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EVALUATION OF HEAT DISTRIBUTION IN A SOUTH CAROLINA RESERVOIR RECEIVING HEATED WATER

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ABSTRACT

Techniques for treating temperature data from thermally polluted lakes are proposed applied to a South Carolina reservoir receiving waste heat. Theoretical justificatio provided for reducing temperature profiles to three biologically meaningful variables: total heat per unit of surface area in excess of a specific base temperature, the m temperature of the upper water column, and an index of thermal heterogeneity. algorithm is provided for calculating these indexes from any vertical temperature profile.

The distribution of waste heat in a reservoir is illustrated using the concepts of ex heat, mean epilimnetic temperature, and thermal heterogeneity. Heat enters the lake about 31°C and is horizontally distributed with great efficiency near the discharge. W heat is largely confined to a surface layer even at the discharge site, where turbulenc great. A diurnal study in March showed that stabilization of the water column by waste h persisted overnight despite some nocturnal cooling but was least marked at stations rem from the discharge. A study of heat distribution on consecutive days showed that total h above the base line can be much lower near the discharge than at other points in the lak a result of internal seiches and possibly of variation in wind exposure. Ther heterogeneity, however, was always highest near the discharge. An extended study of h distribution during late winter and early spring demonstrated the effects of natural s warming, gale winds, interruption of heat flow, and other factors. Extraordin hypolimnetic warming of the lake occurs during early spring and is attributed to addition of waste heat. The relevance of these findings to reservoirs at other latitude discussed.

As rapidly increasing energy demands are satisfied by the construction of pov plants, thermally altered environments will inevitably comprise a substant proportion of all freshwater habitats in the United States. If expansion can carefully planned, the number of natural water bodies in which thermal str actually challenges the physiological plasticity of freshwater organisms will quite limited. Since it certainly will be impossible to restrict the subtle therm alteration of vast amounts of freshwater, it is significant that small continu

…at loads can exercise a diversity of important biological effects …ysiologically stressing organisms. One group of such effects arises …otential influence of waste heat on the thermal regime of lakes.

… limnologists have scarcely begun to study the effects of artificial …es, although the application of numerous fundamental principles …m studies of natural heating is clear enough. Engineering studies … emphasize heat flux at the water surface and are often largely …al. Although total heat balance in lakes has been studied rather …y, both under natural conditions (Anderson and Pritchard, 1951; … 1954) and in one artificially heated lake (Harbeck, Hoberg, and … 1959), vertical and horizontal heat distribution from point sources on … much less adequately understood. Heat distribution is of critical … importance because of potential alterations of natural vertical and … temperature gradients or distortion of the thermal cycle by waste …

… and Mackenzie (1971) have made some interesting speculations on …tial fate of waste heat in Cayuga Lake, N. Y. In considering turbulence …by the discharge as well as its heat content, they conclude that thermal … are likely to alter the dates of overturn and stratification and that …etic warming is inevitable. The work is entirely theoretical, however, … not include any verification from field data. In a related paper Moore …ria (1972) propose that discharge turbulence is a critical factor that … treated theoretically if high values of the Richardson number for … currents could be established as limits of thermal stability. To date, …tic observation seems to have lagged behind theory.

… complete three-dimensional mapping of heated discharges is a highly …ory basis for studies of heat distribution. Data of this type spanning …riods are already available for some very large lakes, notably Lake Huron …v, Crawford, and Pade, 1971) and Lake Michigan (Abu-Shumays, … and Prastein, 1971). This is probably not a feasible approach, however, … routine description and study of heat distribution in support of …al studies. Minimum data collection for complete mapping is prohibi- …extensive for most multipurpose studies, and data summary is inevitably …hen time is added as a necessary fourth dimension.

… paper proposes methods for treating temperature data from thermally … lakes and applies these methods to a South Carolina reservoir. The …cal section aims merely to establish some means by which biologically …tful summary data can be extracted from a large series of thermal profiles … recourse to hydromechanics or heat-budget evaluations. The second … deals with several specific aspects of waste-heat distribution, both as a …the method and as an evaluation of the heat-distribution phenomenon in …ely small lake.

METHODS AND STUDY SITE

Par Pond is an 1120-ha artificial impoundment located in South Carolina at 81°31′ N, 33°14′ W (Fig. 1). Important summary descriptive data for the lake as given by Marshall and Leroy (1971) include mean depth, 6.2 m; shoreline length, 53 km; and replacement time, 6 months. The lake has a single basin extending to a maximum depth of 16 m.

Waste heat from a single nuclear reactor enters Par Pond through an arm, hereinafter referred to as the hot arm, that extends westward from the middle of the lake (Fig. 1). The hot water passes through a canal, two small cooling basins,

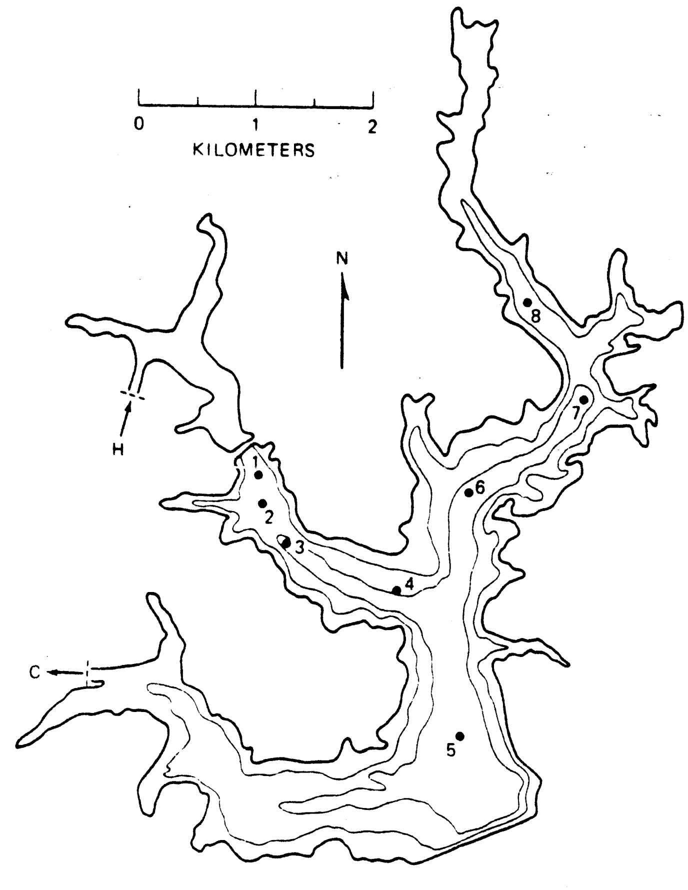

Fig. 1 Map of Par Pond showing 5- and 10-m contour lines (adapted from USAEC map H.P. 482). Cooling water leaves the lake at C and returns at H via a canal to the large cooling basin adjacent to Par Pond. Hot water enters Par Pond through the dam northwest of station 1. The arm of the lake extending west from station 4 is referred to in the text as the hot arm.

and one large cooling basin before it enters the lake through a culvert that connects the large cooling basin with the hot arm. The cooling water is drawn from another arm of the lake through an intake situated about 5 m below the water surface. Hot water flows continuously into Par Pond for extended periods, but heat flow is briefly interrupted at times when the reactor is not operating. The temperature of the water entering the hot arm ranged between 30 and 34.5°C during the February to April study period. The temperature of the discharge entering Par Pond during this period was most frequently between 31 and 32°C.

Eight primary sampling stations were distributed among the hot arm, the central basin, and the north arm of Par Pond (Fig. 1). The stations are numbered in approximate order of proximity to the heat source. Stations 1 to 3 are well within the hot arm and close to the heat source. Stations 4 to 6 are transitional, but station 5 is somewhat distinct because it is located within the region of maximum wind stress and water depth. Stations 7 and 8 are remote from the heat source on Par Pond. Water depth at all stations is greater than 5 m.

Temperatures were measured with a thermistor at 1-m intervals between the surface and bottom and just above the bottom at each station. All profiles were made in the afternoon except as noted.

THEORY

Notation

Notation conforms wherever possible to standard limnologic usage as put forth by Hutchinson (1957).

Θ	Total heat above 4°C, cal/cm^2
Θ_e	Epilimnetic heat above 4°C, cal/cm^2
Θ_{ex}	Epilimnetic heat in excess of hypolimnetic temperature, cal/cm^2
θ_z	Temperature at depth z, °C
θ_h	Hypolimnetic temperature, °C
θ_{ex}	Epilimnetic temperature in excess of hypolimnetic temperature, °C
z	Depth, m
z_e	Thickness of the epilimnion, m
z_b	Thickness of the entire water column, m
Φ_{ex}	Thermal-heterogeneity index for the epilimnion

Distribution of Heat over the Lake Surface

The amount of heat in excess of 0°C beneath a unit area of lake surface at any specified site on a lake can be derived from the depth of the water and the temperature distribution at that site:

$$\Theta = 100 \int_0^{z_b} \theta_z \, dz \qquad (1)$$

Forel (1880) first applied this concept to lakes by considering the ann changes in Θ at the deepest point in the lake. As Hutchinson (1957) indicated his review of limnological heat-budget studies, Forel's method is unsou because advective heat transfer affects Θ. The Forelian heat budget has therefo been discarded in favor of the Birgean heat budget, which uses a hypsograp approach to treat the entire lake. The Birgean heat budget is essentially unbias by the depth of a lake or the amount of advective heat transfer and c therefore be used in comparing and characterizing lakes under natu conditions.

Despite its deficiencies for ordinary limnological work, the Forelian he budget is an excellent point of departure for quantitative studies of he distribution on lakes receiving heated effluent. One goal of such studies is measure the variation between stations extending from the heat source to t most unaffected portions of the lake. With some modification Eq. 1 can be us as the basis for comparison of locations at various distances from the he source. First, some distinction must be made between variation in Θ due differences in depth between stations and variation in Θ due to artificial therm loading. In practice the distinction can be achieved by changing the limits integration on Eq. 1 to coincide with the epilimnion rather than the entire wat column,

$$\Theta_e = 100 \int_0^{z_e} \theta_z \, dz$$

Equation 2 is applicable to a comparison of any group of sites on a lake the depth at each site exceeds z_e. Fortunately a large portion of the surface ar of most reservoirs can be treated within this assumption.

The summertime heat content of temperate lakes in excess of 4°C is so gre that significant variations in heat content are not easy to visualize on the basis Θ_e. It is therefore convenient to consider only the amount of heat in excess the hypolimnetic temperature. This quantity is referred to here simply as exc heat and is given by

$$\Theta_{ex} = 100 \int_0^{z_e} (\theta_z - \theta_h) \, dz$$

Equation 3 assumes that z_e is sufficiently large that most of the artificial a natural heat received by the lake over a specific interval of time will distributed above z_e. Similarly, θ_h is used as a base-line temperature above whi heat accumulates and is therefore not expected to change rapidly. The spec problems connected with the definition of θ_h and z_e during winter and ear spring are discussed in a later section.

The determination of z_e and θ_h from temperature profiles could formalized by setting z_e equal to the depth at which $d\theta/dz$ is maximum a setting θ_h equal to the minimum temperature of the water column. Th procedure is somewhat unsatisfactory because of the differences between real and conceptual schemes of temperature distribution in stratified lakes. The thermocline may be quite thick under some circumstances, and substantial heat may be transferred to points that are within the thermocline but somewhat below the depth at which $d\theta/dz$ is maximum. Furthermore, the hypolimnion is usually not uniform in temperature, but heat transfer through the hypolimnion is nevertheless very slow. It is therefore most satisfactory to set θ_h equal to the temperature at the top of the hypolimnion as determined by inspection and let z_e be the uppermost depth at which this temperature is found in the water column.

Equation 3 can be evaluated by mechanical integration of temperature profiles from the field. This method is tedious and therefore unsuitable for the treatment of large numbers of thermal profiles. Some experimentation with numerical integration showed that the application of the trapezoidal rule gives excellent results, namely,

$$\Theta_{ex} \simeq 100 \sum_i \left\{ \frac{[(\theta_i - \theta_h) + (\theta_{i+1} - \theta_h)](z_{i+1} - z_i)}{2} \right\} \qquad (4)$$

for values of i such that $\theta_{i+1} \geqslant \theta_h$. Limits can be set for the approximation (see the appendix to this paper), but the limits are extremely conservative for temperature curves, even if measurements are made only at 1-m intervals. Among 20 profiles chosen at random from Par Pond data, Eq. 4 gave an estimate of Θ_{ex} that differed by less than 5% from the true value. Equation 4 is therefore assumed to be a completely reliable measure of Θ_{ex} for present purposes.

Distribution of Heat with Depth Within the Epilimnion

The calculation of total excess heat per unit of surface area (Θ_{ex}) provides a convenient means of evaluating the degree of artificial alteration of various sites on a reservoir receiving thermal effluent. It is of biological significance to recognize, however, that equal heat loads can be accompanied by various heat distributions. Two additional statistics, mean epilimnetic temperature and a thermal-heterogeneity index, are useful in evaluating variation in heat distribution.

A mean excess temperature can be defined on the basis of the temperature profile, hypolimnetic temperature, and thickness of the epilimnion (Fig. 2):

$$\theta_{ex} = \frac{1}{z_e} \int_0^{z_e} (\theta_z - \theta_h)\, dz \qquad (5)$$

In practice this quantity is very easily estimated if Θ_{ex} is known since

$$\theta_{ex} \simeq \frac{\Theta_{ex}}{100\, z_e} \qquad (6)$$

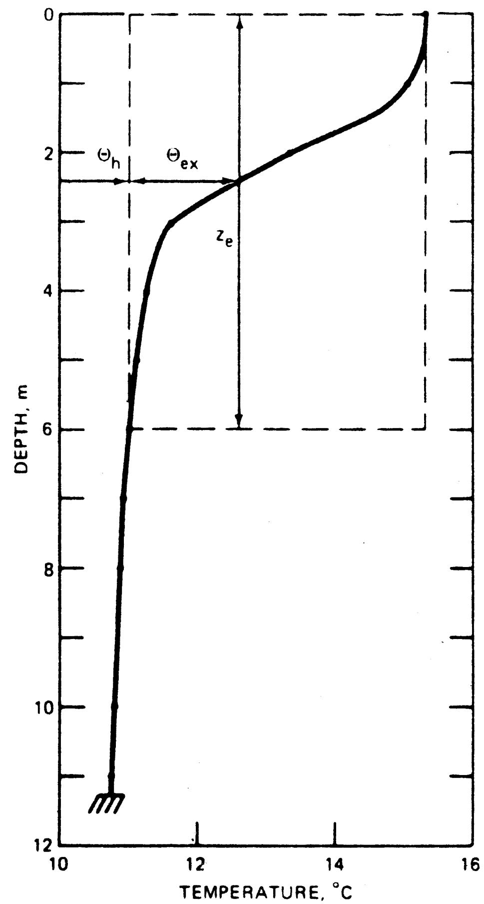

Fig. 2 Distribution of temperature with depth in Par Pond at station 3 o[illegible] Feb. 23, 1973. The curve illustrates the application of concepts described [illegible] the text. $\Theta_{ex} \simeq 960$ cal/cm^2; $\theta_{ex} \simeq 1.6$°C; and $\Phi_{ex} \simeq 2.9$.

It is easy to imagine circumstances under which Θ_{ex} for two or more sites [illegible] be equal but θ_{ex} would differ between sites. Theoretical profiles that meet [illegible] requirements appear in Fig. 3. The constant value of Θ_{ex} suggests [illegible] thermal loading in the four illustrated cases, and the differing mean epilim[illegible] temperatures in each case indicate potential variation in average temper[illegible] which a nonmotile (planktonic) particle would be exposed.

Figure 3 also shows graphically how the probability that a nonmotile [illegible] will be exposed to a given temperature range can vary even though [illegible] constant. If a specific temperature range ($\theta_1 - \theta_2$) is of interest, [illegible] probability can be calculated directly from each temperature cur[illegible]

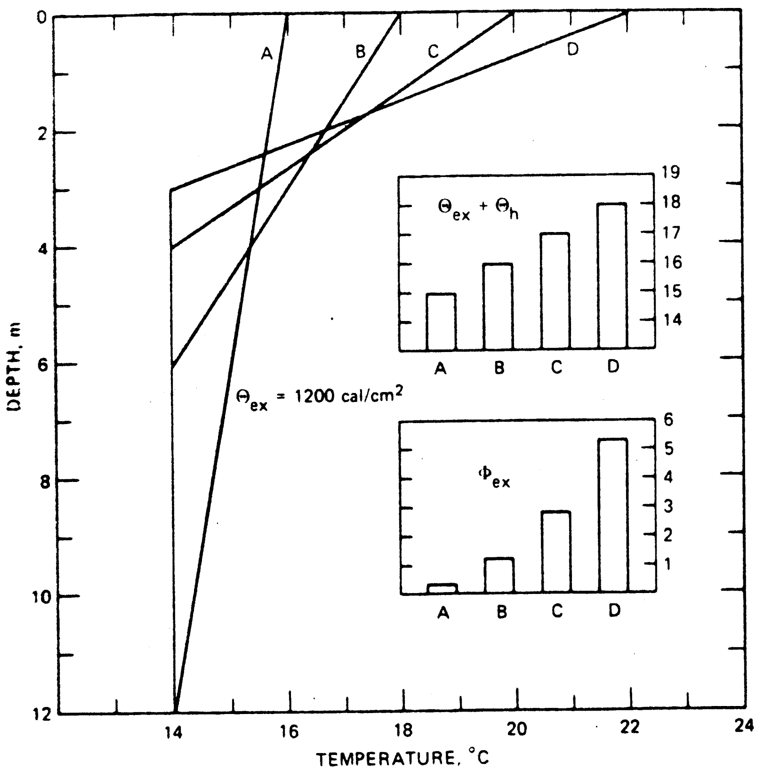

Fig. 3 Theoretical distributions of temperature with depth, assuming constant total heat per unit of surface area. Variations in the mean temperature of the epilimnion ($\theta_{ex} + \theta_h$) and the thermal-heterogeneity index (Φ_{ex}) are indicated for each of four conditions.

assuming that the particle moves throughout the epilimnion and that its movement is random,

$$p(\theta_1, \theta_2) = \frac{z_1 - z_2}{z_e} \tag{7}$$

Equation 7 also provides a measure of habitat space available to motile species with known thermal optimums or requirements. Despite the simplicity of this approach to biological interpretation of thermal heterogeneity, it apparently has not been used to date.

If the thermal optimums or requirements of a species are not known or if one is primarily interested in thermal effects at the community level, a thermal-heterogeneity index of some kind is more useful than a specific probability figure. One obvious option is the temperature range of the

epilimnion. This is a highly unsatisfactory index for temperatures because t[h] shape of the temperature–depth profile varies greatly and because a superfic[i] layer of hot water is characteristic of lakes on calm sunny days owing to t[h] exponential nature of light absorption in water.

One satisfactory measure of temperature variation can obviously be deriv[ed] from the mean excess temperature, and this is adopted here as the therm[al] heterogeneity index,

$$\Phi_{ex} = \frac{1}{z_e} \int_0^{z_e} [\theta_z - (\theta_{ex} + \theta_h)]^2 \, dz$$

The estimate is then

$$\Phi_{ex} \simeq \frac{1}{n} \sum_{i=1}^{n} [\theta_{z_i} - (\theta_{ex} + \theta_h)]^2$$

where n is some number of equally spaced temperature measurements within t[he] interval 0, z_e. For low values of n, the estimate may diverge considerably fr[om] the true value of Φ_{ex}. A better approximation is obtained by increasi[ng] n artificially,

$$\Phi_{ex} \simeq \frac{1}{(2n-1)} \left\{ \sum_{i=1}^{n} [\theta_{z_i} - (\theta_{ex} + \theta_h)]^2 + \sum_{i=1}^{n-1} \left(\frac{\theta_{z_i} + \theta_{z_{i+1}}}{2} - \theta_{ex} - \theta_h \right)^2 \right\}$$

This is defensible because θ_z is a monotonic nonincreasing function of z a[nd] because the depth increment between temperature readings is constant. Fo[r a] representative temperature curve from Par Pond, the true value of Φ_{ex} was 8[...] Eqs. 9 and 10 gave 9.7 and 9.0, respectively.

TEMPERATURE STUDIES ON PAR POND

Par Pond temperatures measured during February, March, and Ap[ril] illustrate the distribution of waste heat from a point source and therefo[re] provide an opportunity for applying the methods proposed in the foregoi[ng] discussion. Par Pond is of course warm monomictic. The mixing period is kno[wn] to extend approximately from November through March (Marshall and Ler[...] 1971; Marshall and Tilly, 1971). This study thus began at the time of minimu[m] water temperature and maximum homogeneity of vertical heat distributi[on]. Natural solar-heat accumulation began in the middle of March, and, by the l[ast] half of April, sufficient net solar uptake had occurred to generate therm[al] stratification of rather high stability at points remote from the source of wa[ste] heat.

Table 1 indicates the trend of changes resulting from deep mixing during the study period. Both minimum temperature, representing the bottom of the water column at the deepest stations, and θ_h, representing the top of the hypolimnion, increased steadily as heat from natural and artificial sources was distributed downward by turbulence. In some instances specific explanations can be given for deepwater temperature changes. The very low minimum for February 21, for example, can be traced to a thin (0.5-m) pocket of exceptionally cold water found just above the bottom at station 8 in 7.5 m of water. At station 5 in 16 m of water, minimum temperature on the same date was 19.8°C. Since a seiche was apparently not involved, it seems safe to infer that the cold layer was a density flow from the shoreline. Another exceptional occurrence was the marked increase in minimum temperature between April 9 and April 15 which can probably be attributed to gale-force winds blowing over the lake between these dates. In general, however, the increase in minimum temperature and θ_h is due to a positive heat balance combined with thermal instability during the study period.

Although the entire study period fell within the circulation period for Par Pond, it was never difficult to identify a thermal discontinuity. This accounts for the apparently paradoxical determinations of θ_h before the stratification period. The distinction between thermal layering during the circulation period and the same phenomenon during stratification is merely a matter of relative stability. The addition of waste heat during the circulation period of course reinforces weak tendencies toward temporary stratification that would result from a

TABLE 1

DEEPWATER-TEMPERATURE TRENDS, PAR POND

Date	Minimum temp.,* °C	θ_h†, °C
February 21	10.0	10.8
February 23	10.5	11.0
February 29	11.0	11.6
March 3	11.2	11.9
March 14	11.4	12.3
March 24	13.4	15.9
April 3	13.8	17.8
April 9	14.6	17.8
April 15	16.7	17.8

*The minimum temperature for each date is the lowest temperature recorded at any of the eight sampling stations.

†Hypolimnetic temperature was determined as described in the text.

combination of sunny weather and low wind stress without additions of artifi heat. Substantial vertical interchange between surface water and water near bottom nevertheless occurs when wind stress is high because the density gradi across the thermocline is insufficient at this time of year to withstand mu turbulence. The progressive warming of the hypolimnion documented in Tabl should therefore be thought of as a discontinuous process punctuated intervals of stratification that vary in duration from a few days to a week more during calm sunny weather.

Heat Distribution near the Discharge

A short, intensive study was made of the distribution of waste heat in vicinity of the discharge into Par Pond. Six concentric rings of sampling poi were oriented around the discharge at distances of 50, 100, 300, 500, 800, a 1100 m from the entry point of the hot water. Figure 4 shows a typical set temperature profiles from these stations during winter.

The discharge from the large cooling pond to the hot arm of Par Ponc located 1 to 2 m below the surface and is directed upward. The hot water t forms a boil just above the discharge and subsequently flows horizontally in directions. Temperatures at a given location close to the boil and from depths 0 to 1 m are of course variable owing to the movement of large water masse response to turbulence. The range of variation over a 1-min period is usually l than 2°C, even near the boil. The temperatures reported here are the midran of temperatures observed over a brief observation period. Rapid variation temperature is infrequent and greatly reduced in range at depths below 1 m distances greater than 500 m beyond the boil; thus variation of this type is of major concern even in the hot arm.

The two most striking features of heat distribution within the hot arm the high efficiency of advective heat transfer and the equally mark inefficiency of vertical heat transfer. Table 2, which summarizes the he distribution data for January 31, shows that incoming waste heat, the ma component of Θ_{ex} on this date, was little different 50 m from the source th 1100 m from the source. Application of the Wilcoxon t-test to the two grou of stations with the most divergent means (100 and 1100 m) indicates significant difference in Θ_{ex} at $\alpha = 0.05$ ($p \simeq 0.10$). Figure 4 shows that a few the profiles in the shallowest portions of the hot arm do not extend fully to but data analysis is unaffected by the exclusion of these samples. Although t slight gradient of heat loss at points distant from the source is undoubtedly r and could be demonstrated with more extensive sampling, waste heat is clea moved very efficiently from the boil to points within 1000 m of the discharg The immediate explanation for this uniformity is the turbulence created by t boil, which exercises its effect in two ways. Turbulence supplies the energy f advection of the heat and reduces the surface temperatures by promoti vertical mixing. The latter process may be an extremely important aspect of t

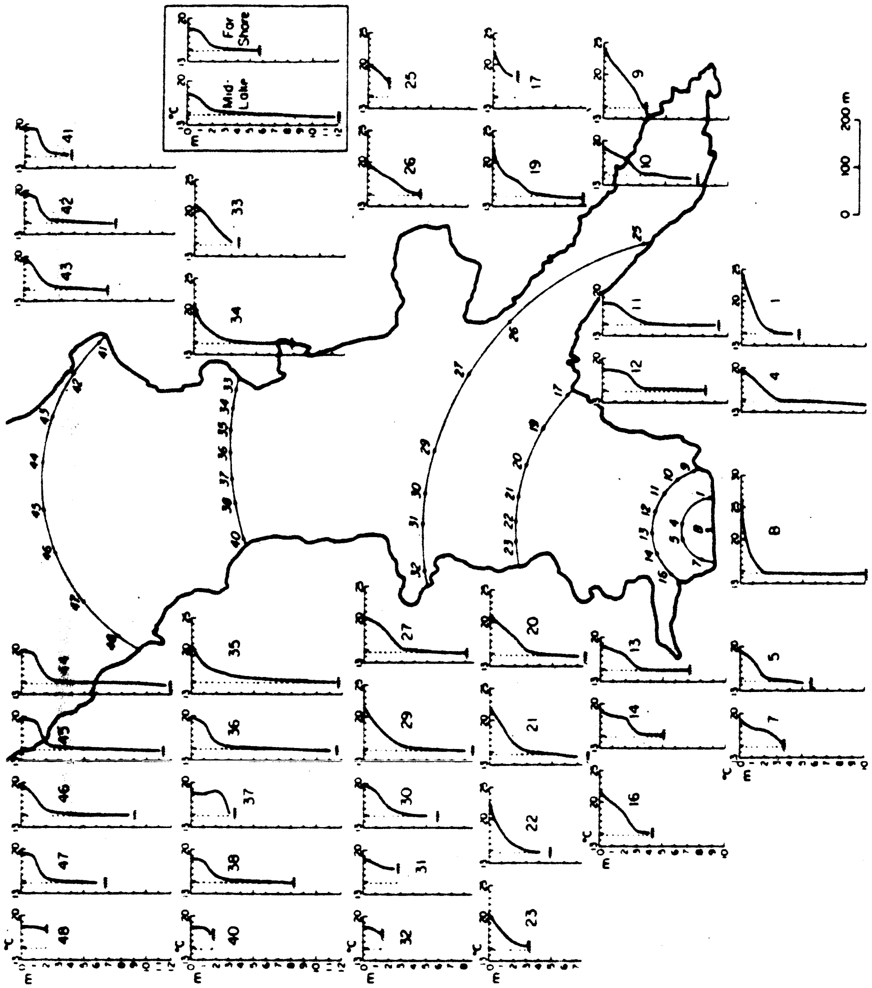

Fig. 4 The discharge area of Par Pond, showing the thermal profiles and arrangement of sampling stations for an intensive study of the hot arm on Jan. 31, 1973.

TABLE 2

HEAT-DISTRIBUTION DATA FOR 40 STATIONS* WITHIN THE HOT ARM (JAN. 31, 1973)

Distance from discharge, m	Number of stations	Mean Θ_{ex}, cal/cm²	Range Θ_{ex}, cal/cm²	Mean $\theta_h + \theta_{ex}$, °C	Mean Φ_{ex}
0	1	700		18.82	23.60
50	4	757	530 to 1000	17.32	5.32
100	7	927	690 to 1470	17.36	3.14
300	6	848	700 to 1035	17.64	4.72
500	7	745	447 to 945	17.52	2.24
800	7	722	452 to 930	16.87	2.44
1100	8	702	605 to 815	16.40	3.27

*Stations are grouped according to their distance from the discharge.

conservation of waste heat owing to the marked effect of surface temperatu on heat dissipation by evaporation and conductance and to a lesser extent long-wave radiation as predicted by the Stefan–Boltzman law.

Table 2 suggests that vertical distribution of heat within the epilimn adjacent to the discharge is somewhat different from that at other points in hot arm. At the 50-m station and beyond, the shape of the temperature curv more dependent on irregular patterns of turbulence than on proximity of discharge.

The most remarkable aspect of vertical heat distribution within the hot a is the persistence of a marked thermal discontinuity despite turbulence. Fig. 4 shows, waste heat is distributed almost entirely within the top 4 m a principally within the top 2 m of the water column. It is of great biolog importance that a pool of cool hypolimnetic water persists at all points wit the hot arm where the depth exceeds z_e. The high winter minimum temperat at this latitude undoubtedly contributes to the confinement of waste heat similar confinement of waste heat was reported by Csanady, Crawford, a Pade (1971) during summertime studies on Lake Huron. Wintertime h addition to a lake such as Par Pond at more northerly latitudes would induc smaller density difference between upper and lower layers, which wo probably lead to an increase in z_e and a consequent reduction in the size of hypolimnetic pool. It is even possible that, if ambient temperatures were n 0°C, the thermal discharge could sink owing to the anomalous increase of wa density between 0 and 4°C.

Diurnal Variation in Heat Distribution

A diurnal transect study was designed as a complement to the wee transect studies to investigate the possibility that the pattern of heat distribut rom one end of the lake to the other might vary markedly overnight owing to eat loss and a consequent reduction of stability in the water column. Weather onditions were ideal for testing this hypothesis. When the afternoon transect 1645) was made, the air temperature was 17.0°C and a light breeze was blowing rom the southeast. By the time the evening transect was taken (2130), the air emperature had decreased to 15.2°C and the wind had increased to the point of roducing whitecaps. The dawn transect (0545) was preceded by the resumption f calm weather and a heavy rain and the air temperature was 13.9°C.

Figure 5 shows that the relative distribution of heat between stations was ssentially constant overnight despite the changing weather conditions and wind tress. There was, of course, an overall heat loss from the lake overnight, and this manifested as a decline in Θ_{ex} for five stations. The increase in Θ_{ex} at ation 4 undoubtedly reflects the rise in wind strength, which must have esulted in more efficient advection of heat from the source. The excess heat at ations 5 to 8 outside the hot arm was initially low and declined to even lower vels during the night. Complete mixing of the water column apparently did not ccur even at station 8, because Θ_{ex} remained significantly above zero roughout the night.

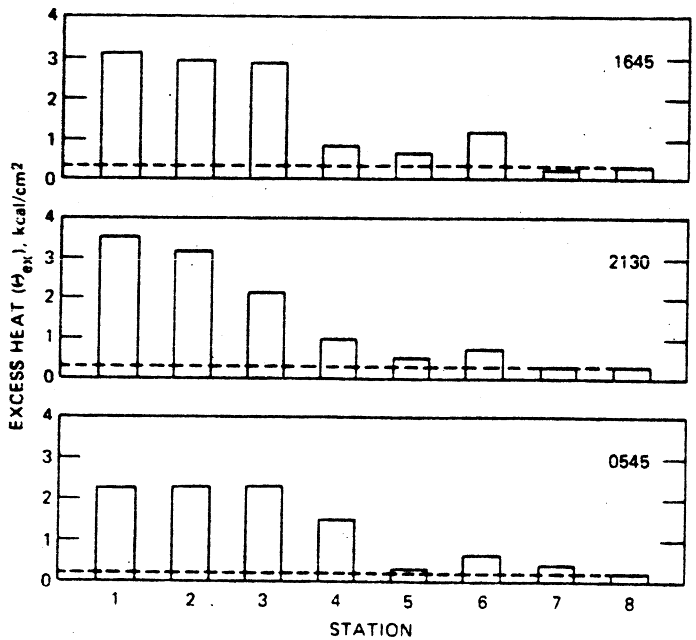

Fig. 5 Excess heat at stations 1 to 8 for afternoon and evening on Mar. 24, 1973, and dawn on Mar. 25, 1973. The dashed line approximates the contribution of solar heat to Θ_{ex}.

The mean epilimnetic temperature (Fig. 6) was most stable near the discharge (stations 1 and 2) and remote from the heat source (stations 7 and 8) and least stable at intermediate stations 3 to 6. The continuous input of heat near the discharge obviously buffers mean temperature against natural temperature changes, whereas the great reservoir of cool water within the north arm buffers the mean temperature against the artificial heat input. Consequently, the greatest variation is found between these extremes, where the balance between natural and artificial heat fluxes depends upon the prevailing weather conditions.

The heterogeneity index (Fig. 6) illustrates still another trend in the transect. Heterogeneity is both higher and more constant near the discharge than at any other point, especially the north arm. This trend is partially attributable to the effect of a temperature rise on the stability of a given thermal gradient. Warm portions of the epilimnion are much more resistant to mixing by wind than are cool portions, even if the thermal gradient is constant. High heterogeneity of temperature within the epilimnion is also maintained near the heat source by a continuous input of heat sufficient to offset the homogenizing effects of natural turbulence.

Diurnal variation in the thermal statistics appears to follow a pattern that agrees well with a priori conceptions of the factors regulating heat transfer and

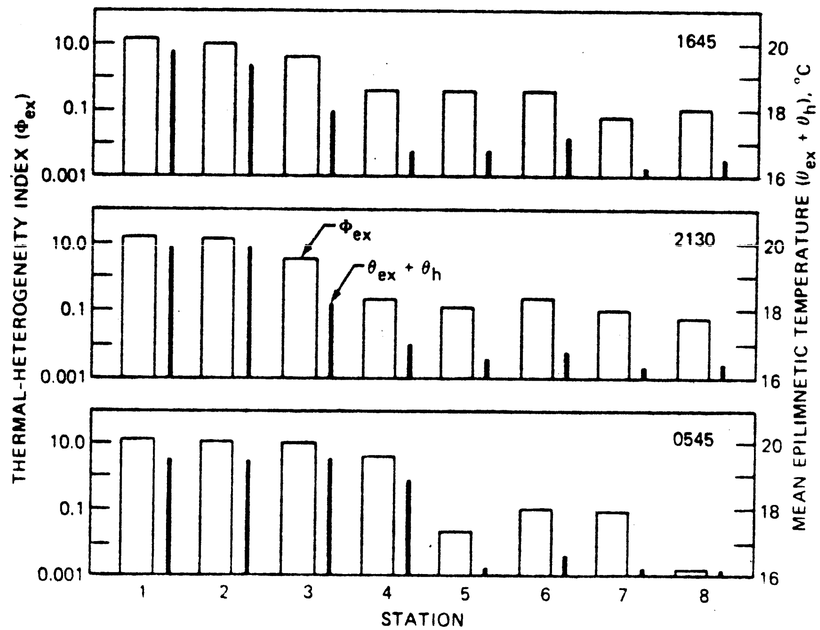

Fig. 6 Thermal-heterogeneity index and mean epilimnetic temperature at stations 1 to 8 for afternoon and evening on Mar. 24, 1973, and dawn on Mar. 25, 1973. The heterogeneity-index scale is logarithmic.

temperature distribution. The ordinal position of each station is highly constant overnight if rank is based on any of the three statistics discussed above. Consequently, it will be assumed in subsequent treatments of transect data that a temperature profile taken in the afternoon is ordinarily representative of the distribution of heat despite some diurnal changes.

Variation in Heat Distribution on Consecutive Days

Between April 3 and April 9, the transect data were taken every afternoon to determine the effect of short-term variations in weather on heat distribution. The value of θ_h during this period was constant at 17.10°C. Weather conditions are summarized in Table 3. Sunlight was measured with a silicon cell pyranometer at the hot arm. Artificial heat input was essentially constant.

Heat distribution varied much more markedly between days than was expected. Figure 7 shows that peak heat content is not found within the hot arm on all occasions. On April 3, 6, 7, and 9, the value of Θ_{ex} declined in a regular manner with increasing distance from the discharge. On April 4, 5, and 8, Θ_{ex} was greatest in the main body of the lake or in the north arm, although temperatures at the boil were unchanged. Two features of the data strongly suggest that the difference between dates cannot be accounted for by short-term irregularities due to turbulence. First, the amount of change between dates in heat content within the hot arm (more than 2000 cal/cm^2) is outside the probable range of variation at any given time within the hot arm as determined by the intensive study of the hot arm. Second, there is a nearly smooth trend in heat distribution on all dates, which is more suggestive of processes involving the entire lake than of local turbulence.

TABLE 3

FACTORS POTENTIALLY RELATED TO VARIABILITY OF HEAT DISTRIBUTION ON PAR POND FOR SEVEN CONSECUTIVE DAYS IN APRIL

Date	Sunlight, cal/cm^2	Wind,* m/sec	z_e at station 1, m	Mean Θ_{ex}, cal/cm^2
3	352	2.7	7.45	1340
4	418	6.8	4.00	1212
5	563	4.5	2.88	1125
6	423	2.3	7.86	1444
7	20	2.3	7.67	1481
8	300	5.4	4.50	958
9	429	3.2	8.50	1764

*Wind speeds were measured at 1300.

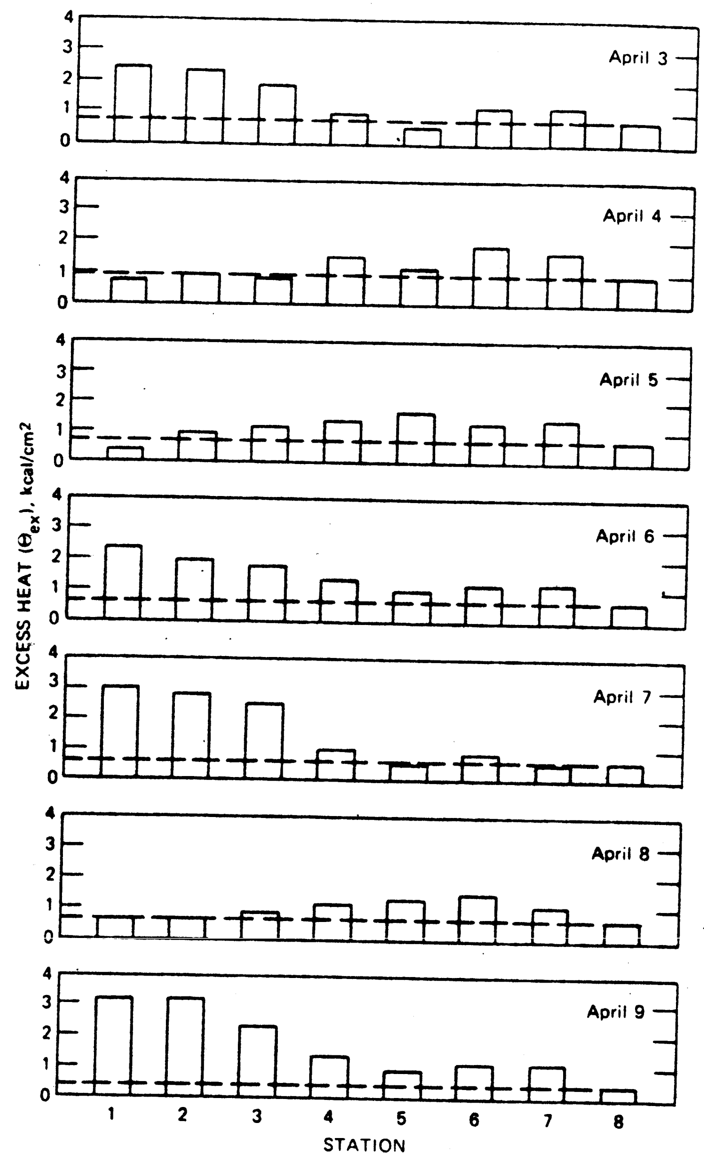

Fig. 7 Size of Θ_{ex} at stations 1 to 8 along the Par Pond transect on seven consecutive afternoons in April.

Factors that might be expected to affect Θ_{ex} are summarized in Table There is no obvious relation between sunlight and mean Θ_{ex} on the same dat nor is any explanation of the variation of heat distribution suggested by th sunlight data. Wind strength may affect Θ_{ex} by changing z_e (Table 3). The siz of Θ_{ex} at station 1, for example, appears to be related to the size of z_e

station 1 (Fig. 7). Thus drastic reduction in z_e at stations within the hot arm seems to be due to local thinning of the epilimnion resulting from a seiche involving all or a major portion of the lake. Location of nodes for the oscillation is not possible from the present data, but the amplitude of the movement observed in this case must have been 4 m or more and thus accounts for the massive translocations of waste heat.

The thermal-heterogeneity index accurately reflects the proximity of the thermal discharge regardless of the variation in heat distribution between stations (Fig. 8). This is consistent with the seiche hypothesis since an oscillation would be expected to affect the total amount of heat in a single vertical profile more markedly than the shape of the temperature–depth curve. The trend of mean epilimnetic temperature along the transect (Fig. 8) is less variable than the trend in Θ_{ex} but not so regular as the trend in Φ_{ex}. This is also consistent with the seiche hypothesis since continued addition of waste heat when the epilimnion is thin will have proportionately greater influence on Θ_{ex} than when the epilimnion is thick. Continuous addition of heat thus prevents the ratio of Θ_{ex} to z_e from falling drastically at points near the discharge.

Seasonal and Other Factors Affecting Variation in Heat Distribution

Variation in heat distribution over extended periods is influenced by seasonal trends as well as the factors discussed above. A sequence of transects taken on Par Pond during late winter and early spring illustrates seasonal effects and some other considerations that must be recognized in long-term studies of lakes receiving waste heat. Seasonal changes in net solar input, interruption of artificial heat flow, and hypolimnetic warming affect winter and spring heat distribution in Par Pond and are likely to be of comparable importance in other reservoirs.

The first two February transects on Par Pond were distinguished by a peak quantity of excess heat outside the hot arm (Fig. 9) despite the continuous addition of heat at the boil. The epilimnion was thickest in midlake on both occasions, suggesting that an oscillation of the kind previously described can account for heat distribution in both instances. Another factor that may be especially important during winter months is the greater amount of mixing that occurs in midlake owing to the higher wind stress there. If heat is distributed downward from the surface, it will be dissipated to the air less rapidly. Wind, particularly intermittent wind that would not cause excessive evaporative cooling, might thus act to conserve heat selectively in midlake. The thermal-heterogeneity index is inversely related to the probable rate of heat loss because it reflects the degree to which waste heat is confined to the surface. The value of Φ_{ex} at station 5 for the two February profiles is in fact lower than at stations within the hot arm, but the effects of advection and dissipation on total heat load cannot be separated on the basis of the available data.

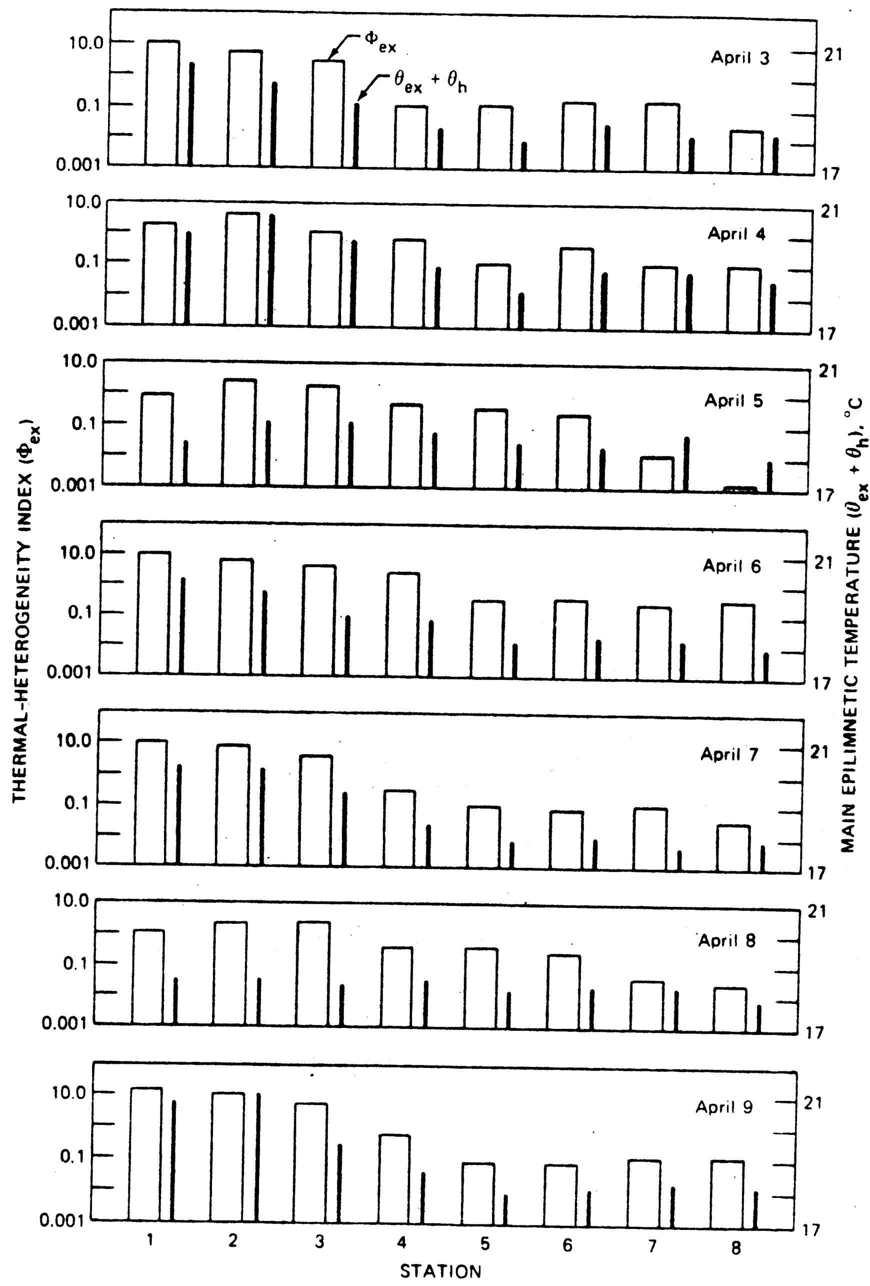

Fig. 8 Size of Φ_{ex} and (θ_{ex} + θ_h) at stations along the Par Pond transect on seven consecutive afternoons in April.

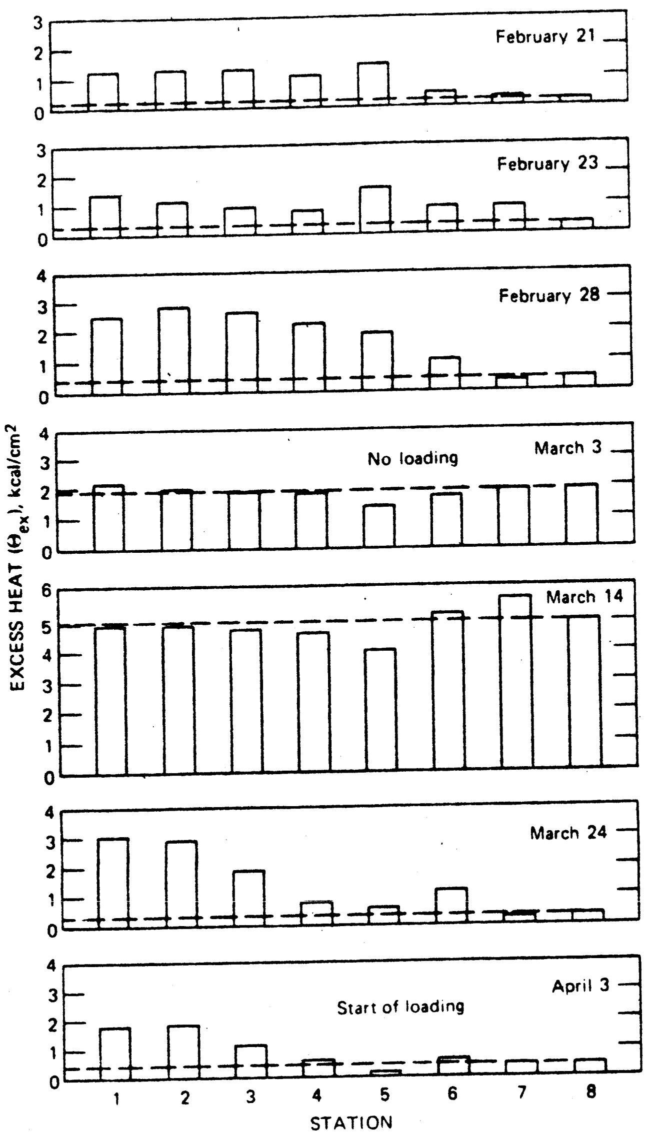

Fig. 9 Size of Θ_{ex} at eight stations along a transect from the heat source in Par Pond to the opposite end of the lake in February, March, and April 1973. The measurements for March 3 represent the distribution of heat without an artificial heat input; April 3 is typical of the conditions just after heat input has begun. All other measurements were taken at times of extended artificial heating and thus approximate the equilibrium condition of waste-heat dissipation. Heat indicated below the dashed line is due principally to natural solar heating.

Heat distribution at the time of the last February transect (Fig
conformed to the pattern that would be expected in the absence of a mar
seiche. The much greater regularity of z_e on this date (coefficient of variat
23%) than on the two previous dates (40% and 43%) confirms the supposi
that any effect of seiches on heat distribution was minimal. Under th
conditions there is very little excess heat at the last two stations within the no
arm. Advection of heat by wind-generated currents is scarcely sufficient
maintain a thermal gradient in the most remote portion of the lake during c
weather.

The first two March transects were distinctive owing to the equality of Θ
over the lake. On the first sampling date, the flow of heat into the hot arm h
been interrupted long enough to permit the horizontal equalization of Θ
There was nevertheless a slight residual downward trend in Φ_{ex} away from
discharge, which indicates that vertical equalization of heat was not qu
complete when the transect was made. High values of Φ_{ex} at all static
(Fig. 10) were due to rapid solar heating of the upper water column.

The second March transect was made after heat flow to the hot arm h
resumed. The effect of heated discharge was trivial in all respects on this d
owing to the rapidity with which natural seasonal changes were occurring in
lake. Solar heating was maximal and accounts for radical rises in Θ_{ex}; Φ_{ex}, a
$\theta_{ex} + \theta_h$ at all stations. Downward transfer of solar heat is not blocked b
well-developed thermal discontinuity at this time of the year; hence the v
high mean value of z_e (mean, 8.8 m) implied by high values of Θ_{ex} should
regarded as a temporary seasonal phenomenon.

Wind strength did not exceed 4 m/sec between the first two March transec
Solar heat was thus transferred relatively slowly to deeper portions of
epilimnion, and great heterogeneity in vertical heat distribution develope
Immediately following the second transect, however, very heavy winds (13
sec) promoted the vertical distribution of heat to such an extent that the deep
portions of the lake were warmed by more than 2°C. Most of Θ_{ex} was th
transferred to the hypolimnion, and a higher base-line temperature (θ_h, Table
and a lower mean Θ_{ex} for the last transect date in March (Fig. 9) resulted.

Cool weather in late March reduced Θ_{ex} at points distant from the dischar
The importance of waste heat in stabilizing the water column under th
circumstances is particularly evident from the April data that were taken j
following the resumption of heat flow after a brief interruption.

The distribution of substantial amounts of heat to the deepest portions
Par Pond during March suggests that waste heat can significantly affe
hypolimnetic temperatures. This possibility can be evaluated by comparison
deepwater temperatures in Par Pond with those of other lakes. One must bear
mind that no lake can serve as a perfect control for another since minimu
temperature is affected by mean depth, size, exposure to wind, and lo
weather variations. Large exposed lakes, in general, can be expected to ha
higher hypolimnetic temperatures than small sheltered lakes of about the sa

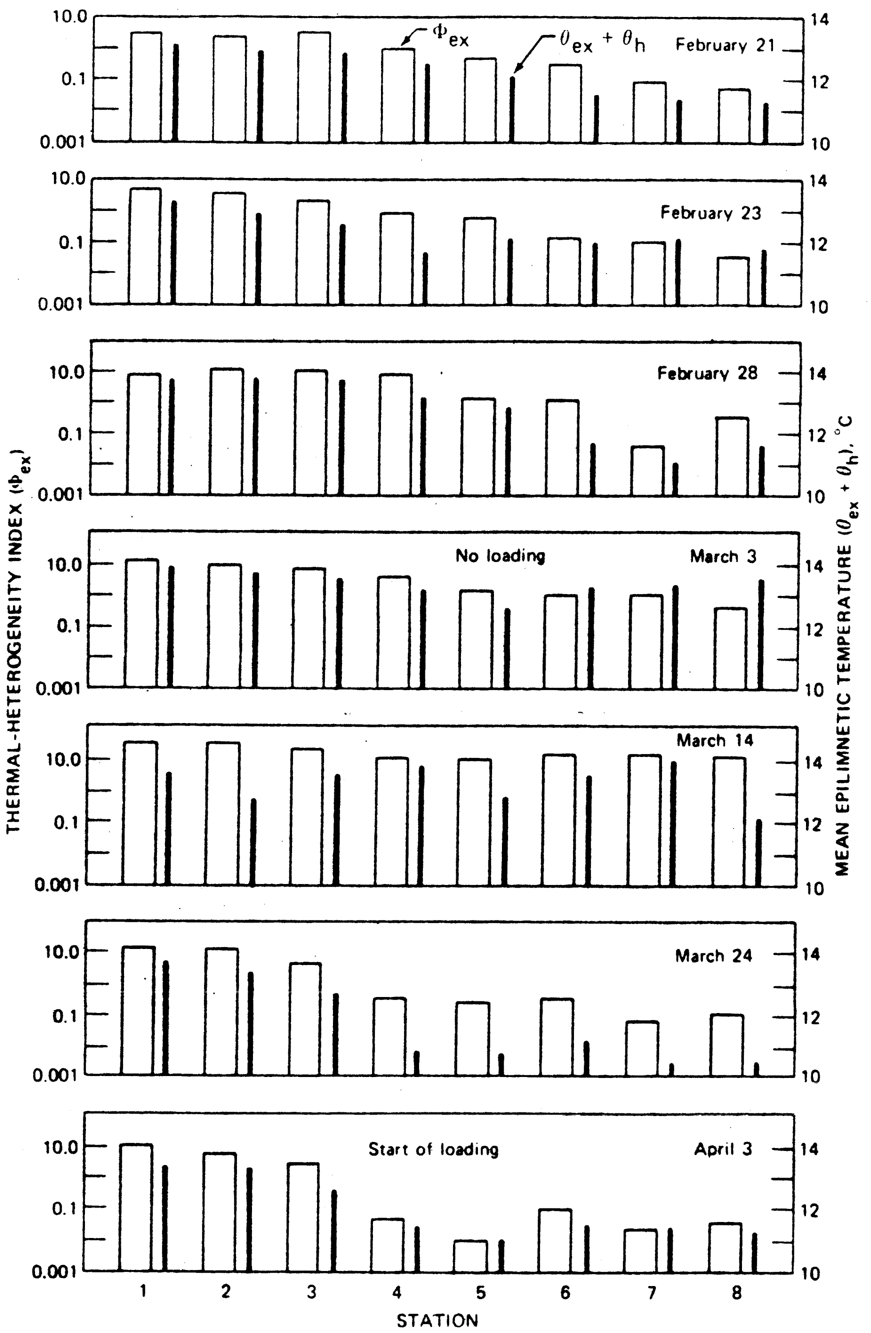

Fig. 10 Values of ($\theta_{ex} + \theta_h$) and Φ_{ex} on Par Pond foı seven days in February, March, and April 1973. On March 3 the lake was not receiving heated effluent and on April 3 the addition of heat had begun shortly before the measurements were made.

depth. Probable maximum and minimum values for deepwater temperature Par Pond under completely natural conditions were thus established f temperature data taken nearby on a larger, more exposed lake and on a sma more sheltered lake (Table 4).

Lake Sinclair, the larger lake on which the probable upper limit is ba receives a light artificial thermal load of its own that is ignored here becaus the small amount of heat added compared to the size of the lake. If the ther load does have any effect on the deep water of Lake Sinclair, the infe thermal alteration of Par Pond will only be more conservatively estimated. data from the two control lakes indicate that during middle April, when hypolimnion had reached its maximum temperature for the oncoming stratif tion season, the temperature near the bottom of Par Pond should have b between 10 and 13°C (Table 4). The deep portion of Par Pond was actu about 17°C. It thus appears that the hypolimnion of Par Pond is about higher than it would be in the absence of thermal loading.

DISCUSSION

The foregoing analysis of the effects of heated effluent on winter spr heat distribution in Par Pond can to some extent be generalized to other lak

TABLE 4

THERMAL PROFILES OF THREE LAKES FOR COMPARISON OF DEEPWATER TEMPERATURES

Depth, m	Par Pond* (April 15), °C	Lake Sinclair (April 12), °C	Pond B (April 15), °C
0	18.8	13.3	16.8
1	18.8	13.1	16.3
2	18.7	13.1	16.0
3	18.2	13.1	15.7
4	18.0	13.1	15.3
5	17.6	13.1	15.0
6	17.4	13.1	14.9
7	17.2	13.0	14.8
8	17.1	12.9	14.7
9	17.0	12.5	13.9
10	17.0	12.3	10.7
11	17.0	12.3	10.0
12	17.0	12.3	
13	16.9	12.3	
14	16.8	12.3	
15	16.7	12.3	

*Station 8.

The most important consideration of such a generalization, aside from the amount of waste heat and the size of the water body receiving it, is the influence of water temperature on the rate of density change with temperature.

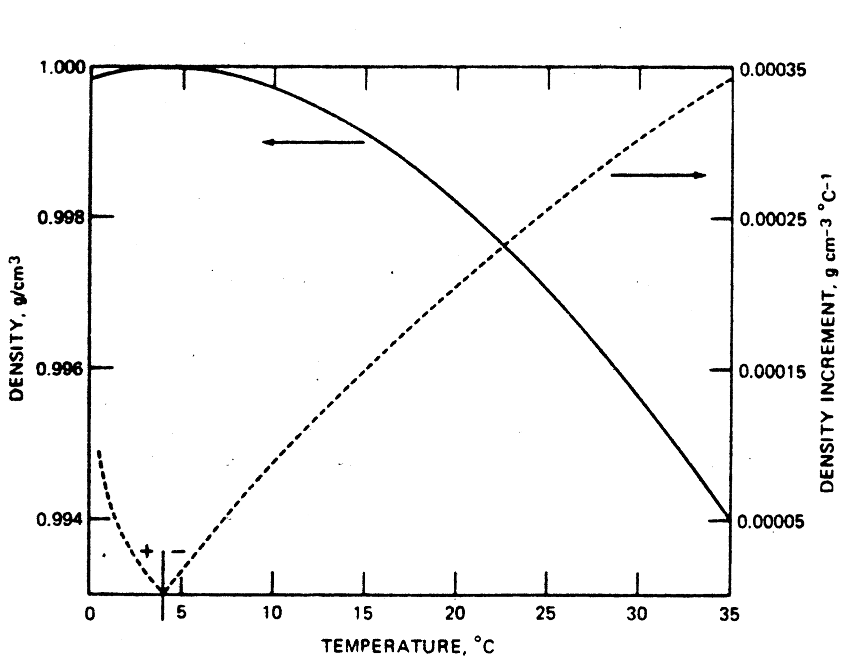

Fig. 11 Density of water as a function of temperature and change in density with temperature as a function of temperature, expressed as density increment per °C change in temperature. Note the steady rise in density increment with increasing temperature.

Figure 11 illustrates the increasing rate of density change as a function of :emperature. Although Birge (1910) long ago commented on the relevance of :his phenomenon to limnology, its special significance to thermal pollution of akes is yet to be recognized fully. The clear implication of Fig. 11 is that a fixed ıeat load may have radically different effects on lakes with different base emperatures.

The Par Pond studies clearly demonstrate the ability of a heated effluent to tabilize the water column during the circulation period, i.e., to induce a emistable artificial stratification. This effect is certain to be most marked at the owest latitudes since the winter temperatures of lakes at low latitudes are high nd the ability of waste heat to induce stratification is correspondingly great.

Figure 11 shows, for example, that, when sufficient heat is added to a lake t raise its winter surface temperature from 4°C to 5°C, a density gradient of abou 1×10^{-5} g/cm^3 will be generated between the warmed water and the unaffecte water beneath it. If sufficient heat is added to a reservoir at lower latitude t raise its winter surface temperature from 10°C to 11°C, the resulting densit increment is an order of magnitude greater. Resistance to the vertica distribution of heat will consequently be much greater in the warmer reservoi Numerous biological and chemical consequences could obviously follow fro reduced vertical turbulence.

The Par Pond data demonstrate the potential importance of harmonic wate movements to the rapid translocation of large amounts of heat. The differin winter temperatures of lakes on a latitude gradient are relevant to internal wate movements insofar as they affect the likelihood that a pycnocline will for during cool weather. If a pycnocline does form, seasonal hypolimnetic warmin may tend to be much more erratic since vertical heat transfer will be efficien only when deeper layers are exposed at the surface owing to tilting during heav wind stress.

The thermal-heterogeneity index, which proved in Par Pond to be the onl variable consistently related to the proximity of the heat source, will likewise b affected by mean epilimnetic temperature and hence by latitude. A fixe amount of heat added to a cool epilimnion generates approximately the sam amount of thermal heterogeneity as an identical amount of heat added to warm epilimnion. Thermal heterogeneity in a warm epilimnion is much mor residual, however, because of the more marked density gradient. The uppe water column of lakes at low latitudes during the cool season will consequentl be a more thermally heterogeneous environment than that of lakes at highe latitudes receiving an identical heat load.

Subtle alterations in the stability of the water column, in the temperature o the hypolimnion, and in other aspects of the thermal regime in thermall polluted lakes are likely to be of great biological significance. It is in fac probable that the effect of these alterations on the availability of nutrients an other resources to the biota of lakes is of considerably greater importance tha the direct effect of temperature changes on physiological processes. Until th fate of waste heat in reservoirs has been studied more completely, it is virtuall impossible to assess the full biological consequences of thermal pollution.

ACKNOWLEDGMENTS

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APPENDIX

A Fortran IV program for computing excess heat, limits of error on excess heat, depth of the epilimnion, mean epilimnetic temperature, and thermal heterogeneity index is presented in Table A.1. Input data include date, station identification number, depth, and temperature for each measurement as specified in line 9 of the program. One additional data card bearing the value of θ_h is needed at the end of the deck for each date (line 14). The total number of temperature measurements is specified in line 7, the number of dates is specified in line 12, and the number of stations is specified in line 19.

TABLE A.1

```
      C    THIS PROGRAM COMPUTES MEAN TEMPERATURE OF THE HYPOLIMNION
      C    AND HETEROGENEITY INDEX FOR EPILIMNETIC TEMPERATURES
0002          INTEGER DAY
0003          DIMENSION DAY(900),ID(900),DEPTH(900),TEMP(900),HEAT(900)
0004          DIMENSICN BASE (500),ERR(900),ERRPCT(900)
      C    INITIALIZE
0005          CATA ERR,ERRPCT/1800*0.0/
0006          CATA CAY,ID,DEPTH,TEMP,HEAT,BASE/5000*0.0/
      C    READ K DATA CARDS
0007          DO 13 I=1,655
0008          READ (5,1) DAY(I),ID(I),DEPTH(I),TEMP(I)
0009        1 FORMAT (2I10,F10.0,F10.2)
0010       13 CCNTINUE
      C    COMPLTE TOTAL HEAT CVER BASE TEMPERATURE
0011          I=0
0012          DC 10 III=1,7
0013       11 FORMAT (F10.1)
0014          READ (5,11) BASE (III)
0015          WRITE (6,17) BASE(III)
0016       17 FORMAT (///,1X,'BASE TEMP IS',F7.2)
0017          WRITE (6,25) DAY(I+1)
0018       25 FCRMAT (/,1X,'DATE',I5)
0019          DO 8 II=1,8
0020          DEGCAL=0.0
0021          ERROR=0.0
0022          XJ=-1.0
0023          IK=I
0024          DO 3  J=1,20
0025          I=I+1
0026          WRITE (6,6) ID(I),DEPTH(I),TEMP(I)
0027        6 FORMAT (10X,I10,F10.1,F10.2)
0028          IF (TEMP(I).LE.BASE(III)) GO TO 30
0030          XJ=XJ+1.0
0031          DEGCAL =DEGCAL+((TEMP(I)-BASE(III))+(TEMP(I+1)-BASE(III)))*100.0
             1*(DEPTH(I+1)-DEPTH(I))/2.0
0032          ERROR=ERROR+ABS((TEMP(I)-TEMP(I+1))/2.0)*100.0*(DEPTH(I+1)-DEPTH(I
             1))
0033       30 IF (ID(I+2).NE.IC(I+1)) GC TO 2
0035        3 CONTINUE
0036        2 I=I+1
0037          WRITE (6,6) ID(I),DEPTH(I),TEMP(I)
0038          HEAT(II)=DEGCAL
0039          ERR(II)=ERROR
0040          ERRPCT(II)=(ERROR/DEGCAL)*100.0
      C       PRINT HEAT CONTENT
0041          WRITE (6,7) HEAT(II),ERR(II),ERRPCT(II)
0042        7 FORMAT (//,1X,'HEAT IN EXCESS OF BASELINE TEMP IS',F10.2,'CAL/CM2'
             1/,1X,'MAXIMUM POSSIBLE ERROR BY TRAPEZOIDAL RULE IS',F10.2,'  OR',
             2F5.1,'PERCENT')
      C    COMPUTE THE MEAN TEMPERATURE
0043          IJ=IFIX(XJ)+1
0044          IF (TEMP(IK+IJ).EC.TEMP(IK+IJ+1)) GO TO 105
0046          XJ=XJ+((TEMP(IK+IJ)-BASE(III))/(TEMP(IK+IJ)-TEMP(IK+IJ+1)))*(DEPTH
             1(IK+IJ+1)-DEPTH(IK+IJ))
0047      105 TBAR=HEAT(II)/XJ/100.0+BASE(III)
0048          WRITE (6,106) XJ,TBAR
0049      106 FORMAT (1X,'THE DEPTH TO BASE TEMPERATURE IS',F5.2,'  MEAN TEMPERA
             1TURE IS',F7.3)
0050          XH=0.C
0051          HET=0.0
0052          DC 107 IM=1,20
0053          IF (IM.GT.XJ) GO TO 107
0055          HET=HET+(TBAR-TEMP(IK+IM))**2
0056          XH=XH+1.0
0057      107 CONTINUE
0058          HET = HET/XH
0059          WRITE (6,108) HET,XH
0060      108 FORMAT (1X,'HETEROGENEITY INDEX IS ',F10.3,'  SAMPLE SIZE IS',F5.1
             1)
0061          XH=0.C
0062          HET=0.0
0063          DC 110 IM=1,20
0064          IF (IM.GT.XJ) GC TO 110
0066          HET = HET + (TBAR-TEMP(IK+IM))**2
0067          XH=XH+1.0
0068          XIM=FLOAT(IM)+0.5
0069          IF (XIM.GT.XJ) GC TO 110
0071          HET=HET+(TBAR-(TEMP(IK+IM)+TEMP(IK+IM+1))/2.0)**2
0072          XH=XH+1.0
0073      110 CCNTINUE
0074          HET=HET/XH
0075          WRITE (6,111) HET,XH
0076      111 FORMAT (1X,'HETERCGENEITY INDEX WITH 2N SAMPLE SIZE IS', F10.3,
             1'SAMPLE SIZE',F5.1)
0077        8 CCNTINUE
0078       10 CCNTINUE
0079          STOP
0080          END
```