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Water Budget and Lake-Level Stability of Harding Lake in the Interior Alaska

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Abstract

Harding Lake is situated about 160 km to the south of the Arctic Circle, at latitude 64°25′N and longitude 146°50′W; it is in the cold arid zone of the Interior Alaska lying between the Brooks Range to the north and the Alaska Range to the south; it is a closed dammed lake with none of outlet and inlet rivers.

Its morphometric features are: 9.88 km^2 in area, 43 m in maximum depth and 16 m in mean depth, the lake surface being 217 m above sea level.

The basin around the lake is found in the area characterized by discontinuous permafrost and a continental climate with an extreme difference in air temperature between summer and winter, the mean annual air temperature and the annual precipitation being respectively −4°C and 370 mm.

In a cold arid region, the value of f, which shows the ratio of evapotranspiration and evaporation, was estimated as 0.30 under a stable state during secular change in lake level.

In this area, the lake-level stability is affected mainly by variations in precipitation and additionally by the evaporation and the thawing of underground ice in summer.

1. Introduction

Situated about 160 km to the south of the Arctic Circle, Harding Lake is in the cold arid zone of the Interior Alaska lying between the Brooks Range to the north and the Alaska Range to the south; it is a closed dammed lake with none of outlet and inlet rivers.

The basin around the lake is found in an area of discontinuous permafrost,

Table 1 Averaged over 29 years from November 1944 to December 1973, annual and monthly mean values of meteorological data observed at Eielson Air Force Base near Harding Lake.

Month	Air Temperature (°C)	Precipitation (mm/month)	Relative Humidity (%)	Vapor Pressure (mb)	Saturated Vapor Pressure (mb)	Wind Velocity (m/s)	Cloud Cover
JAN	−25.0	25.4	73.3	0.68	0.63	0.51	6
FEB	−20.6	20.3	71.5	1.02	0.97	1.03	6
MAR	−13.3	15.2	68.0	1.69	1.93	1.54	6
APR	− 1.7	15.2	63.5	3.39	5.30	2.06	7
MAY	8.3	20.3	58.0	5.76	10.94	2.06	7
JUN	14.4	40.6	62.5	9.82	16.40	2.06	8
JUL	15.6	61.0	69.5	11.85	17.71	2.06	8
AUG	13.3	61.0	73.5	10.50	15.27	1.54	8
SEP	6.7	38.1	73.0	6.77	9.81	1.54	7
OCT	− 4.4	25.4	78.0	3.39	4.23	1.03	7
NOV	−16.7	22.9	75.0	1.35	1.41	1.03	6
DEC	−23.3	22.9	72.0	0.68	0.75	0.51	6
ANN	− 3.9	368.3	70.0	3.05	4.41	1.54	7

which has the mean annual air temperature of −4°C and a continental climate characterized by an extreme difference in air temperature between summer and winter.

In his previous studies, Nakao (1974, 1976) elucidated that the outflow characteristics of groundwater constituted the main factor in lake-level stability of this lake, which regulated a greater fluctuation in water level on closed lakes in such a humid zone as in Japan.

Harding Lake was subjected to this study aimed at clarifying regulating factors of a closed lake in a cold arid area and estimating changes in ancient precipitation from a water budget when the lake level was different at that time from the present time.

The writers carried out field observations of a water budget at Harding Lake in July 1978.

The lake-level stability in this area is affected markedly by the inflow of groundwater to the lake as a result of the melting of ice in the permafrost.

2. Climate near the lake

Meteorological data are continually recorded at the Eielson Air Force Base (64°40′N, 147°06′W) located 32 km to the northwest of the lake halfway between Fairbanks and Harding Lake. Averaged over 29 years from November 1944 to December 1973, annual and monthly mean values of meteorological data are tabulated in Table 1. The air temperature is –4°C in annual mean, exceeding 0°C only five months in summer (from May to September); the mean annual precipitation is 368 mm; the mean annual evaporation was 608 mm.

Evaporations were calculated fundamentally by the Penman's method (1956, 1971), using the meteorological data as follows:

$$E_0 = (0.417\Delta H_e + \gamma E_a)/(0.417+\gamma)$$

where E_0: evaporation (mm day^{-1});

Δ: variation in saturation vapor pressure at the air temperature of mb°k^{-1};

γ: psychrometer constant, namely 0.27 (mmHg $°\mathrm{F}^{-1}$);

E_a: $E_a = f(u)(e_a - e_d)$ in which $f(u)$ is the function of wind speed $u(\mathrm{ms}^{-1})$, as given by $f(u) = 0.26\ (0.5 + 0.54\ \mathrm{u})$, and

e_a: saturation vapor pressure at the mean air temperature (mb), and

e_d: vapor pressure in the air at the screen height (mb).

Besides, H_e is shown in evaporation units for the incoming heat of the net radiation H_0: namely, $H_e = H_0/59$ (mm).

The value of H_0 is obtained by the following equation:

$$H_0 = R_i(1-r) - R_b^* ,$$

where R_i is the shortwave income; r is the reflection coefficient, namely albedo was obtained by taking $r=0.05$ for the open water surface during the summer when the air temperature is over 0°C and by taking $r=0.63$ for the snow surface during the winter when the air temperature is below 0°C. The value of R_i is estimated by the following Savinov's equation:

$$R_i = R_a\{1-(1-k)C\} ,$$

where k is the constant varying with the latitude, its being 0.45 in latitude 65°N; C is the cloud amount ranging from 0 to 1 value; R_a is the Angot value of a possible radiation, using the solar constant of 2.00 cal $\mathrm{cm}^{-2}\mathrm{min}^{-1}$, their values beging tabulated in Table 2 with a possible duration of sunshine.

Meanwhile, R_b is the net longwave back radiation outward from the water surface and the income from the atmosphere, as given by Brunt's equation:

$$R_b = \sigma T_a^4 (1 - a - b\sqrt{e_d}) ,$$

where T_a is the air temperature (°K); σ is the Stefan's constant, namely, $1.183 \cdot 10^{-7}$ (cal $\mathrm{cm}^{-2}\ \mathrm{day}^{-1}°\mathrm{K}^{-4}$); a and b are the constants, for which 0.51 and 0.066 were obtained by G. Yamamoto. As for R_b^*, the effective back radiation,

Table 2. The Angot values of a possible radiation and possible duration of sunshine calculated at Harding Lake in 1978.

	JAN	FEB	MAR	APR	MAY	JUN	LUL	AUG	SEP	OCT	NOV	DEC
Angot value (cal cm^{-2} day^{-1})	28.0	127.5	332.8	598.4	846.8	991.8	962.2	695.5	432.4	200.3	57.4	12.8
Possible Duration of Sunshine (hr)	4.56	7.74	11.12	14.42	17.68	20.22	19.70	15.72	12.48	9.19	5.85	3.59

Latitude=64.42°N. Solar Constant=2.0 cal cm^{-2} min^{-1}

Table 3. Monthly evaporation calculated from the meteorological data at Eielson Air Force Base.

Month	Д mb°K^{-1}	R_i ly day^{-1}	R_b^* ly day^{-1}	H_0 ly day^{-1}	H_e mm day^{-1}	E_0 mm day^{-1}
JAN	0.063	19	107	−101	−1.70	−0.21
FEB	0.094	85	112	− 80	−1.36	−0.20
MAR	0.176	223	120	− 37	−0.63	−0.08
APR	0.442	368	112	− 24	0.40	0.63
MAY	0.743	521	117	378	6.40	4.53
JUN	1.061	555	92	436	7.39	5.74
JUL	1.135	539	86	425	7.21	5.59
AUG	0.996	389	88	282	4.78	3.61
SEP	0.675	266	110	143	2.42	1.78
OCT	0.360	123	108	− 62	−1.06	−0.07
NOV	0.132	38	116	−102	−1.73	−0.30
DEC	0.074	9	110	−107	−1.82	−0.19

it is affected by the cloud amount, as given by Angström's equation:

$$R_b^* = R_b(1-\beta C)\,,$$

where $\beta=0.75$.

The annual value evaporated from the lake, as shown in Table 3, indicates such a large quantity as 640 mm, compared with the annual precipitation of 370 mm, the vapor reversely condensing from the air to the ice surface covering the lake in winter from October to March.

In the first spring month with the mean air temperature rising above 0°C, the income radiation must be used to melt snow. Then, the snow melting correction is calculated for evaporation in May according to Penman (1954) as follows:.

The evaporation from the snow surface is expressed by the equation, $E=f(u)\ (e_0\text{-}e_d)$, where e_0 is the saturated vapor pressure at 0°C and $e_0=6.107$ mb during the melting period. The value of M_e, which denotes the amount of heat used to melt snow in evaporation units (mm), can be obtained by the following equation:

$$E = \{0.417\text{Д}(H_e - M_e) + \gamma E_a\} / (0.417\text{Д} + \gamma)$$

Then, given M_e, number of days, D, of a melting period is estimated from, $D=80$ P/590 M_e, P being the total precipitation during the period having the air temperature lower than 0°C.

As P=147 mm, the actual evaporations are 110 mm (D·E=1 mm; (31–D) $E_0=109$ mm) in May and 608 mm in annual value, where $E=0.146$ mm day^{-1}; $H_e=1.29$ mm day^{-1}, using $r=0.63$ in case of the snow surface; $M_e=2.91$ mm day^{-1} and D=7 days according to the values obtained.

3. Water budget on Harding Lake

Harding Lake has an area of 9.88 km^2 and a lake level of 216 m above sea level; also the Tanana and the Salcha River in the neiborhood of the lake are 213 m (700ft) and 198 m (650 ft) above sea level, respectively.

The basin around the lake has an area of 12.8 km^2 at present. Kane et al. (1979) reported that the additional basin area of 25.8 km^2 (A_3 in Fig. 1) might once have drained into the lake, and the stream of the basin might have converted into the Salcha River thereafter.

The altitude of the divide ranges approximately between 460 m at the highest site and 220 m at the lowest site.

On a closed lake, a water budget is given by the following equation because almost no surface inflows occur except for intense rainfalls:

$$A_1 \Delta h = (Q_{gi} - Q_{go})\Delta t + (P - E_0)A_1 ,$$

where A_1 is the surface area; h is the water level of a lake; Δt is the period of a water budget; P and E_0 denote the precipitation and evaporation during Δt respectively; Q_{gi} and Q_{g0} are the inflow and the outflow groundwater respectively.

Observations of a water budget were carried out, using as a base two trailer houses near the southwest shore of the lake, and the self-recording data were obtained of the evaporation through measurements by an evaporimeter, from which Nakao et al. (1967) determined the ratio of the evaporation from the large water body to the evaporation from the evaporimeter to be 0.67. Meanwhile, three-cup anemometer and that of the totalizing-dial type were also used for measurements of wind speed and direction.

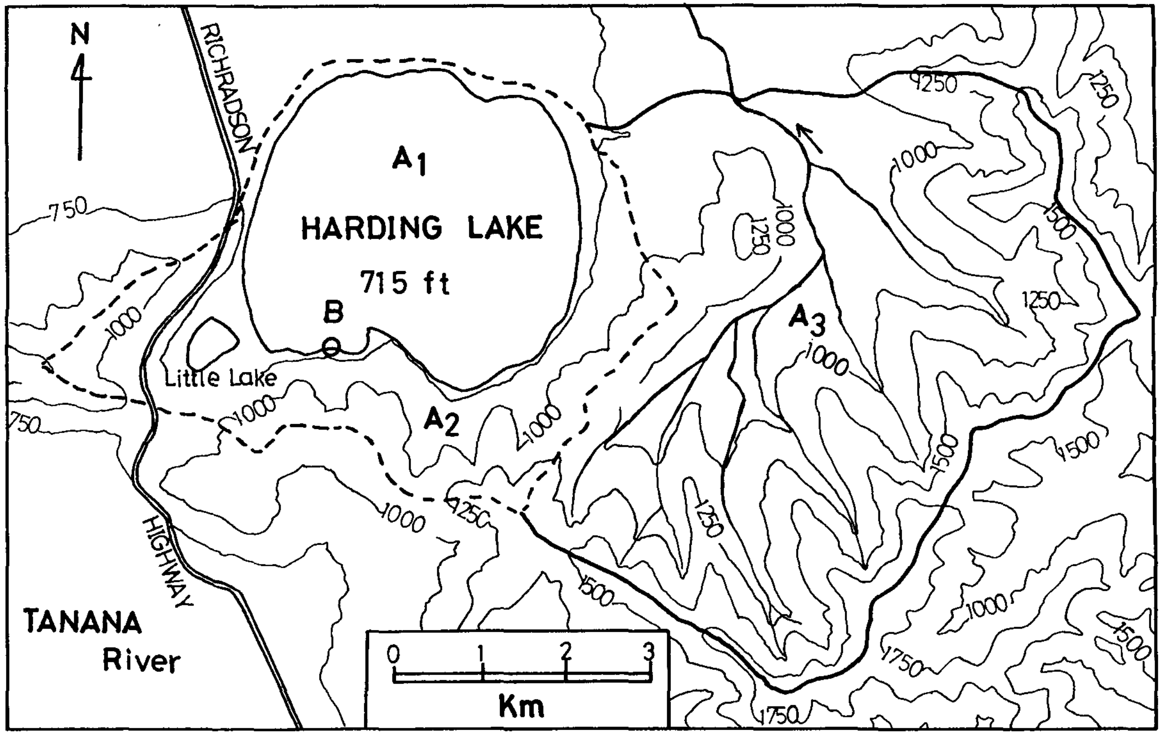

Fig. 1 Surrounding basin of Harding Lake, divide indicates dotted line and topographic contours denote in feet.

Used for measurements of humidity, air temperature and rainfall were respectively a self-recording hair hygrograph, a thermograph of the bimetal type in a shelter, supplemented by an Assman psychrometer, and a self-recording rain gauge. The water level of the lake was measured by a water-stage recorder, which had a pen carriage directly connected to a counterweight, then acting in concert with the water level. Meantime, accurate measurements were also carried out of the water level by a water-stage gauge of the hand-operation type, whose accuracy of measurement is 0.03 mm, in which the measured water surface is in a chloroethylene cylinder 14.8 cm in diameter connected to the lake water through a fine vinyl tube 1 m in length and 0.5 cm in diameter to damp the oscillation of a lake level in a short period.

Water budgets in four periods were calculated, as shown in Table 4, using water-level variations measured by an accurate water-stage gauge as shown in Fig. 2. The calculated evaporation from the lake is 5.6 mm day^{-1} in July, which is larger than the measured evaporation of 4.5 mm day^{-1} during the budget period except for the third period of rainfall because the calculation neglected changes in heat capacity in a lake-water body.

Comparing the rises in water level after the the rainfalls on the 12th and 14th, they happened to be very different from each other in that the former

Photo. 1. Observation site of a water budget, using as a base two trailer houses near the southwest shore of Harding Lake.

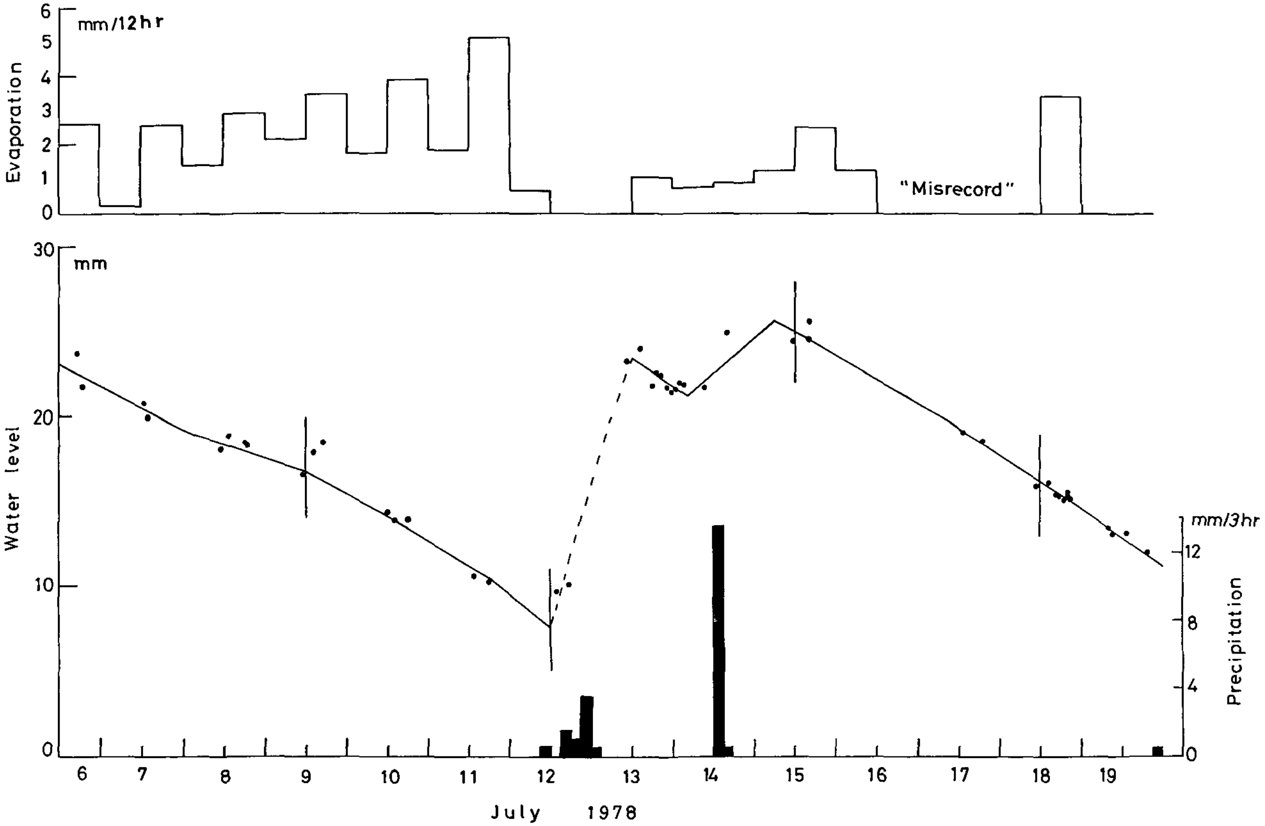

Fig. 2 Water-level variations measured by an accurate water-stage gauge and measured evaporation and rainfall at Harding Lake.

Table 4 Results of water budget on Harding Lake in July 1978.

Period July 1978 date time	Δh (mm)	E_0 (mm)	P (mm)	$(Q_{gi}-Q_{go})\Delta t/A_1$ (mm day^{-1})
6.12~ 9.12	− 6.4	12.05	0	1.88
9.12~12.12	− 9.1	17.00	0.5	2.47
12.12~15.12	17.2	4.03	20.5	0.31
15.12~16.12	− 2.8	3.83	0	1.03

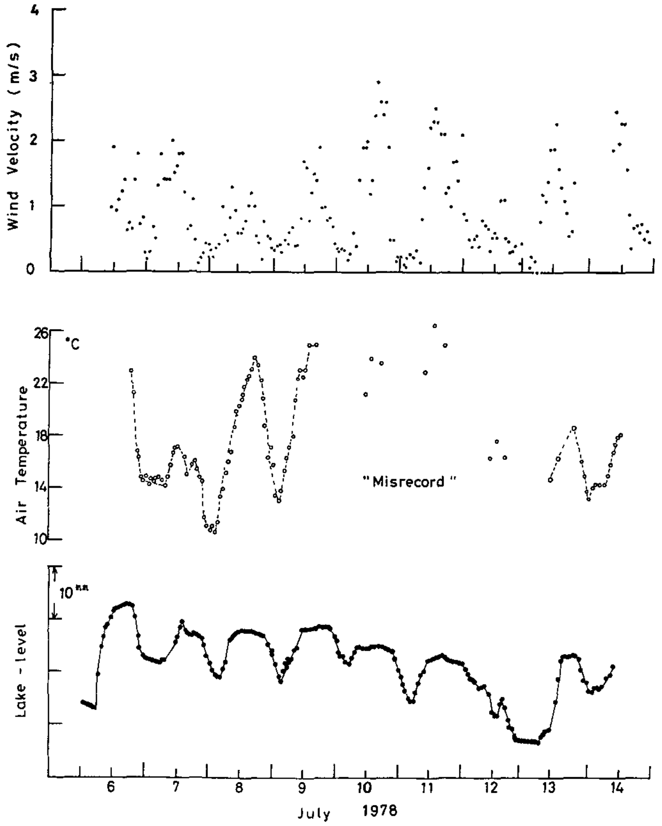

Fig. 3 Daily variations in water level, of wind speed and air temperature, during from 6th to 14th July 1978 at Harding Lake.

showed the rise of 16.2 mm for the precipitation of 7 mm, while the latter showed the rise of only 3.3 mm for the precipitation of 14 mm. The writers are of the opinion as to the difference that the rainfall on the 14th was a localized

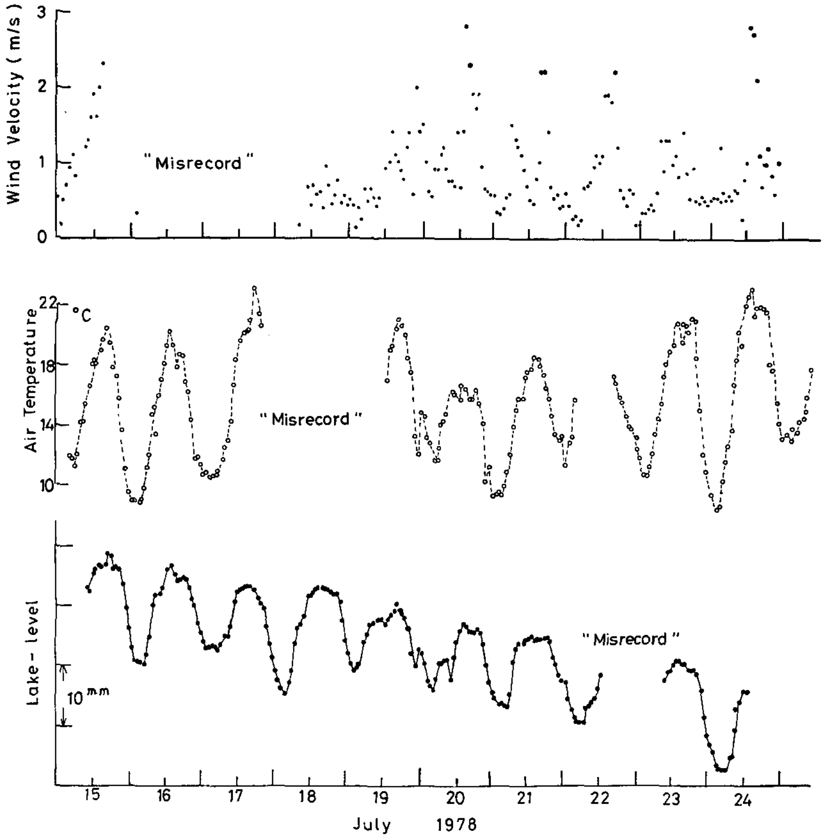

Fig. 4 Daily variations in water level, of wind speed and air temperature, during from 15th to 24th July 1978 at Harding Lake.

one in the lake basin, accompanying a severe storm with melting hail, while the rainfall on the 12th was uniform throughout the basin and the warm rain helped melting ice in the permafrost.

The value of $(Q_{gi}-Q_{go})\Delta t/A_1$, which is 1.80 mm day^{-1}, was estimated by the water budget averaged excepting the rainy period, if the groundwater outflow does not exist, the value being equivalent to the inflow rate of groundwater in summer when ice thawing occurs in the permafrost.

Daily variations in water level are periodically repeated with a daily cycle during which the maximum rise occurs at about 4 p.m. when the wind speed becomes strongest and the air temperature highest and the maximum fall occurs at about 5 a.m. on the opposite meteorological condition. The mean daily rise is 12 mm in water level, as shown by Fig. 3, 4.

The variations exactly coincide with those of wind speed and air temperature, resulting principally from a water accumulation by a wind shearing force with northern wind direction and additionally by the thawing of underground ice, as was found by the electrical depth soundings.

4. Consideration of an annual water budget

An annual water budget of Harding Lake was estimated, using the meteorological data tabulated in Table 1.

When the period of water budget is longer in yearly units, the changes in groundwater storage and in surface storage due to the snow cover are neglected in comparison with other values; then $(Q_{ri}-Q_{gi})\Delta t=(P-E_g)A_2$, where Q_{ri} is the surface inflow to the lake; E_g and A_2 denote, respectively, the evapotranspiration from the watershed around the lake and its area.

An equation for a water budget in a closed lake is given by

$$\Delta h = aP-bE_0-Q_{g0}\Delta t/A_1 ,$$

where

$$a=(A_1+A_2)/A_1 , \qquad f=E_g/E_0 ,$$

$$b=(A_1+fA_2)/A_1 .$$

If Q_{g0} is zero and no inflow comes an additional watershed (A_3), the stable equation of water level is expressed in secular variations; so, $aP-bE_0=0$; then, the value of f is estimated as 0.30, where $a=2.3$ and $b=1.6$.

As for values of f in humid regions, Nakao (1971) estimted $f=0.65$ in the Ishikari River, Hokkaido, Japan, and Penman (1949) estimated $f=0.75$ in England. As for a value of f in an arid region Nakao (1975) estimated it to be 0.15 at Lake Lahontan, Nevada, U.S.A., using the hydrological data of Broecker et al. (1958).

This value $(f=0.30)$ gives the annual evapotranspiration of 182 mm for 608 mm of E_0, which the writers judged to be a proper value in the area of discontinuous permafrost where part of the income radiation is expended to melt underground ice.

In this area, the lake-level stability is mainly affected by variations in precipitation and additionally by the evaporation and the thawing of ice in summer.

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References

Broecker, W.S. and P.C. Orr, 1958. Radiocarbon chronology of Lake Lahontan and Lake Bonneville, Geol. Soc. America Bull., **69**, 1009–1032.

Kane D, L., P.M. Fox, J.D. Fox and R.F. Carlson, 1979. Effect of diverting additional drainage area runoff into Harding Lake, Report to Division of Land and Water Management Department of Natural Resoruces State of Alaska, 1–28.

Nakao, K., S. Otsuki, R. Tanoue and R. Naruse, 1967. Watershed leakage from the closed lake-Lake Kuttara-, (in Japanese) Geophys. Bull. Hokkaido Univ., **17**, 47–64.

Nakao, K., 1971. A hydrological study on the stability of water-level of a lake or a swamp (in Japanese). Geophys. Bull. Hokkaido Univ., **25**, 25–87.

Nakao, K., 1974. Hydrological regime on the regulation of lake-level -A contribution to the paleolimnological study of Lake Biwa-, Proc. Japan Acad., **50**, 665–670.

Nakao, K., 1975. Ancient precipitation estimated from the past shore-line of a closed lake (in Japanese), Water Temperature Research, **18**, No. 6, 17–26.

Nakao, K., 1976. Estimations of ancient precipitation during the pluvial and dry epochs about three closed lakes, Paleolimnology of Lake Biwa and the Japanese Pleistocene, **4**, 149–152.

Penman, H.L., 1949. A general survey of meteorology in agriculture and an account of the physics of irrigation control, Quart, Jour. Royal Meteorol. Soc., **75**, 293–302.

Penman, H.L., 1954. Evaporation over parts of Europe, Assemblee Generale Rome, I.A.S.H., **III**, 168–176.

Penman, H.L., 1956. Estimating evaporation, Trans. Amer. Geophys. Union, **37**, 43–50.