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Hydrological Regime in Tundra Plain, St. Lawrence Island in Bering Sea

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Abstract

St. Lawrence Island is 4,900 km^2 in area, with a tundra plain occupying 70.8 % of it and the remaining area covered by a mountainous region including the Kookooligit Mountains with the highest peak 673 m above sea level. There are a large number of shallow lakes in the swampy tundra ground which the lake area occupies 26 %. The tundra has generally an active layer 15 cm in depth in summer and the permafrost depths were evaluated by electrical depth soundings, the values varying from 14 m to 27 m.

The water budget in the tundra plain holds a balance on the hydrological regime in which the excess water of the swampy tundra ground is evaporated after discharging to a lake with the runoff ratio of 0.2 through the year, the lake serving just as a discharging window. Then the ratio (f) of evapotranspiration (E_g) over the tundra ground to evaporation (E_0) of the lake surface, namely, $f=E_g/E_0$, is estimated to be 0.5. Also, f is expected to be 0.15～0.30 in case of the evapotranspiration of a mountainous region covered by a debris with a poor vegetation. The water of rivers in St. Lawrence Island is mainly supplied from the mountainous region.

1. Introduction

St. Lawrence Island is situated about 250 km to the south of Bering Strait, at latitude 63°20′N and longitude 170°15′W in Bering Sea. The island is 4,900 km^2 in area, with a tundra plain occupying 70.8% of it and the remaining area covered by a mountainous region including the Kookooligit Mountains with the highest peak 673 m above sea level.

The continental shelf of Bering Sea is bounded by a deep sea about 780 km to the south of the island. And through the Ice Age this boundary constituted the southernmost coast of the Bering-Chukchi Plateau of the continental shelf. The plateau, the so-called Beringia, used to serve as a land bridge 1500 km wide connecting Alaska and Siberia, but was submerged when a postglacial transgression caused the sea level to rise about 10,000 years before present (Fig. 1).

Pollens of the historical vegetation in Beringia were studied in detail by Colinvaux (1967) at Flora Lake in St. Lawrence Island and also by him (1981) in St. Paul Island near the southernmost coast of Beringia.

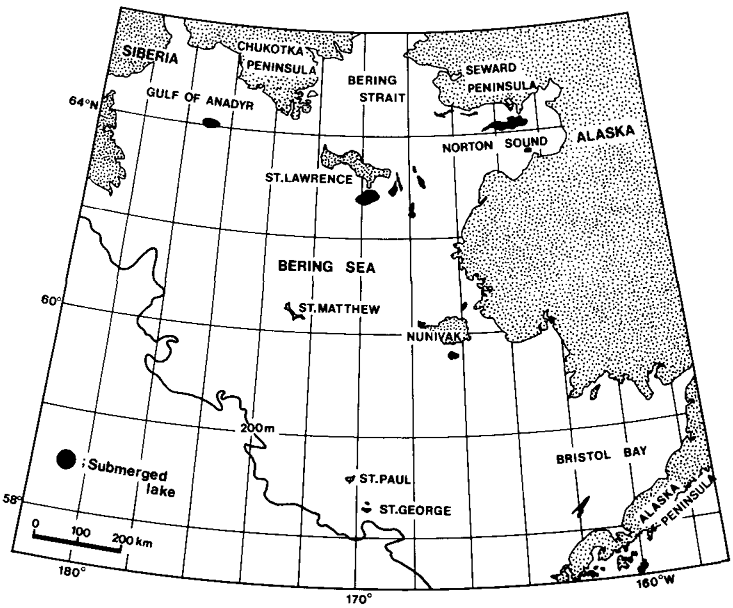

Fig. 1 Location map of St. Lawrence Island, thick line indicated the southernmost shore line in the Beringia.

2. Climate

Meteorological observations have been carried out at two observatories in St. Lawrence Island : one at Gambell along in the northwesternmost cape and

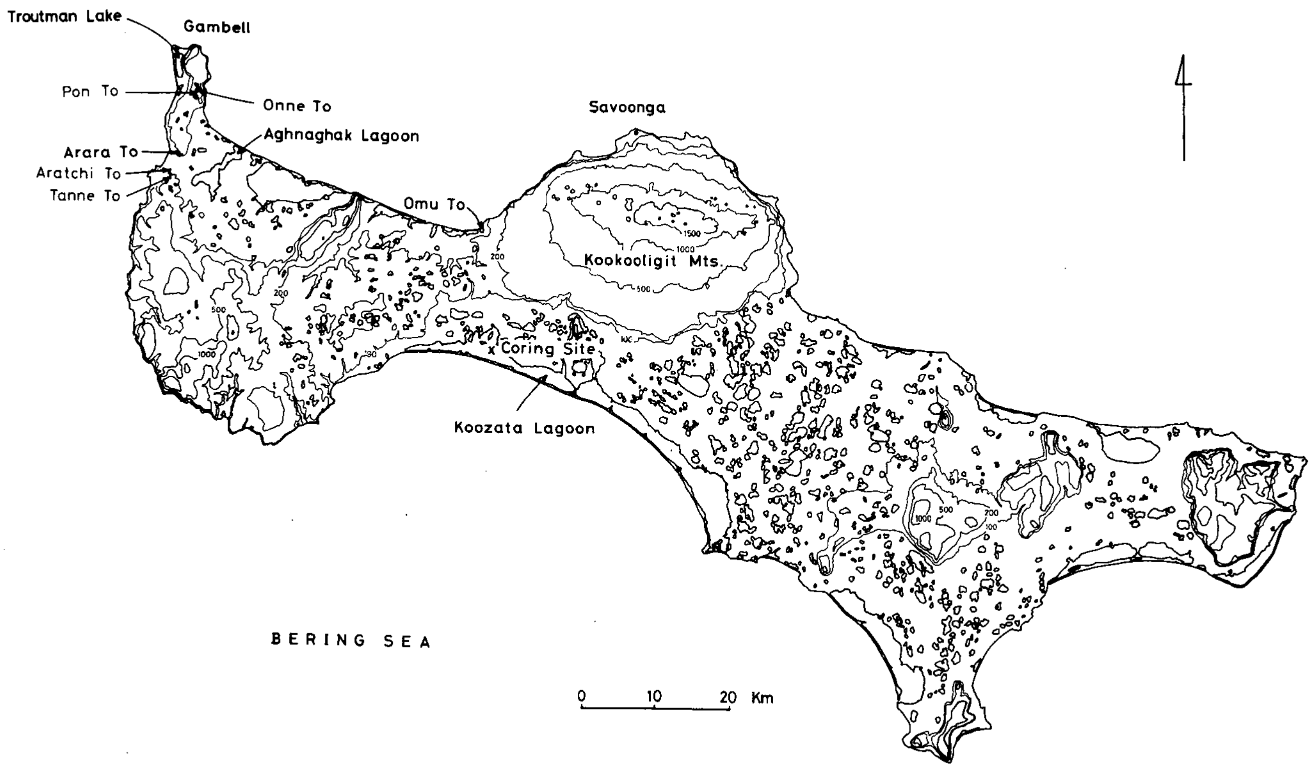

Fig. 2 Topographic feature and the surveyed area in St. Lawrence Island.

the other at Savoonga the north coast behind the Kookooligit Volcanic Mountains (Fig. 2).

The climate of the island is characterized by the presence of continuous permafrost and an oceanic climate with a slight difference in air temperature between summer and winter in marked contrast with Fairbanks in interior Alaska. The mean annual air temperature and the annual precipitation are respectively −3.5℃ and 568 mm at Gambell, based on the record from 1944 to 1954 ; −4.9℃ and 270 mm at Savoonga, based on the record from 1929 to 1949, which are similar to those found in the longer record from 1941 to 1982 at Nome observatory, about 170 km to the northeast of the island and at the westernmost coast of the mainland of Alaska.

The seasonal variations in precipitation are characterized by an increase in

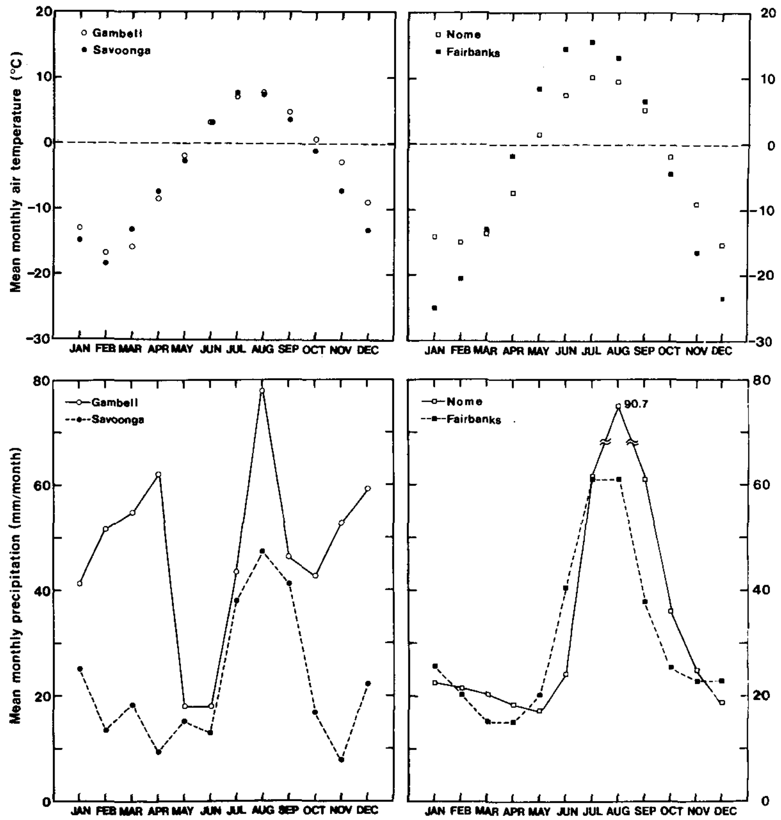

Fig. 3 Seasonal variations of mean monthly air temperature and mean monthly precipitation in Alaska.

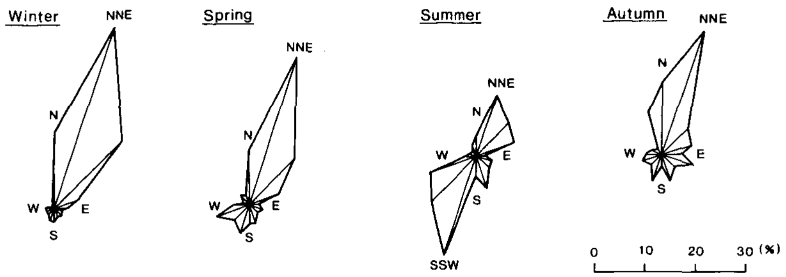

Fig. 4 Percentage frequency of surface winds observed by Gambell Air Weather Service.

the July~September period and a decrease in winter at Savoonga, Nome, Fairbanks in Alaska, but Gambell's record shows much snow in winter from November to April, as it may be caused by blowing snow from the sea ice plain by the northerlies as shown in Fig. 3.

According to the Gambell air weather service the NNE wind prevails through all seasons; and the SSW wind also prevails in the summer season alone as shown in Fig. 4. Finally the meteorological data at Nome was used for the estimation of evaporation in St. Lawrence Island, because Nome is similar in climate to the island and has a long and detailed meteorological record.

3. Water budget on Arara To*

Arara To subjected to a water budget study is surrounded by a tundra plain spreading about 30 m above sea level and the lake accounts for 26% of the area of the plain. The tundra has generally an active layer 15 cm in depth in summer and the permafrost depths Z_p were evaluated by electrical depth soundings, the values varying from 14 m to 27 m as reported by Nakao et al. (1986).

The value of Z_p is calculated basically by the following equation:

$$Z_p = -(K/q)\ T_a$$

where K : thermal conductivity of permafrost;

q : terrestrial heat flow, namely 1.5×10^{-6} cal/cm^{2}s;

T_a : mean annual air temperature, namely -3.5℃ at Gambell and -4.9℃ at Savoonga.

* "Arara To" is the name given by Nakao, as it means "beautiful lake" in the language of the Ainu, the native people of Hokkaido Island; and other lakes were likewise named Onne To (noble lake), Pon To (small lake) and Omu To (dammed lake).

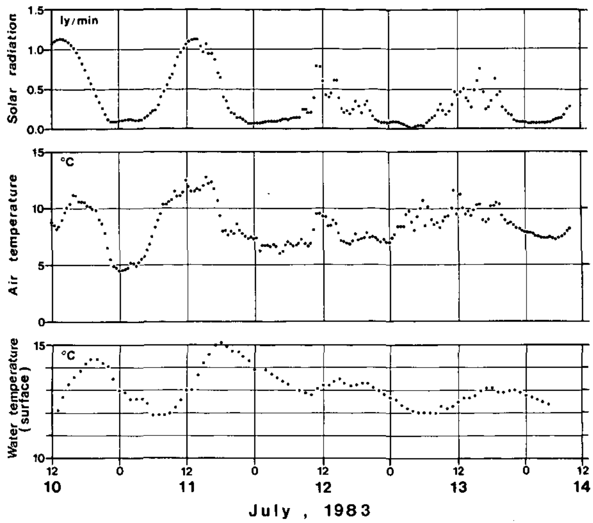

Fig. 5 Daily variations of solar radiation, air temperature and water surface temperature, during from 10th to 14th July 1983 at Arara To.

The values of Z_p calculated the depths ranging from 50 m to 100 m for K given as 2 or 3×10^{-3} cal/cm s℃. They are much deeper than the depths evaluated by electrical depth soundings, it may be caused by the higher surface temperature of the tundra than air temperature because the lake area having a small albedo occupies a large part of the plain.

A water budget was observed at the camping site near the Arara To, and self-recording data were obtained on global solar radiation, dry and wet bulb temperature, wind velocity, water and ground temperature and precipitation, using a computer memory system (Fig. 5). Meantime, accurate measurements were 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 level of the surface to be measured is that of water 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 so that the oscillation of a lake level in a short period should be damped.

A water budget is given by the following equation:

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

where A_l is the surface area; h is the water level of the lake; Δt is the period of calculation of a water budget; P and E_0 denote the precipitation and

Table 1 Components of water budget on Arara To.

Date July 1983	Δh mm	P mm	E_o mm	$Q_{gi}\ \Delta t/A_i$ mm
11. 0~12h	−0.4	0	0.6	0.2
12~24	2.0	0.5	1.9	3.4
12. 0~12	3.1	0.5	1.9	4.5
12~24	0.8	0	1.7	2.5
13. 0~12	0.0	0	0.6	0.6
12~24	−0.4	0	0.9	0.5
			sum.	11.7

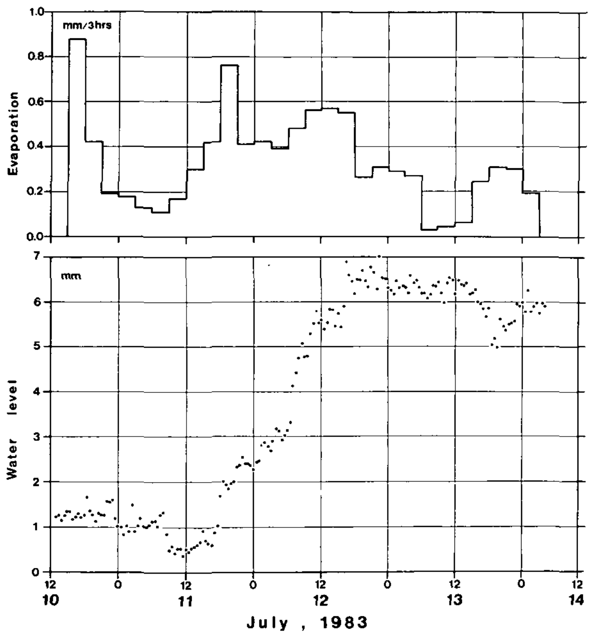

Fig. 6 Water-level variations measured by an accurate water-stage gauge and calculated evaporation at Arara To.

evaporation during Δt respectively; Q_{gi} is the rate of groundwater inflow.

The components of the water budget were evaluated every 12 hours for three days from 11 to 13th July as tabulated in Table 1, using water-level variations measured by an accurate water-stage gauge as shown in Fig. 6. The amounts of evaporation were calculated basically by the Thornthwaite and Holzman's method (1939), using the meteorological data observed at the Arara

To as follows:

$$E_0=8.64\times10^5\frac{0.622}{B}\rho_a\frac{k^2u(e_s-e_d)}{\{\ln(Z/Z_0)\}^2},$$

where E_0: evaporation (mm/day);
B: atmospheric pressure, 1013 mb;
ρ_a: air density, 1.25×10^{-3} g/cm^3;
Z: screen height, 200 cm;
Z_0: roughness height, 0.5 cm;
e_d: vapor pressure in the air at screen height (mb);
e_s: saturation vapor pressure on the warer surface (mb);
k: Von Karman's constant, 0.4.

The sum of calculated amounts of groundwater inflow was 11.7 mm in the lake level, meanwhile the melting water of frozen ice in the tundra ground was 11.4 mm in water equivalent according to the estimate by Urakami (1986) who evaluated the heat flux conducted through an active layer to the frozen ground during the calculated period of the water budget.

At this time, the runoff ratio η obtained was 0.36, taking $A_l/A_t=0.35$, where A_t is the area of the tundra ground.

4. Hydrological regime in the island

The mean annual precipitation at Savoonga adopted as a representative record of the island was 270 mm; and the amounts of evaporation were calculated using the Penman's method (Penman, 1954, 1956 and Nakao, 1971), from the meteorological data at Nome observatory as shown in Table 2 as follows:

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

where Δ: variation in saturation vapor pressure at the air temperature (mb/℃);
γ: psychrometer constant, 0.27 mmHg/°F;
E_a: $E_a=f(u)(e_a-e_d)$ in which $f(u)$ is the function of wind speed u (m/s), as given by
$f(u)=0.26\,(0.5+0.54u)$;
e_a: saturation vapor pressure at the mean air temperature (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:

Table 2 Mean meteorological data based on record for the 1941~1970 period at Nome meteorological station.

Month	Air Temperature (℃)	Precipitation (mm/month)	Relative Humidity (%)	Vapor Pressure (mb)	Saturated Vapor Pressure (mb)	Wind Velocity (m/s)	Rate of Sunshine
JAN	−14.4	22.9	72	1.26	1.75	5.3	0.37
FEB	−14.9	21.3	68	1.14	1.67	5.0	0.47
MAR	−13.7	20.1	70	1.30	1.86	5.0	0.43
APR	− 7.3	18.5	73	2.40	3.29	4.7	0.52
MAY	1.6	17.8	71	4.87	6.86	4.6	0.52
JUN	7.5	24.1	73	7.56	10.36	4.5	0.46
JUL	10.1	61.5	75	9.26	12.35	4.5	0.40
AUG	9.6	90.7	76	9.08	11.95	4.7	0.48
SEP	5.6	61.0	72	6.54	9.09	5.0	0.34
OCT	− 1.9	36.1	73	3.81	5.22	4.9	0.54
NOV	− 9.1	24.9	73	2.05	2.82	5.4	0.27
DEC	−15.3	18.8	69	1.11	1.61	4.6	0.37
ANN	− 3.6	417.6	72	3.25	4.52	4.8	0.45

$$H_0=(1-r)\ R_A\ (0.18+0.55n/N)$$
$$-\sigma T_a^4\ (0.56-0.078\sqrt{e_a})\ (0.10+0.90n/N),$$
$$R_A=\{I_0\Pi/\pi\Omega^2\}\ (t_o\sin\delta\sin\varphi+\cos\delta\cos\varphi\sin t_0),$$
$$\cos t_o=-\tan\varphi\tan\delta,$$
$$N=(24/\pi)\ t_0,$$

where r : reflection coefficient, albedo ;
R_A : Angot value (cal/day cm²) ;
n : duration of bright sunshine (hour) ;
N : possible duration of sunshine (hour) and n/N is rate of sunshine ;
σ : Stefan's constant, 1.18×10^{-7} (cal/cm² K⁴ day) ;
T_a : air temperature (K) ;
I_0 : solar constant, 1.94 cal/cm²min ;
Ω : radius vector of earth for sun ;
Π : total hours of day, $\Pi=1{,}440$ min. ;
t_0 : hour angle of half day ;
δ : apparent declination of sun ;
φ : latitude.

The reflection coefficient for the shortwave income, namely albedo, was obtained by taking $r=0.05$ for the open water surface during the summer when the air temperature is over 0℃ and by taking $r=0.63$ for the snow surface during the winter when it is below 0℃. Meanwhile, the albedo values were measured under several surface conditions by the portable albedometer of Aburakawa and Fukami (1978) in St. Lawrence Island as tabulated in Table 3. The annual amount of evaporation calculated was 423 mm as shown in Table 4.

The island has two land features: a mountainous region and a swampy

Table 3 Albedo values over the surface conditions measured by the portable albedometer in St. Lawrence Island.

Surface condition	Albedo
Tundra plain	
Brown grass	0.16−0.23
Green grass	0.27−0.31
Marshy moss	0.10−0.20
Peat soil	0.07−0.14
Debris	0.10−0.14
Sand bar	
Gravel	0.11−0.12
Sand (wet)	0.03
Reddish fine sand	0.25
Water surface	
Lake	0.02−0.04
River	0.05−0.08
Patched snow	0.54−0.61

Table 4 Monthly evaporation calculated from the meteorological data at Nome, Alaska, based on record for the 1941~1970 period.

Month	R_A ly/day	Ho ly/day	He mm/day	Δ mb/K	E_0 mm/day
JAN	42.3	−102	−1.74	0.160	0.00
FEB	154.3	−106	−1.80	0.154	0.01
MAR	366.1	− 67	−1.13	0.170	0.13
APR	635.0	− 38	−0.64	0.286	0.29
MAY	874.7	239	4.05	0.492	2.22
JUN	997.7	280	4.75	0.708	3.50
JUL	941.0	245	4.15	0.827	3.36
AUG	745.2	184	3.11	0.803	2.73
SEP	473.5	61	1.03	0.631	1.58
OCT	231.9	−112	−1.90	0.436	−0.07
NOV	74.2	− 79	−1.35	0.248	0.12
DEC	19.3	−105	−1.79	0.149	−0.02

Table 5 Occupying areas of land feature in St. Lawrence Island.

Region		Area	Occupied percentage
Mountain		1430 km²	29.2%
Tundra Plain	lake	910	18.6
	tundra	2560	52.2
Total		4900	100

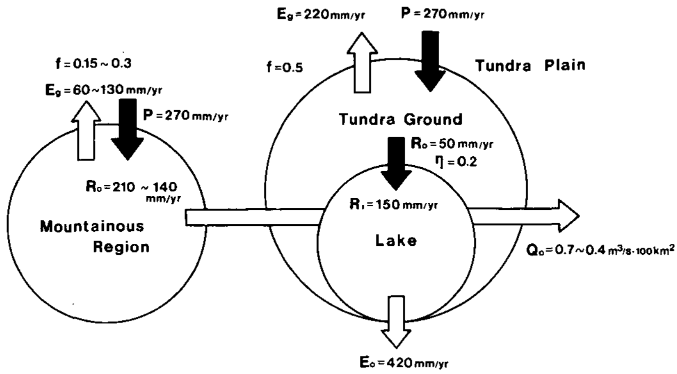

Fig. 7 Schematic diagram of hydrological regime in St. Lawrence Island.

tundra plain. The former is covered with a debris with poor vegetation and occupies 29.2% of the total land area and the latter accounts for 70.8% of it (Table 5).

The water budget in the tundra plain holds a balance on the hydrological regime in which the excess water of the swampy tundra ground is evaporated after discharging to a lake with $\eta = 0.2$, the lake serving just as a discharging window as shown in Fig. 7

Then the ratio (f) of evapotranspiration (E_g) over the tundra ground to evaporation (E_0) of the lake surface, namely $f = E_g/E_0$, is estimated to be 0.5.

As for the values of f in humid regions, Nakao (1971) estimated $f = 0.65$ in the Ishikari River, in Hokkaido, Japan, and Penman (1949) estimated $f = 0.75$ in England. As for values of f in an arid region Nakao (1975) estimated $f = 0.15$ in the Lahontan Basin, Nevada, U.S.A.; and in a cold arid region Nakao et al. (1981) estimated $f = 0.3$ in the Harding Lake Basin, Alaska, which is characterized by the presence of discontinuous permafrost. This value ($f = 0.3$) is judged to be a proper value in the area of discontinuous permafrost where part of incoming radiation is expended to melt underground ice.

Meanwhile, the value ($f = 0.5$) may be larger than the value at Harding Lake

Table 6 Results of stream gauging and the specific discharge.

Location	Discharge	Drainage area	Specific discharge
Arara To	0.0567 m^3/s	1.69 km^2	3.36 m^3/s 100 km^2
	0.00614	4.04	0.152
	0.0240	4.70	0.511
	0.00145	1.53	0.0948
	0.00829	0.572	1.45
	0.0250	1.80	1.39
	0.0139	0.627	2.22
Koozata Lagoon	0.0845	19.2	0.440
	0.183	22.3	0.821
Omu To	0.00505	1.67	0.302
	0.00122	7.49	0.0163
Savoonga	0.00294	1.99	0.148
	0.000535	0.745	0.0718
	0.00379	17.3	0.0219
Total	0.417	85.7	11.0
Mean			0.786

due to the swampy ground condition although part of incoming radiation is expended to melt underground ice.

Also, f is expected to be 0.15～0.30 in case of the evapotranspiration of a mountainous region covered by a debris with a poor vegetation; from the results the mean annual runoff is 0.7～0.4 m^3/s 100 km^2. The specific discharges of a river were measured around the island and the average value of 0.79 m^3/s 100 km^2 obtained was coincident with the values estimated by the hydrological regime (Table 6). The water of rivers in St. Lawrence Island is mainly supplied from the mountainous region.

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