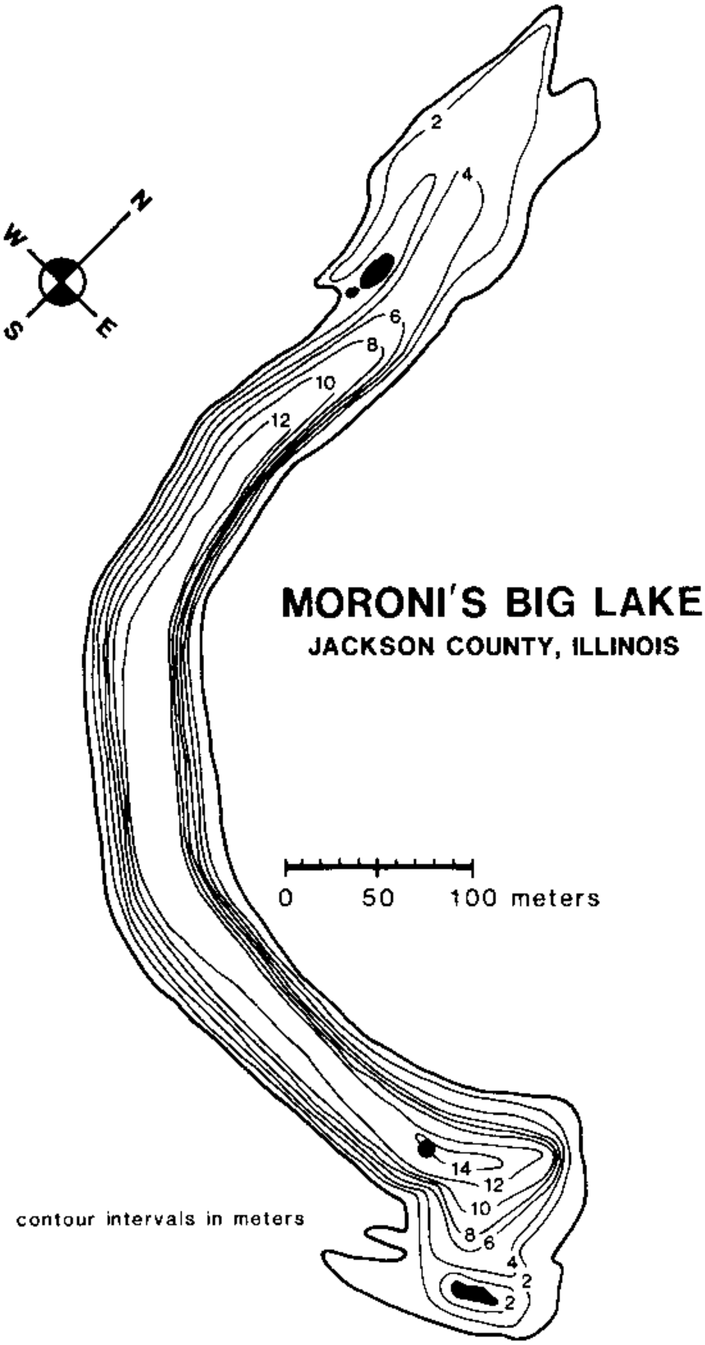

Figure 1. Bathymetry of Moroni's Big Lake (●) = location of sampling station.

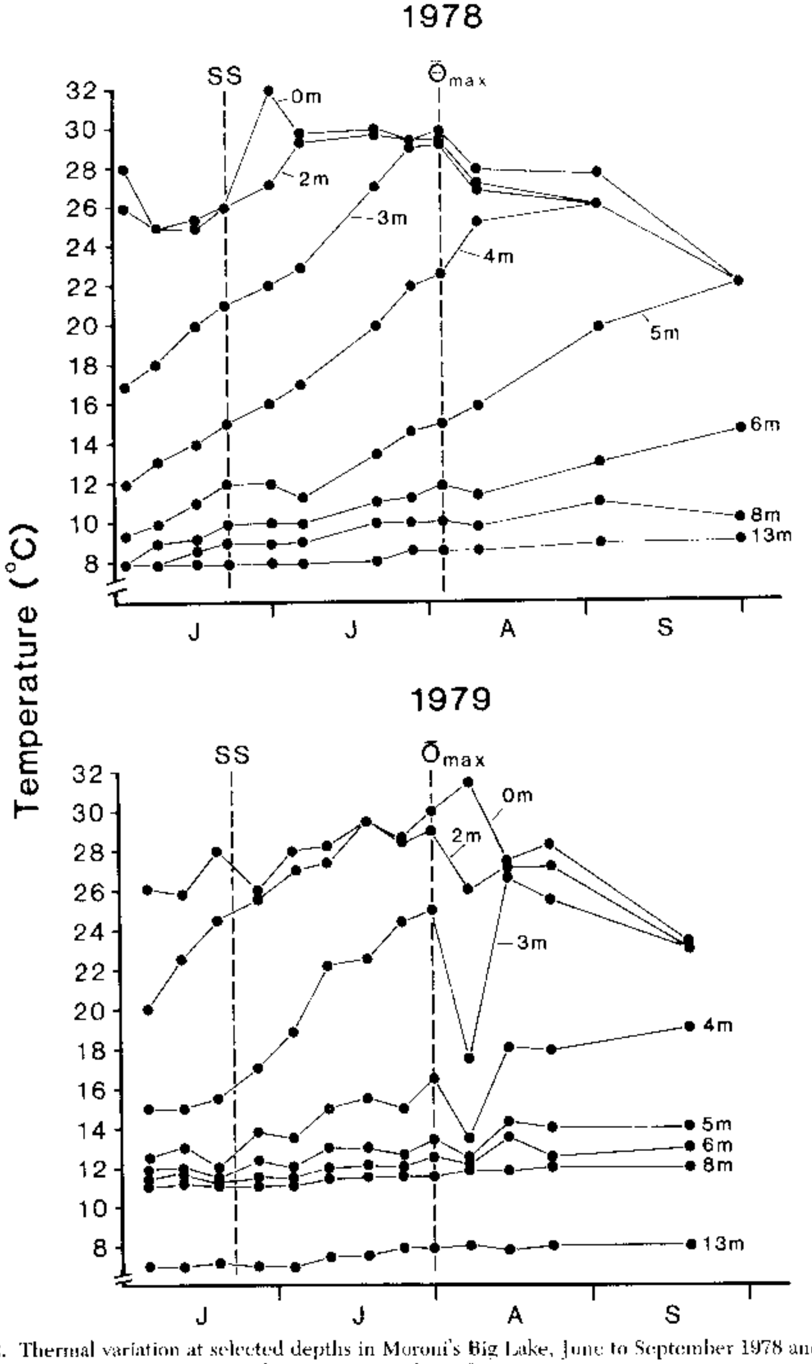

Figure 2. Thermal variation at selected depths in Moroni's Big Lake, June to September 1978 and 1979. (SS) = date of summer solstice; (θ_{max}) = date of maximum mean temperature.

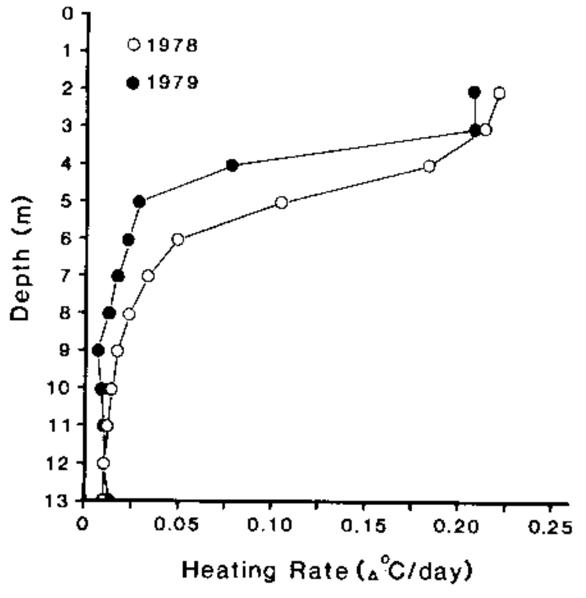

Figure 3. Heating rates in Moroni's Big Lake, June to September 1978 and 1979.

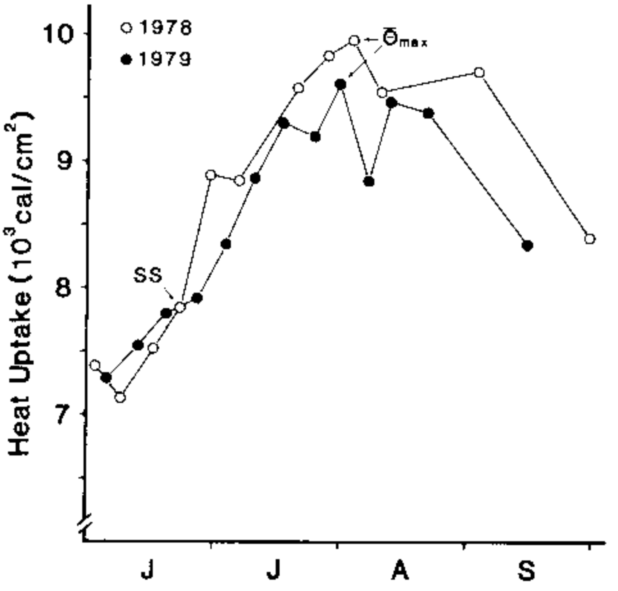

Figure 4. Heat uptake by Moroni's Big Lake, June to September 1978 and 1979. (SS) = date of summer solstice, (θ_{max}) = date of maximum mean temperature.