

Thomas J. Loranger

and

David F. Brakke

Institute for Watershed Studies
Western Washington University
Bellingham, Washington 98225

Temperature Characteristics, Annual Heat Storage, and River Diversion Influence on a Monomictic Lake

Abstract

The mean annual change in heat storage in Lake Whatcom was determined to be $23,100 \text{ cal cm}^{-2} \text{ year}^{-1}$. Isotherm development in one basin of the lake occurs independently of the other two basins; a shallow sill separating it from the rest of the lake appears to be the major isolating factor. River water diverted into the lake at the rate of $2.31 \times 10^5 \text{ m}^3 \text{ day}^{-1}$ had negligible effects on total heat storage in the lake.

Introduction

Biochemical cycling in lakes is regulated by temperature and density gradients. Consequently, knowledge of heat structure and content in lakes is an important aspect of limnology. Much of the literature dealing with lentic thermal structure and heat flux, published in North America, has been concerned with dimictic lakes influenced by a continental climate (Birge and Juday 1914, Hutchinson 1957, Stewart 1973, Blanton 1973). Less literature is available concerning monomictic lakes, particularly those influenced by a maritime climate.

A temperature and heat content inventory is provided for Lake Whatcom, in the Puget Sound Lowland of Washington State. Data on isotherm and thermal profile development are presented for the entire lake as well as for individual basins within the lake. The heat content of the lake was calculated as a Birgean heat budget. In 1962 a portion of the Nooksack River was diverted into Lake Whatcom; the effect of this cool diversion water on lake heat structure was negligible.

Location

Lake Whatcom is located 29 km south of the Canadian border in western Washington State. The east-west axis of the lake lies at $48^{\circ}43' \text{ N}$. latitude; the north-south axis lies at $122^{\circ}20' \text{ W}$. longitude. Lake Whatcom is 95 m above mean sea level.

Methods

The Institute for Watershed Studies at Western Washington University provided data for the study of Lake Whatcom. From 1962 until 1972 and from 1979 until 1981, physical and chemical data were recorded at 5 m depth levels from five major sampling stations on the lake. These data were recorded weekly. Temperature was recorded with a thermistor calibrated with a standard thermometer. Temperature data used in annual

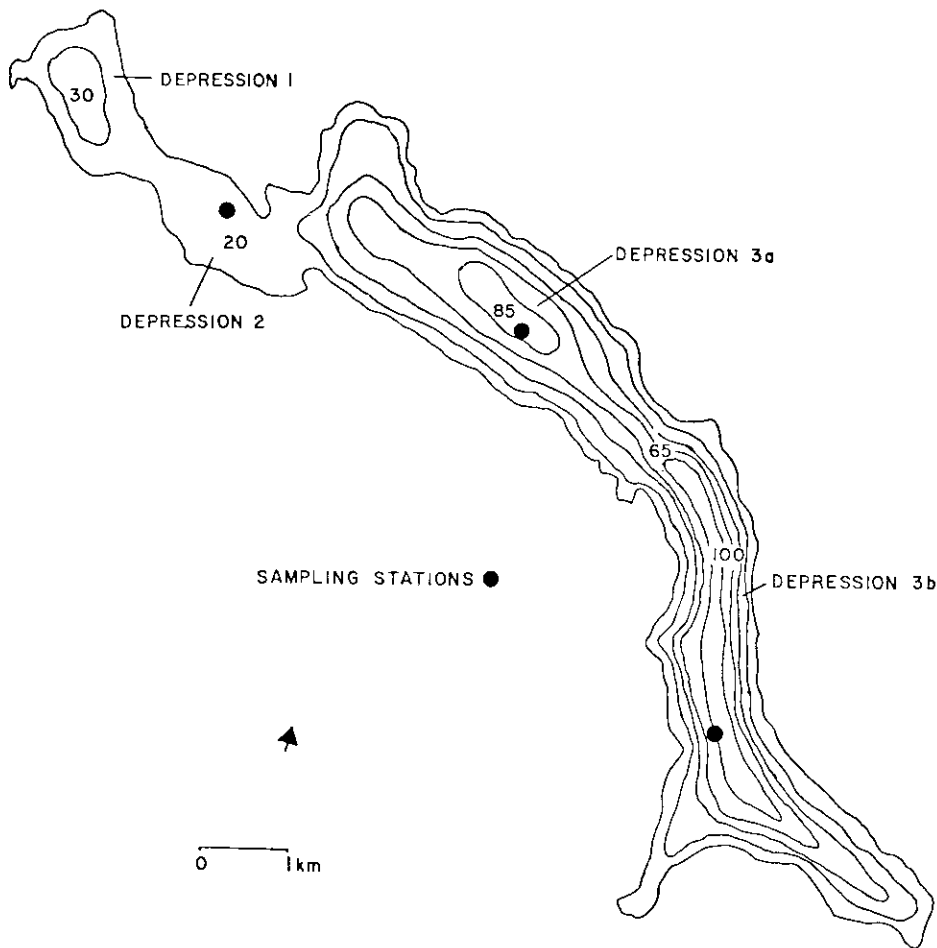


Figure 1. Morphometry of Lake Whatcom.

heat budget calculations represent mean water column temperatures taken from three sampling stations located at representative locations on the lake (Fig. 1). Basin to basin isotherm development, as well as mean epilimnetic and hypolimnetic temperatures, was determined in the lake. For ease of calculation, one year (1970) was chosen for these comparisons based on temperature profile development. Profile development during this year was representative of that during all other years of study.

The most widely accepted means of expressing heat content in lakes is by means of a Birgean heat budget (Hutchinson 1957). The amount of heat that would be released

from Lake Whatcom upon cooling to 0°C was determined by:
$$\Theta_w = \sum_{z_0}^{z_m} t_z a_z h_z,$$

where Θ_w = heat content of the lake water in calories; z_0 = surface of the lake; z_m = maximum depth of the lake; t_z = average temperature in degrees celsius of a unit layer of water of thickness h_z (cm) with midpoint at depth z and a_z the area at depth

z (cm²) (Wetzel and Likens 1979). Sufficient temperature data were available to calculate eight years of change in annual heat storage (Birgean heat budget) for Lake Whatcom.

The area of Lake Whatcom at each successive 5 m depth interval was determined by planimetry from a 1/24,000 scale contour map of the lake produced by Lighthart *et al.* (1972). Volumes of the lake were determined between each depth interval.

In 1962 a portion of the Middle Fork of the Nooksack River was diverted into Lake Whatcom, at the rate of $2.31 \times 10^5 \text{ m}^3 \text{ day}^{-1}$, for a six-month period to maintain water level and supply. Figures on diversion quantity were obtained from the city of Bellingham water treatment plant, for comparison with heat storage fluctuation in the lake.

Results and Discussion

Morphometry

Lake Whatcom has a surface area of 20 km². The lake has a maximum depth of 100 m and a mean depth of 45 m, with a total volume of $8.948 \times 10^8 \text{ m}^3$. The lake has three major depressions (Fig. 1). Depression 1 is located at the north end of the lake and has a maximum depth of approximately 30 m. Depression 2 is separated from depression 1 by a sill 5 m in depth; depression 2 has a maximum depth of approximately 20 m. Depression 3 dominates the central and southern portion of the lake and contains 95 percent of the lake's volume; it is separated from depression 2 by a sill 10 m in depth and has a maximum depth slightly over 100 m.

Thermal Stratification

Lake Whatcom reaches maximum thermal stratification by mid-August. A distinct metalimnion was consistently present by June 1 in each year. In 1970, at the time of maximum thermal discontinuity, the depth to the thermocline was approximately 17 m. The lakewide mean temperature was found to be 10.9° C at the time of maximum thermal discontinuity in August (1963, 1966-1972). The lakewide mean epilimnetic temperature for this period was 15.9° C, and the mean hypolimnetic temperature (below 25 m) was 6.7° C.

Basin to Basin Comparisons

Thermal profile development occurred simultaneously in the three major depressions of Lake Whatcom (1970). Depression 3, the deepest, has the largest difference between mean epilimnetic and hypolimnetic temperatures at the time of maximum thermal stratification (Fig. 2).

Isotherm evolution in Depression 1 occurred independently of the other two depressions. At the time of maximum thermal stratification in Depression 1, depth to the thermocline was greater and mean hypolimnetic temperatures were higher than in the other two depressions (Fig. 2). Depressions 1 and 2 have very similar morphometries with volumes of $19.4 \text{ m}^3 \times 10^6$ and $18.0 \text{ m}^3 \times 10^6$, respectively (Lighthart *et al.* 1972). The shallow sill between the two depressions (5 m deep) determines the independent nature of isotherm formation in depressions 1 and 2 (Fig. 3). The sill between depressions 2 and 3 is approximately 10 m deep. A prevailing southerly wind promotes mixing between basins, but is limited mainly to effects of basin 3 on basin 2. Mixing

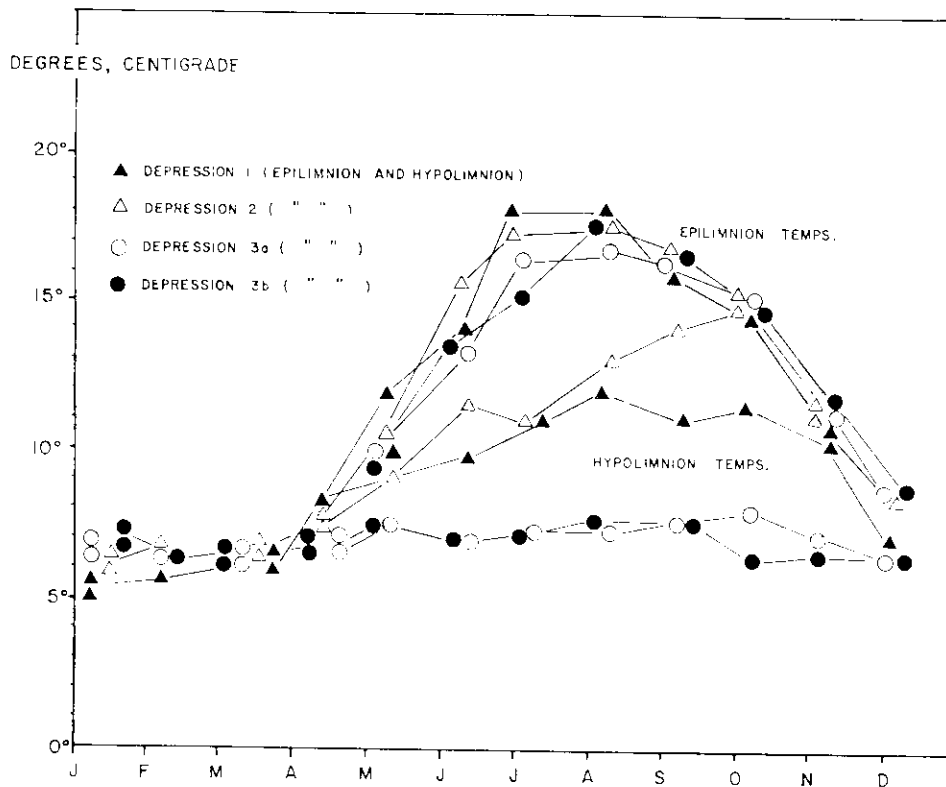


Figure 2. Mean water column temperatures of the epilimnion and hypolimnion in the three basins of Lake Whatcom, 1970.

is compounded by a $2.3 \times 10^5 \text{ m}^3$ daily water withdrawal from the hypolimnion of Depression 2 for supply to the city of Bellingham.

Birgean Annual Heat Budgets

Birgean annual heat budgets (change in annual heat storage) of Lake Whatcom were calculated for eight separate years. The mean maximum heat storage for the eight years of study was $49,400 \text{ cal cm}^{-2} \text{ year}^{-1}$. The mean minimum winter heat storage for the study years was $26,300 \text{ cal cm}^{-2} \text{ year}^{-1}$. The resulting mean annual change in heat storage for the eight-year period was $23,100 \text{ cal cm}^{-2} \text{ year}^{-1}$. By comparison, we have calculated a Birgean heat budget for Lake Washington of $21,000 \text{ cal cm}^{-2} \text{ year}^{-1}$ (Loranger and Brakke 1983). At $28.85 \times 10^8 \text{ m}^3$, Lake Washington has a significantly greater volume than Lake Whatcom, as a result there is greater total heat storage in Lake Washington. The deeper water column of Lake Whatcom, however, permits greater total heat storage per cm^2 of lake surface and promotes a larger heat budget in the lake. In temperate lakes that are sufficiently deep to maintain hypolimnetic temperatures near 4° C year round, Birgean heat budgets usually vary between $30,000$ to $40,000 \text{ cal cm}^{-2} \text{ year}^{-2}$ (Wetzel 1975). Very few lakes have heat budgets in excess of $50,000 \text{ cal cm}^{-2} \text{ year}^{-1}$. In temperate latitudes, Birgean annual heat budgets are strongly correlated with lake mean depth, area, and volume, rising continuously with lake dimensions

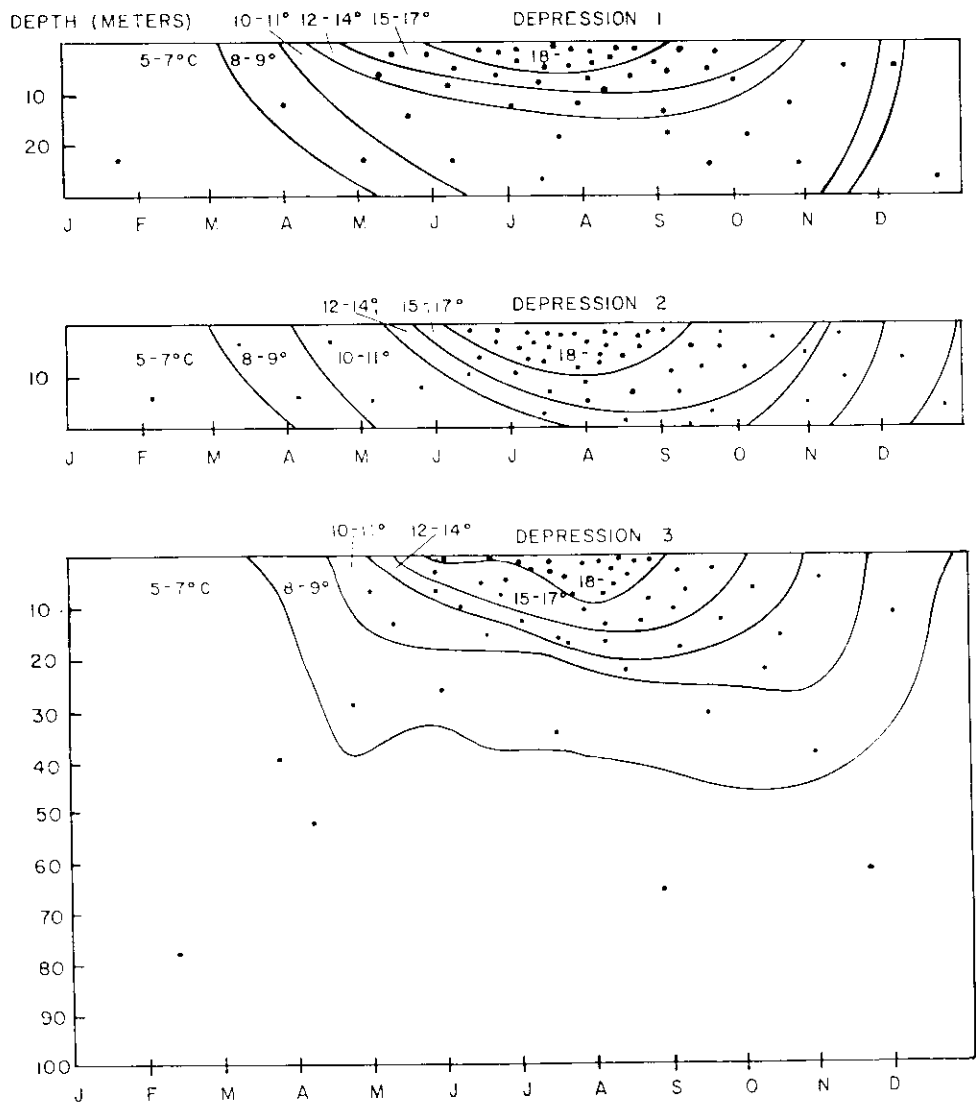


Figure 3. Isotherm evolution, 1970.

(Gorham 1964). Dimictic lakes tend to exhibit higher changes in mean annual heat storage than monomictic lakes of similar size.

Diversion Water Influence on Heat Storage

Beginning in 1962, water from the Nooksack River was diverted into Lake Whatcom at the south end of Depression 3b (Fig. 1), to counteract water use by the city of Bellingham and industrial uses, and to stabilize lake level. The Nooksack River water is diverted at the rate of $2.31 \times 10^5 \text{ m}^3 \text{ day}^{-1}$. The diversion gates are usually opened in the spring, when the lake level begins dropping, and closed again in the fall. Warmer, dryer years often require more total days of diversion.

The river water is cooler than the mean water temperature of Lake Whatcom. In January and February the river water cools to 5° C and in August it is often near 11° C. This large volume of cool diversion water input could be a factor in depressing heat storage in Lake Whatcom. The maximum amount of diversion time before mid-August, in any year to date, has been five months. This translates into 34.0 x 10⁶ m³ of river water. Using 8° C as a conservative spring mean diversion water temperature and 10.9° C as the lakewide mean temperature at the time of maximum heat storage, the mean temperature of the lake would be lowered to 10.79° C. In terms of heat storage, this amounts to a loss of 503 cal cm⁻². Stewart (1973) showed that in three mid-western lakes of moderate size (mean depth of 15 m) and moderate heat budgets (25,000 cal cm⁻² year⁻¹), there could be a 2,000 to 3,000 cal cm⁻² fluctuation in heat storage in two days time during summer months. In light of this, a heat loss of 503 cal cm⁻² in a water column with 48,150 cal cm⁻² in storage is an insignificant amount.

Stewart (1973) showed that power plant thermal discharge input to Lake Monoma (Wisconsin) that could theoretically cycle the entire volume of the lake (105 x 10⁶ m³) in one year, had at most localized effects on heat structure and had negligible effects on total heat storage in the lake. He concluded that diurnal variations in temperature appear to have a much greater effect on total heat storage in the lake than any anthropogenic thermal inputs. Similarly, cool water influx from river diversion in Lake Whatcom appear to have little more than localized effects on heat structure in basin 3 of the lake.

Conclusion

Lake Whatcom was found to have reached maximum thermal discontinuity by mid-August. Lakewide mean temperature at maximum thermal discontinuity was 10.9° C. Thermal profile development occurred simultaneously in the three major depressions of Lake Whatcom. Isotherm evolution in Depression 1 occurred independently of evolution in the other two depressions; the shallow sill separating Depression 1 from the rest of the lake appeared to be the major isolating factor. The lake was found to have a mean annual Birgean heat budget of 23,100 cal cm⁻² year⁻¹ (eight-year mean).

Diversion of the Nooksack River into Lake Whatcom was found to have a negligible effect on heat storage in the lake. The maximum amount of water diverted into Lake Whatcom before 1 August in any year was 34 x 10⁶ m³. This volume of water caused a 0.11° C drop in lakewide temperature at the time of maximum heat storage in the lake.

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TABLE 1. Volume at depth, Lake Whatcom.

Depth Interval (m _v)	Volume (m ³)	Percentage of Total Volume
0-5	9.517 x 10 ⁷	10.6%
5-10	8.659 x 10 ⁷	9.7%
10-15	7.717 x 10 ⁷	8.6%
15-20	6.908 x 10 ⁷	7.7%
20-25	6.559 x 10 ⁷	7.3%
25-30	6.163 x 10 ⁷	6.9%
30-35	5.812 x 10 ⁷	6.5%
35-40	5.522 x 10 ⁷	6.1%
40-45	5.237 x 10 ⁷	5.8%
45-50	4.929 x 10 ⁷	5.5%
50-55	4.520 x 10 ⁷	5.0%
55-60	3.476 x 10 ⁷	4.4%
60-65	3.387 x 10 ⁷	3.8%
65-70	2.898 x 10 ⁷	3.2%
70-75	2.464 x 10 ⁷	2.7%
75-80	1.958 x 10 ⁷	2.2%
80-85	1.434 x 10 ⁷	1.6%
85-90	1.013 x 10 ⁷	1.1%
90-95	.542 x 10 ⁷	.6%
95-100	.380 x 10 ⁷	.4%
Total Volume	89.481 x 10 ⁷	100%

TABLE 2. Maximum and minimum temperature profiles, Whatcom, 8-year mean, (63, 66-72).

Lake Whatcom		
	Mean temperature at contour interval	
	max	min
0-5	20.2	6.1
5-10	19.7	5.9
10-15	18.1	5.9
15-20	14.4	5.9
20-25	10.4	5.9
25-30	8.2	5.9
30-35	7.5	5.9
35-40	7.0	5.9
40-45	6.8	5.9
45-50	6.6	5.9
50-55	6.6	5.9
55-60	6.5	5.9
60-65	6.5	5.9
65-70	6.5	5.9
70-75	6.4	5.9
75-80	6.4	5.8
80-85	6.4	5.8
85-90	6.3	5.8
90-95	6.3	5.8
95-100	6.3	5.7

TABLE 3. Comparative volume and isotherms at depth, Lake Whatcom.

Whatcom		
Depth	% volume	Isotherm at max. depth of interval
0-10	20.5	18° C
10-15	8.5	14.5° C
15-20	7.5	10.5° C
20-25	7.5	8.0° C
25-100	6.6	6.0° C

TABLE 4. Yearly totals of Nooksack River diversion to Lake Whatcom.

Year	Total days of Diversion	Total m3 diverted
1962	180	41.5 x 106
1963	270	62.3 x 106
1964	231	53.3 x 106
1965	225	51.9 x 106
1966	237	54.7 x 106
1967	195	45.0 x 106
1968	108	24.9 x 106
1969	180	41.5 x 106
1970	204	47.1 x 106
1971	120	27.7 x 106
1979	219	50.5 x 106