ESTIMATION OF EVAPORATION FROM NED WILSON LAKE, FLAT TOPS WILDERNESS AREA, COLORADO

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CONVERSION FACTORS

The inch pound units in this report may be converted to metric units by use of the following conversion factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
acre	4.047×10^{-1}	square kilometer
acre-foot	1.233×10^{-3}	cubic hectometer
langleys per day	29.06	watts per square meter
foot	0.3048	meter
inch	2.54	centimeter
mile	1.609	kilometer
mile per hour	4.470×10^{-1}	meter per second
millibars	1.0000×10^{2}	newtons per square meter
square mile	2.590	square kilometer

To convert degrees Celsius (°C) to degrees Fahrenheit (°F) use the following formula:

$$(°C \times 9/5) + 32 = °F$$

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ABSTRACT

As part of an effort to define the hydrology and water quality of Ned Wilson Lake, evaporation rates were estimated for the summer periods of 1983 and 1984. Mass-transfer and energy-budget techniques and the Morton model were used to estimate evaporation using data collected at the lake and data collected at a meteorological station 0.1 mile from the lake.

The estimate of evaporation for July 29 through September 27, 1983, using the mass-transfer technique, was 9.50 inches; the estimate using the energy-budget technique was 8.10 inches; the estimate using the Morton model was 9.90 inches. The evaporation estimate for July 18 through September 25, 1984 using the mass-transfer technique was 8.71 inches; the estimate using the energy-budget technique was 7.88 inches; the estimate using the Morton model was 10.49 inches. These estimates will provide values to be used in future analyses of the interaction of the lake and ground water; however, refinement of data collection will be necessary to determine specifically the rate of evaporation.

INTRODUCTION

The development of mineral and energy resources in the Western United States will increase the release of atmospheric emissions upwind of areas sensitive to acidic deposition. The Flat Tops Wilderness Area in northwestern Colorado contains lakes having alkalinity values less than 100 microequivalents per liter (Turk and Adams, 1983). The area is downwind from present and projected sources of acidic, atmospheric emissions. These sources include coal-fired and electric-generation powerplants, oil-shale retorts, sulfide-ore smelters, and projected population centers related to energy development.

The Ned Wilson Lake watershed was selected as an index watershed representing the lakes in the Flat Tops Wilderness Area most sensitive to acidification. This lake is being used as a site to monitor natural and anthropogenic changes in lake chemistry and biology, and to determine processes controlling lake chemistry and biology. One such process is the interaction of ground water with the lake. Models of the distribution of lake alkalinity in the Flat Tops Wilderness Area suggest that lakes located in ground-water discharge areas have greater alkalinity than lakes located in ground-water recharge areas (Turk and Campbell, 1984). Because Ned Wilson Lake is among the least-alkaline lakes it is hypothesized to receive little ground-water inflow. One test of this hypothesis is to construct a hydrologic budget for the lake, then use the budget to calculate the ground-water component as a residual. Direct measurements of the ground-water component virtually are impossible, because of the wilderness character of the surrounding area and lack of access to the lake.

Purpose and Scope

A major component in the hydrologic budget is lake evaporation. These methods are used to calculate the evaporative losses from Ned Wilson Lake. Each method is tested for its sensitivity to errors in the independent variables used to calculate evaporation. These tests identify the variables that would benefit most from greater accuracy. Quantitative estimates of the error in some of these variables cannot be assigned at this time. Comparison of the results obtained from the three independent estimates of evaporation can be used to estimate the uncertainty in evaporation estimates.

Acknowledgments

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DESCRIPTION OF STUDY AREA

Ned Wilson Lake is located in the Flat Tops Wilderness Area of northwestern Colorado (fig. 1). Turk and Adams (1983) describe the geologic, soil, and general hydrologic conditions of the area. The altitude of Ned Wilson Lake is approximately 11,120 feet. The lake has a surface area of about 2.5 acres and an average depth of about 12 feet (Turk and Adams, 1983).

EVAPORATION COMPUTATIONS

Three methods were used to estimate evaporation rates for Ned Wilson Lake for the summer periods of 1983 and 1984. The three methods include the mass-transfer and the energy-budget techniques, and a model described by Morton (1984).

Mass-Transfer Evaporation Estimates

The mass-transfer technique as presented by Harbeck (1962) is based on the quasi-empirical equation:

$$E = N\,U\,(e_o - e_a) \qquad (1)$$

where: E = evaporation, in inches per day;
N = mass-transfer coefficient;
U = wind speed, in miles per hour at 2 meters above the water surface;
e_o = saturation vapor pressure at the water-surface temperature, in millibars; and
e_a = vapor pressure of the air, in millibars.

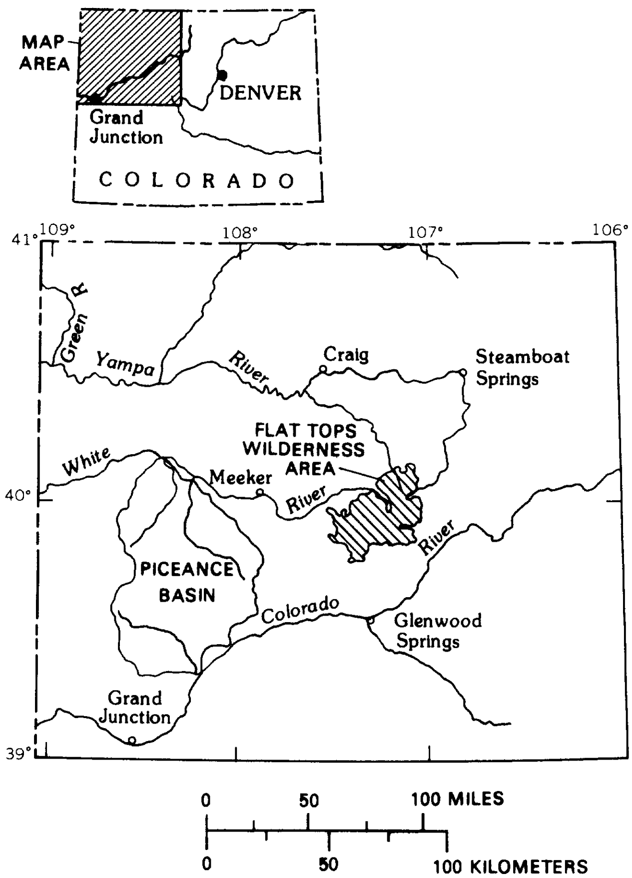

Figure 1.--Location of the Flat Tops Wilderness Area.

Data required for the mass-transfer technique are wind speed at 2 meters above the lake surface, lake water-surface temperature, air temperature, and a method to determine the vapor pressure of the air. In this study, relative humidity and air temperature were used to determine vapor pressure of the air. Because the lake is in a wilderness area, unique constraints were involved in the data collection for evaporation estimation. Methods and assumptions used to determine values for each term in the mass-transfer equation are described in the following sections.

Data Collection and Manipulation

A meteorological station was installed approximately one-tenth of 1 mile east of Ned Wilson Lake. Wind speed at 18 feet above the surface was measured using a Campbell data logger and a Met-one anemometer[1]. Wind speed was measured every 10 seconds; hourly and daily averages were generated by the data logger. Wind speed was adjusted to the 2-meter height, using a power function of the form (American Society of Civil Engineers, 1973):

$$U_{2.0} = U_{18} \, (0.365)^{0.2} \; . \qquad (2)$$

where: $U_{2.0}$ = wind speed at 2-meters;
U_{18} = wind speed at 18-feet; and
0.365 = adjusted height in meters (2) divided by measurement height in feet (18) divided by a metric conversion factor.

It was assumed that wind speed, adjusted to a 2-meter height at the meteorological station, was equal to wind speed at 2 meters above the lake surface. Wind-speed profile over water may be different from that over land; however, putting a raft on the lake for direct measurement of the lake's effect on the wind profile was not feasible. The small size of the lake, about 2.5 acres, probably minimizes the effect of the lake on the wind profile.

Water-surface temperatures were measured every three hours for a 24-hour period at approximately 2-week intervals from July through September during 1983 and 1984. The three-hour values were averaged to obtain a daily water-surface temperature. The daily-average values from each year were used to calibrate a harmonic function to estimate daily water-surface temperatures for the July through September period (Steele, 1978). The harmonic function used was:

$$T_x = a \, [\text{sine} \, (0.0172 \, x + b)] + c \qquad (3)$$

where: T = water-surface temperature on day x, in degrees Celsius;
x = day of the year (using the water-year format of October 1 as day 1); and
a, b, c = coefficients determined by calibration.

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[1]The use of brand names in this report is for identification only and does not constitute endorsement by the U.S. Geological Survey.

Values of a, b, and c for 1983 were 46.3, 2.3, and -29.3; values of a, b, and c for 1984 were 44.7, 2.3, and -28.5. The harmonic function was truncated at 0 degrees Celsius. Saturation-vapor pressure was calculated using equation 4 (Tennessee Valley Authority, 1972, appendix D, page A-7), and using the daily water-surface temperatures from equation 3, such that:

$$e_o = \exp\left[2.3026 \left(\frac{7.5\ T_x}{T_x + 237.3}\right) + 0.7858\right] \qquad (4)$$

where: e_o = saturation-vapor pressure, in millibars.

Vapor pressure of the air was determined using hourly average-air temperature and relative humidity values measured at the meteorological station using a Campbell Scientific 201 temperature and humidity probe. Hourly vapor-pressure data were averaged to determine daily values.

Mass-Transfer Results

Using the daily values of wind speed, saturation-vapor pressure, and vapor pressure of the air, mass-transfer estimations of evaporation were determined for approximately 2-week intervals using equation 1. A value of 0.00323 for N was determined, using equation 5 (Harbeck, 1962).

$$N = 0.00859/A^{0.05} \qquad (5)$$

where: N = mass transfer coefficient; and
A = surface area, in acres.

Results of the mass-transfer evaporation values are listed in table 1.

Table 1.--*Mass-transfer evaporation values and supporting data*

Period From (month/day)	Period Through (month/day)	Number of days	Wind speed (miles per hour)	Saturation-vapor pressure (millibars)	Air-vapor pressure (millibars)	Evaporation (inches)
			1983			
7/1	7/14	14	5.4	8.5	5.4	0.76
7/15	7/28	14	5.6	13.8	8.0	1.47
7/29	8/11	14	4.3	17.5	10.3	1.40
8/12	8/29	18	4.6	19.5	8.3	2.99
8/30	9/9	11	5.5	18.0	7.3	2.09
9/10	9/27	18	5.6	13.7	4.9	3.02
7/1	9/27					11.73
			1984			
7/1	7/17	17	3.9	10.0	6.4	0.76
7/18	7/31	14	4.3	15.0	9.5	1.07
8/1	8/14	14	3.9	18.2	8.4	1.72
8/15	8/28	14	4.5	18.8	9.5	1.89
8/29	9/11	14	5.4	17.0	6.1	2.66
9/12	9/25	14	5.5	12.2	6.7	1.37
9/26	10/7	12	3.8	8.2	4.9	0.49
7/1	10/7					9.96

Errors in Mass-Transfer Estimates

Error in the measurement or adjustment of the wind speed will result in errors in the mass-transfer estimates of lake evaporation. A 10 percent error in the wind speed will result in a 10 percent error in the evaporation value. The error, as a result of the adjustment of wind speed to 2 meters, cannot be quantified without actual measurement of wind speeds at 2 meters above the lake surface.

The value used for N was based on an empirical relation and was not determined through an independent measurement of evaporation, which is the optimum procedure. Any error in the value of N will be reflected in the evaporation values; however, this error cannot be quantified without further study.

Errors in evaporation values as a result of using the harmonic function to derive daily water-surface temperature were investigated by raising and lowering water-surface temperature one and two degrees. Changes in total evaporation as a result of changes in water-surface temperature are:

Change in water-surface temperature (degrees Celsius)	Total evaporation for data collection period (inches)	Change in total evaporation (percent)
	1983	
-2	8.81	-25
-1	10.10	-14
1	12.97	11
2	14.61	25
	1984	
-2	7.39	-26
-1	8.60	-14
1	11.26	13
2	12.79	28

Energy-Budget Evaporation Estimates

The energy budget is an accounting of the gains and losses of energy to or from the lake. The form of the energy budget used is given in equation 6.

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_x}{L\ (1 + R) + T_o} \qquad (6)$$

where: E = evaporation, in centimeters per day;

Q_s = incoming solar radiation, in langleys per day;

Q_r = reflected solar radiation, in langleys per day;

Q_a = incoming long-wave radiation, in langleys per day;

Q_{ar} = reflected long-wave radiation, in langleys per day;

Q_{bs} = long-wave radiation from the water, in langleys per day;

Q_v = net energy advected into the lake, in langleys per day;

Q_x = change in stored energy, in langleys per day;

L = latent heat of vaporization, in calories per gram;

R = Bowen ratio; and

T_o = water-surface temperature, in degrees Celsius.

Data required for the energy-budget technique are air temperature, water temperature, a method to determine vapor pressure of the air, solar radiation, long-wave radiation, stored energy within the lake, and volume and water temperature of inflow to and outflow from the lake.

Data Collection and Manipulation

Solar radiation was measured at the meteorological station using a black-and-white Eppley radiometer. Values were measured every 10 seconds, and daily average radiation was determined by the data logger. Reflected solar radiation was computed using a relation developed by Koberg (1964).

Incoming long-wave radiation was computed using a procedure described by Koberg (1964). In Koberg's method, long-wave radiation is estimated using air temperature and vapor pressure. Reflected long-wave radiation was assumed to be 3 percent of incoming long-wave radiation (Anderson, 1952). Long-wave radiation from the water surface was determined by using the Stefan-Boltzman law, the water-surface temperature, and an emissivity of 0.97 (Anderson, 1952).

The energy-budget technique only was used during the summer period, when surface outflow from the lake was zero. Therefore, the only advection term considered was precipitation. Precipitation was measured at the meteorological station, using a Belfort weighing-bucket precipitation gage. Precipitation temperature was considered to be equal to the wet-bulb temperature; this temperature was determined using relative humidity and air-temperature data. Advected energy due to interaction of the lake and ground water was not considered.

Changes in stored energy were determined by changes in lake temperature between successive measurements of temperature profiles. A temperature profile was measured approximately every two weeks at the deepest point in the lake. Average lake temperature was assumed to be the average temperature of the profile. Average lake temperature was multiplied by lake volume to determine the amount of stored energy.

Latent heat of vaporization was computed using water temperature. The Bowen ratio was determined using equation 7.

$$R = 0.61 \frac{(T_o - T_a)}{(e_o - e_a)} P \qquad (7)$$

where: T_a = air temperature, in degrees Celsius;

P = atmospheric pressure, in millibars; and

T_o, e_o, and e_a are as described previously.

Water-surface temperatures were the same as used in the mass-transfer technique.

Energy-Budget Results

Results of energy-budget evaporation values are listed in table 2.

Errors in Energy-Budget Estimates

Incoming long-wave radiation is a major term in the energy budget (eq. 6). Measurements of long-wave radiation were not available, and specific errors resulting from the estimation of long-wave radiation cannot be identified. By changing the long-wave radiation term in equation 6, and recomputing evaporation, an indication of the magnitude of the resultant error can be identified. Because reflected long-wave radiation is assumed to be 3 percent of incoming long-wave radiation, changes were made to the net long-wave radiation term. Resultant changes in total evaporation caused by variation in net long-wave radiation are:

Percent change in net long-wave radiation	Total evaporation for data collection period (inches)	Percent change in evaporation
	1983	
-25	3.59	-55
-10	6.28	-22
10	9.90	22
25	12.59	55
	1984	
-25	2.86	-64
-10	5.87	-26
10	9.89	26
25	12.89	64

Table 2.--*Energy-budget evaporation values and supporting data*

Number	Period From (month/day)	Period Through (month/day)	Length (days)	Solar radiation (langelys per day)	Reflected solar radiation (langelys per day)	Net long-wave radiation (langelys per day)	Long-wave radiation from water surface (langelys per day)	Advected energy (langelys per day)	Change in stored energy (langelys per day)	Bowen ratio	Evaporation (inches)
						1983					
1	7/29	8/11	14	423	31	605	787	3	63	0.200	1.15
2	8/12	8/29	18	528	36	566	805	2	-22	0.225	2.67
3	8/30	9/9	11	495	35	543	791	2	-49	0.228	1.55
4	9/10	9/27	18	468	34	480	745	0	-107	0.268	2.73
	7/29	9/27									8.10
						1984					
1	7/18	7/31	14	471	33	584	760	3	67	0.153	1.57
2	8/1	8/14	14	526	36	570	792	1	39	0.229	1.72
3	8/15	8/28	14	346	28	571	798	4	-74	0.331	1.17
4	8/29	9/11	14	508	36	515	781	1	-82	0.252	2.12
5	9/12	9/25	14	401	30	497	726	2	-43	0.335	1.30
	7/18	9/25									7.88

Error in evaporation values associated with error in water-surface temperature was investigated by changing water-surface temperature and recalculating the evaporation. Water-surface temperature affects the Bowen ratio, the latent heat of vaporization, and the long-wave radiation from the water surface. Resultant changes in total evaporation from changes in water-surface temperature are:

Change in water-surface temperature (degrees Celsius)	Total evaporation for data collection period (inches)	Percent change in evaporation
	1983	
-2	9.14	13
-1	8.57	6
1	7.64	-6
2	7.24	-11
	1984	
-2	9.44	20
-1	8.63	10
1	7.18	-10
2	6.56	-17

Morton-Model Evaporation Estimates

Operational estimates of lake evaporation can be made by use of a model presented by Morton (1984). The model, as used in this study, provides monthly estimates of lake evaporation. Input components to the model include latitude and altitude of the lake, annual precipitation, and monthly values of vapor pressure, air temperature, and solar radiation. Results of application of the model to Ned Wilson Lake are:

Month	Evaporation (inches)
1983	
August	5.12
September	4.06
Total	9.18
1984	
July	6.18
August	4.72
September	3.58
Total	14.48

Only August and September values were computed for 1983, because solar-radiation data was unavailable prior to July 29, 1983. Because all values required for the model were measured at the site, errors associated with the estimation of model inputs were not made.

SUMMARY AND CONCLUSIONS

Evaporation estimates for the mass-transfer and energy-budget techniques, and the Morton model are available for the periods of July 29 through September 27, 1983 and July 18 through September 25, 1984. For this comparison, results from the Morton model were converted to daily values and totaled for 2-week periods. Evaporation estimates from the three methods are given in table 3.

Table 3.--*Comparison of evaporation estimates*

Period		Evaporation (inches)		
From	Through	Mass-transfer	Energy-budget	Morton
		1983		
7/29	8/11	1.40	1.15	2.31
8/12	8/29	2.99	2.67	2.97
8/30	9/9	2.09	1.55	1.71
9/10	9/27	3.02	2.73	2.91
7/29	9/27	9.50	8.10	9.90
		1984		
7/18	7/31	1.07	1.57	2.79
8/1	8/14	1.72	1.72	2.13
8/15	8/28	1.89	1.17	2.13
8/29	9/11	2.66	2.12	1.77
9/12	9/25	1.37	1.30	1.67
7/18	9/25	8.71	7.88	10.49

The data listed in table 3 show that the Morton model estimated the largest rates of evaporation, and the energy-budget technique estimated the smallest rates of evaporation. Without further refinement of data collection, the most reliable result cannot be determined.

Futher refinement of the mass-transfer technique could be accomplished by defining the relation between wind speed at 2 meters above the lake surface and wind speed at the meteorological station. Additional surface-water temperature data also would provide more accurate mass-transfer results.

The single most important factor in improving the energy-budget results would be the actual measurement of incoming long-wave radiation. Secondly, additional measurements of surface-water temperatures would improve the value of long-wave radiation from the water surface (Q_{bs}), which is the largest term in the energy-budget equation.

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