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Work Energy in a Final-Cut Strip Mine Lake in Southern Illinois

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ABSTRACT

The work parameters: Birgean Work (B), Schmidt Stability (S), and Total Direct Work (G), were calculated for a final-cut strip mine impoundment located in southern Illinois using density data compensated for 1) temperature (= uncorrected work parameters: B, S, G) and 2) temperature, pressure, and salinity (= corrected work parameters: B′, S′, G′). Maximum work energies ocurred after the summer solstice and were comparable to levels observed in similar holomictic lakes. In general, $B' < B$, $S' > S$, and $G' < G$; These differences were attributed mainly to salinity; pressure was less important. Corresponding corrected and uncorrected work parameters were highly correlated with, and at the same time statistically different from, each other. Only differences between B′ and B were regarded as limnologically significant however.

INTRODUCTION

Prior to the enactment of federal legislation (P.L. 95-87), surface coal mines were often abandoned unreclaimed at the end of mining operations. This practice left areas of highly disturbed topography that easily collected water, creating thousands of freshwater strip mine lakes and ponds nationwide. Impoundments which formed in final-cut pits are often morphologically, chemically, and biologically distinct from lentic systems of other origins. However, despite their abundance and unusual characteristics, few final-cut strip mine lakes have been intensively studied, especially with respect to their physical limnology.

Calculation of the work parameters: Birgean Work, Schmidt Stability, and Total Direct Work (Birge 1916; Schmidt 1915, 1928), provides useful comparative data on the lacustrine energy dynamics within a lake (Hutchinson 1957, Johnson et al. 1978). Yet, these parameters seldom have been employed as working limnological tools (Johnson et al. 1978). There are no work energy data available for final-cut strip mine impoundments, nor were the raw data from published studies sufficient to permit accurate computation of these parameters. To this end, I will present an analysis of work energy within such a system located in southern Illinois.

METHODS

This study was conducted on Moroni's Big Lake (MBL), a dimictic final-cut impoundment (5.47 ha) located in Jackson County, Illinois. A description of the study area can be found in Chimney (1982). Data necessary to compute the work parameters were collected May to December 1978 and March to December 1979 at a single open-water station located in the deepest portion of MBL (Chimney 1982, Fig. 1). Temperature and specific conductance measurements were recorded at 1 m intervals (0-13 m) using the thermistor on a YSI 57 oxygen meter and a Barnstead DM-70 CB conductivity bridge. All specific conductance values were corrected to 25°C.

Birgean Work is defined as the energy expended by the wind in creating the observed density distribution starting with an initial condition of isothermy and minimum heat (generally 4°C) (Cole 1979, Idso 1973):

$$B = A_o^{-1} \int_o^{z_m} z(p_i - p_z) A_z \, dz \qquad (1)$$

where B = Birgean Work (g-cm cm^{-2}), A_o = surface area (cm^2), A_z = surface area at depth z (cm^2), z = depth (cm), z_m = maximum depth (cm), Pi = initial density (g cm^{-3}), and p_z = observed density at depth z (g cm^{-3}). Schmidt Stability is the subsequent work that would have to be performed on the observed density structure to overcome stratification and mix the lake to uniformity without adding or substracting heat in the process (Cole 1979, Idso 1973):

$$S = A_o^{-1} \int_o^{z_m} (p_z - \bar{p}) A_z (z - z_{\bar{p}}) \, dz \qquad (2)$$

where S = Schmidt Stability (g-cm cm^{-2}), $\bar{p}$ = final density attained upon mixing the lake to uniformity (g cm^{-3}), and $z_{\bar{p}}$ = depth where $\bar{p}$ exists prior to mixing (cm). Total Direct Work is the sum of these two parameters for a given density distribution (Hutchinson 1957):

$$G = B + S \qquad (3)$$

where G = Total Direct Work (g-cm cm^{-2}). Equations 1 and 2 were evaluated using standard numerical analysis techniques (Adams 1963, McCarty 1975).

Discussions of work energy in limnology texts are usually found in sections dealing with heat. This is because limnologists commonly regard the density of freshwater as a function of its temperature, ignoring other factors such as pressure and salinity. While this is a valid approach in many situations, it is known that at even moderate levels of pressure (> 1.0 bar) or salinity (> 0.15 ppt), the actual density of water differs appreciably from values based solely on temperature (Chen and Millero 1977). Only studies of meromictic lakes (e.g. Effler et al. 1981, MacIntyre and Melack 1982, Walker 1974) have, to date, corrected density for pressure/salinity before work parameters were calculated. The importance of pressure/salinity to work energy in MBL was examined by deriving two separate density distributions for each date. First, "uncorrected" densities were computed from temperature data using the equation of Tilton and Taylor (1937). Second, "corrected" densities, compensaterd for temperature, pressure, and salinity, were derived following Chen and Millero (1977). Salinity was estimated from specific conductance values (Kemp 1971). Subsequently, "uncorrected" (designated B,S,G,) and "corrected" (designated B',S',G') work parameters were computed using the appropriate density estimates.

All statistics were calculated using SAS (SAS Institute 1982). The critical level of significance (α) was set at 0.01 in all cases.

RESULTS AND DISCUSSION

Maximum work energies in MBL (Table 1) were comparable to values reported for other strongly stratified holomictic lakes of similar size and depth (cf. Hutchinson 1957, Johnson et al. 1979). All work parameters reached their maximum values after the summer solstice (Fig. 1). This would be expected as MBL gained an appreciable proportion of its summer heat budget (21.4% and 18.8% in 1978 and 1979) between this date and the end of the heating period (the date of maximum mean temperature) (Chimney 1982).

Throughout the study, $B' < B$ (Fig. 1). Maximum Birgean Work was achieved as MBL began to cool and other measures of lake energy (e.g. mean temperature, Schmidt Stability, Total Direct Work) were on the decline. However, until stratification was completely destroyed, heat continued to be transported down through the metalimnion. Net heat gain in the meta- and hypolimnion apparently more than offset epilimnetic loss during the initial stages of turnover, resulting in the continued increase in Birgean Work for a short period of time.

Densities in the lower hypolimnion, when corrected for pressure/salinity, often actually increased relative to p_i (see equation 1). This resulted in negative values of Birgean Work for these strata. It is suggested that no wind-related work was done at these depths; rather, density currents, produced biogenically (Stahl 1979), were responsible for heat transport at these times.

Changes in Schmidt Stability were highly correlated with thermal variation in the 0-1 m stratum of MBL (Table 2) with maximum values for this parameter occurring on the dates of highest surface temperatures (except S' in 1979) (Fig. 1). Correcting density for pressure/salinity generally resulted in $S' > S$. Note however, that from June to August 1979 the opposite was true.

Variability in Total Direct Work closely paralled changes in mean lake temperature (Table 2). The dates of maximum Total Direct Work also marked the maximum mean lake temperature (Fig. 1) and the highest summer heat budget (Chimney 1982). Overall, levels of Total Direct Work, when corrected for pressure/salinity, were less than those based on temperature profiles alone.

Differences between corresponding corrected and uncorrected work parameters (Fig. 1) were attributed mainly to the influence of salinity; pressure was thought to be of minor importance. Salinity ranged from 1.5 to 2.1 ppt (i.e. 2294 to 3136 μmhos cm^{-1}) (Fig. 2), levels an order of magnitude greater than the critical value of Chen and Millero (1977) and typical of other strip mine lakes in the region (cf. Lewis and Peters 1954, McConathy and Stahl 1982). By comparison, only $\sim$ 10% of total lake volume was at a pressure > 1.0 bar.

Corresponding corrected and uncorrected work parameters, while highly correlated (Table 3), were statistically different from each other with the exception of Schmidt Stability in 1979 (Table 4). However, only the differences between corrected and uncorrected Birgean Work were felt to be limnologically significant in terms of accurately documenting the lacustrine energy dynamics of MBL.

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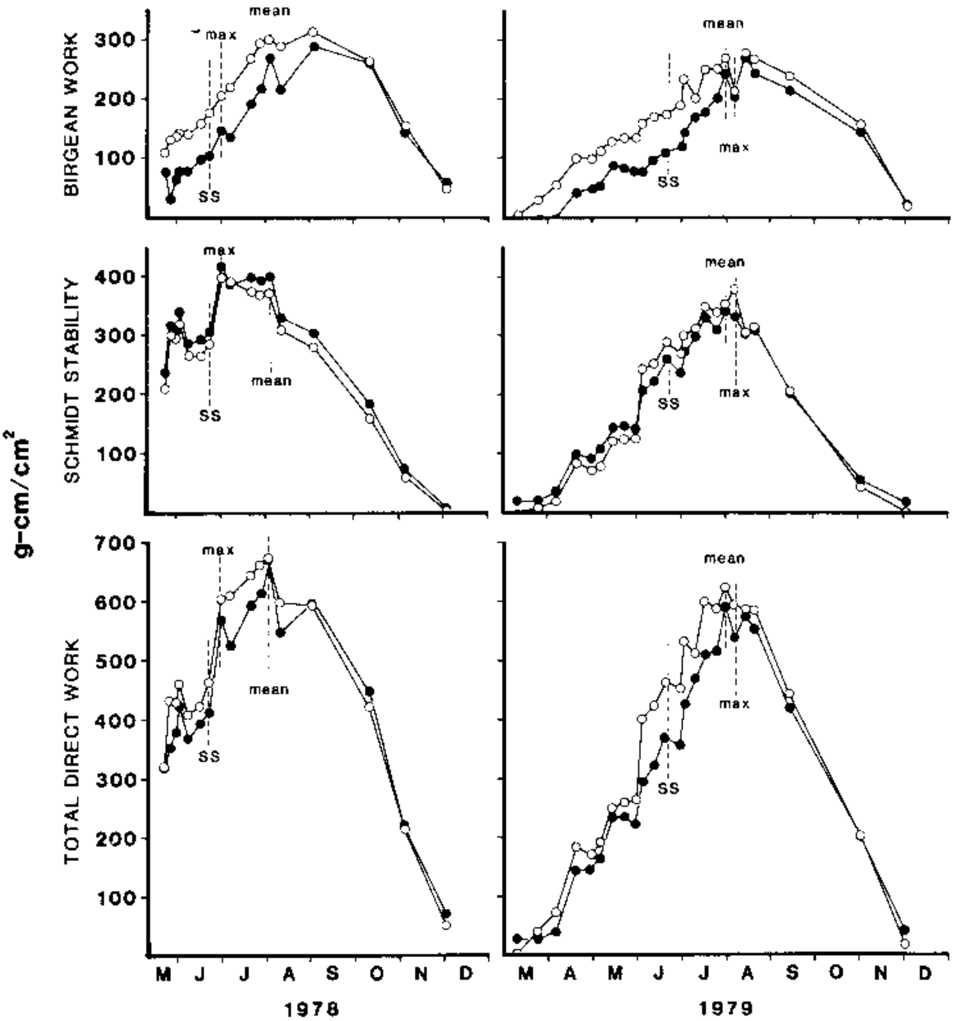

Fig. 1. Birgean Work, Schmidt Stability, and Total Direct Work in Moroni's Big Lake. (•) = values corrected for pressure/salinity; (o) = values uncorrected for pressure/salinity; (SS) = date of summer solstice; (mean) = date of maximum mean lake temperature; (max) = date of maximum surface temperature.

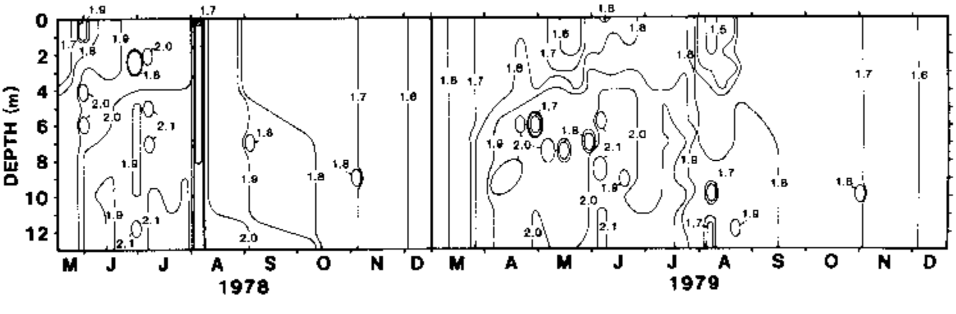

Fig. 2. Time-depth diagram of salinity (ppt) for Moroni's Big Lake.

Table 1. Maximum Birgean Work, Schmidt Stability, and Total Direct Work from Moroni's Big Lake.*

Parameter	Year 1978	Year 1979
Birgean Work		
B	316.3	281.8
B′	289.6	273.3
Schmidt Stability		
S	398.0	380.8
S′	420.5	346.1
Total Direct Work		
G	675.9	627.2
G′	673.4	592.3

*All values expressed as g cm cm^{-2}.

Table 2. Pearson product-moment correlations of work parameters with surface and mean lake temperature from Moroni's Big Lake.

1978	B	B′	S	S′	G	G′
surface	ns	ns	0.9747	0.9795	0.9216	0.8616
mean	0.9228	0.7316	0.8008	0.8142	0.9658	0.9767

1979	B	B′	S	S′	G	G′
surface	0.9104	0.7914	0.9580	0.9618	0.9621	0.9240
mean	0.9713	0.8780	0.9235	0.9383	0.9645	0.9481

Table 3. Pearson product-moment correlations between corrected and uncorrected work parameters from Moroni's Big Lake.

1978	B′	S′	G′
B	0.9262		
S		0.9979	
G			0.9829

1979	B′	S′	G′
B	0.9478		
S		0.9939	
G			0.9855

Table 4. Paired comparison t-tests between corrected and uncorrected work parameters from Moroni's Big Lake.

Year	Parameter	T	df	PR > T
1978	Birgean Work	6.92	23	0.0001
	Schmidt Stability	-11.39	23	0.0001
	Total Direct Work	3.89	23	0.0013
1979	Birgean Work	7.90	16	0.0001
	Schmidt Stability	0.18	16	0.8621
	Total Direct Work	5.40	16	0.0001