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The water balance of Lake Krasnoye

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THE WATER BALANCE OF LAKE KRASNOYE

By Graevskii, I.P. and D.D. Kvasov

Lake Krasnoye has already been the object of complex limnological 111*
research for twenty years. In connection with this, it is of great importance to know its water balance, for this determines its in- and outflow of mineral and organic matter and sediments and affects the thermal regime of the lake, the dynamics of the water mass, sedimentation and littoral processes. Indirectly, the water balance also influences the biological processes occurring in the lake, in particular, its biological productivity. Research work on the water balance of the lake was done from 1964 to 1967.

There were earlier attempts to assess the water balance of Lake Krasnoye. Thus, N.I. Semenovich (1958), on the basis of material from his field research, assessed the components of the water balance for August 1947.

Interesting data concerning the regime of one of the streams in the catchment basin of Lake Krasnoye are contained in the work of

*Numbers in the right-hand margin indicate the corresponding pages in the original.

A.F. Izotova (1960).

The border of the catchment basin of Lake Krasnoye was determined during field work in the summer of 1964. The size of the catchment area is 168 km^2. The area can be divided into two main parts. The bigger, southeastern part lies within the central plateau of the Karelian isthmus; the smaller, northwestern part lies within the terraces of large water basins which existed here in late-glacial and post-glacial times. The lake borders directly on the terrace of the Ladoga transgression; at the time of this transgression Lake Krasnoye formed a deep inland bay of Lake Ladoga. The back seam of this terrace is about 5 m above the level of the lake (20 m of absolute height). The terrace levels that are situated higher and reach 50 m and 65 m of absolute height were formed probably as a result of the activity of the large glacial lake Ramsey which existed in the middle Dryas, approximately, 12 to 13 thousand years ago. At the 112
northeastern shore of the lake these terraces are accumulative and made up of sand; at the southwestern shore they are abrasive and on their surface they have numerous boulders - remains of a washed-out moraine. A clearly outlined abrasive bench separates the terraces from the Central plateau of the Karelian Isthmus, within whose bounds are various forms of glacial relief. The southeastern end of the lake with the Strannitsa river valley as its extension cuts into the plateau like a sort of bay.

Twenty-four permanent and temporary streams flow into Lake Krasnoye (Semenovich, 1958). The Strannitsa river is the main one; its catchment area is 82 km^2, i.e., approximately half of the entire catchment area of the lake. The Strannitsa river drains the central plateau of the Karelian Isthmus and has a narrow and very deep canyon-like valley. The subterranean catchment of the Strannitsa river probably exceeds its surface catchment. In particular, the Strannitsa river drains the deep water-bearing horizons in the area of Lake Michurinskoye. Most of the remaining tributaries have no names, and so they are given ordinal numbers in an anticlockwise direction (the Strannitsa river is tributary No. 1). The streams from No. 2 to No. 13 are short tributaries, some of them temporary. They drain a steep slope of the plateau which descends towards the northeastern shore of the lake. Stream No. 14 extends quite far down the slope of the plateau, which departs here from the lake shore, and drains both the plateau and the terraces. Streams No. 15 to No. 22, which also flow into the lake from the northeast, have their catchments within the terrace bounds. Only two tributaries (No. 23 and No. 24) flow into the lake from the southwest: here the watershed [divide] of Lake Pravdinskoye is quite near the shore. Stream No. 23 has its upper reaches on the plateau but it does not drain deep subterranean water and it almost dries up in the summer period of low-water level.

The catchment area of the lake (168 km^2) is 18.4 times bigger than the size of the lake itself (9.13 km^2). This makes water inflow a decisive factor in the incoming portion of the water balance. Drainage from the 113
lake accounts for most of the outgoing portion of the balance. The run-off from Lake Krasnoye occurs via the Krasnaya river which flows into Lake Pravdinskoye. The run-off from Lake Pravdinskoye occurs via the Pchelinka river; Lake Pravdinskoe belongs to the catchment area of the Vuoksa river.

In the years from 1949 to 1960 an electric power station was in operation on the Pchelinka river. This power station produced a considerable backwater effect and raised the water level in both lakes. In 1960 the water level dropped a little but was still higher than the original one, and on September 4, 1964, when the water engineering works were finally dismantled, the water level dropped sharply (Fig. 1).

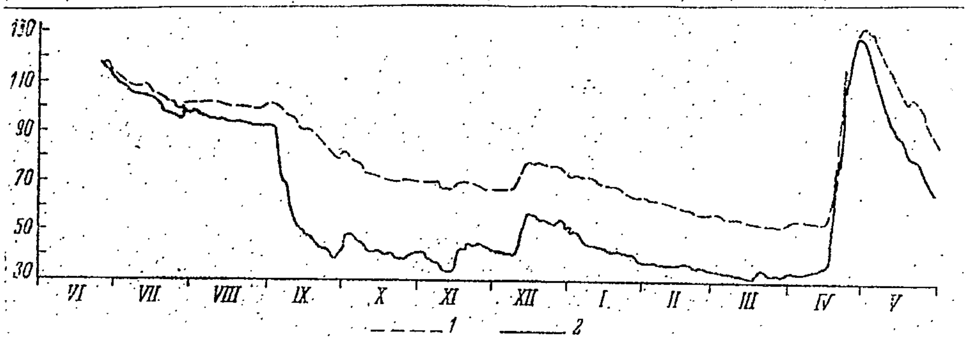

Fig. 1

Graph showing the fluctuation of the level of Lake Krasnoye and Lake Pravdinskoye from June 1964 to May 1965.

1 - Lake Krasnoye; 2 - Lake Pravdinskoye;
The zero of the graph of Lake Pravdinskoye has been accepted as the zero of the graph.

If prior to this date the difference between the water levels of Lake Krasnoye and Lake Pravdinskoye was but a few centimeters, it now amounted to 40-50 centimeters. It is only in springtime that the water levels of both lakes are, for approximately 10 days, equal, due to the faster rising of the water in Lake Pravdinskoye. Then the run-off from Lake Krasnoye into Lake Pravdinskoye stops.

The average level of Lake Krasnoye in the years 1965 - 1967, i.e., when there was no backwater effect, was 21 cm above the zero of the diagram (15.15 m is the mark accepted for zero in the diagram). The year to year variations in the average levels were insignificant (Table 1). 115

The equation of the water balance of Lake Krasnoye runs as follows:

$$X + Y_{пр.пов} + Y_{пр.подз} = Z + Y_{ст} + \Delta h,$$

where X = precipitation; $y_{пр.пов}$ = inflow to the lake from permanent and temporary tributaries; $y_{пр.подз}$ = subsurface inflow; z = evaporation; $y_{ст.}$ = run-off from the lake; Δh = increase in the level. All the quantities were calculated in millimeters of a layer of water in the lake. Subsurface drainage from the lake was not taken into account since it was probably too insignificant.

Data on precipitation on the surface of the lake were derived from meteorological data of the Limnological station (Table 2). The average yearly precipiation for 4 years was 690 mm. It must be noted that not only the precipitation in summertime but also the precipitation that falls on the ice surface in winter has an immediate effect on the level of the lake. Since the ice is afloat, the weight of the snow immerses it further.

Inflow into the lake was determined from systematic observations of the discharge of the Strannitsa river and occasional observations of other tributaries. On February 6, 1964, a temporary water gauging post was set up on the Strannitsa river above the highway bridge, and on June 27, 1964, a permanent post replaced the temporary one downstream. The catchment area of the temporary and permanent posts was 73.2 and 82.0 km^2, respectively. In 1964 both posts were monitored only occasionally; and hence the drainage for the days not monitored was extrapolated on the basis of atmospheric precipitation. The drainage for periods involving longer lapses was calculated according to I.B. Volftsun's method. From 1965 systematic observations were maintained on the Strannitsa river. The levels were measured every day, and the water discharge was measured about 25 times a year. The daily rate of discharge was determined on the basis of diagrams showing annual relationships between rates of discharge and water levels (Fig. 2). The winter discharge was found by extrapolation from the data

Table I   Таблица I

Уровни оз. Красного за I964-67 г.

Levels of Lake Krasnoye for the period 1964--67

Год year	Декада ten-day period	I	II	III	IУ	У	УI	УII	УIII	IX	X	XI	XII	Средний за год average for year
I964	Ist	73	6I	54	50	I36	96	63	55	52	32	23	20	
	2nd	69	59	52	73	I30	83	59	53	44	25	22	30	
	3rd	65	56	50	I3I	II5	7I	54	53	36	24	22	29	
	Среднемесячный average monthly	69	59	52	85	I27	83	58	54	44	27	22	26	59
I965	I	25	I5	8	7	76	28	6	4	8	I8	3I	23	
	2	22	I2	6	I4	58	I6	4	5	I3	I9	30	23	
	3	I8	I0	5	74	45	9	I	5	I9	I8	26	22	
	Среднемесячный average monthly	22	I3	7	30	59	I7	4	5	I3	I9	29	22	20
I966	I	I9	I7	I3	20	II9	80	26	8	I	32	37	26	
	2	I9	I6	I2	46	I34	54	22	I3	7	4I	29	22	
	3	I7	I6	II	5I	I09	33	I3	5	20	42	26	I8	
	Среднемесячный average monthly	I8	I6	I2	39	I20	56	20	9	I0	38	3I	22	33
I967	I	I6	I0	II	36	68	I8	-3	-20	-22	-27	I5	I2	
	2	I5	I0	28	66	57	I0	-8	-2I	-24	-I7	I7	8	
	3	I3	I0	32	76	40	3	-I6	-2I	-27	- 8	I7	6	
	Среднемесячный average monthly	I4	I0	24	59	54	I0	-I0	-2I	-24	-I7	I6	8	I0
Средние averages	I965-I967	I6	I3	I4	43	78	28	5	-2	0	I3	I5	I7	2I
	I964-I967	3I	24	24	53	90	42	I8	I2	II	I7	I4	20	30

for the discharge measured in autumn, since because of ice-blocking, the state of the levels of the Strannitsa river in winter does not reflect changes in water discharge.

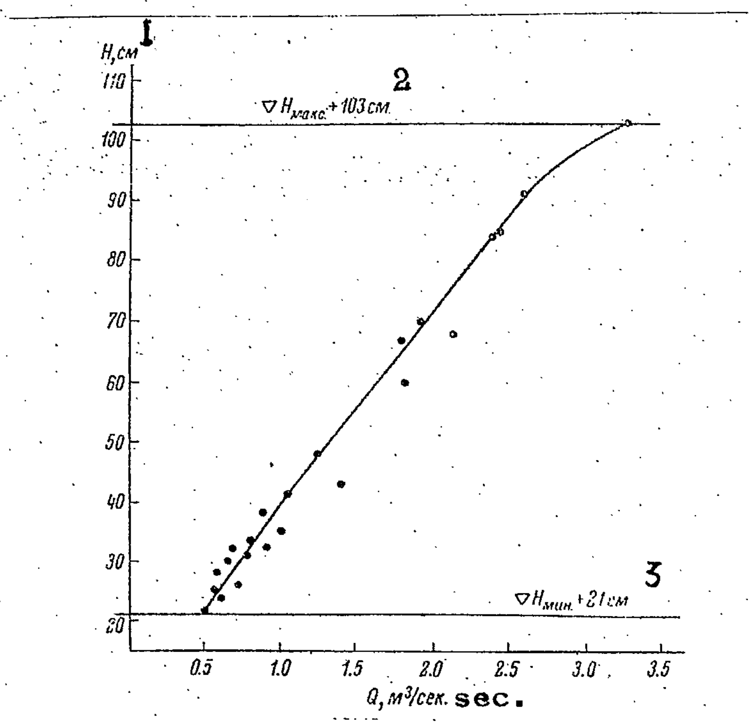

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Рис. 2.

Кривая зависимости расходов от уровней р.Странницы за 1967 год.

Fig. 2

Water-level--water-discharge curve of the Strannitsa river for 1967.

1 - H,cm; 2 - $\nabla H_{maximum}$ + 103 cm; 3 - $\nabla H_{minimum}$ + 21 cm;

The fluctuation range of the discharge from the Strannitsa river is small--the absolute maximum during 4 years of observations only 13 times exceeded the minimum. The water discharge of the Strannitsa river never drops below 0.5 m^3/sec. (M 6 l/sec. km^2) . Minimum discharge is usually

Table 2 Составляющие водного баланса (в мм) оз.Красного за 1964–1967 гг.

Components of the water balance (in mm) of Lake Krasnoye for 1964--1967.

Составляющие components	I	II	III	IУ	У	УI	УП	УШ	IX	X	XI	XП	Годовая yearly
						1964 г.							
a X	62.6	30.4	I0.I	28.8	27.7	20.5	5I.I	55.4	I05	42.8	47.0	75.I	556
b $У_{пов}$	259	244	296	I490	64I	30I	225	264	35I	402	300	348	5I20
c $У_{подз}$	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	72.0
d пр	328	280	3I2	I520	675	328	282	326	46I	45I	353	429	5750
	3.0	I.5	2.5	2.I	36.5	88.I	I00	87.4	50.4	27.3	I6.I	2.0	4I7
e $У_{ст}$	425	378	350	650	988	600	302	238	60I	544	367	367	58I0
f ст	428	380	352	652	I024	688	402	325	65I	57I	383	369	6230
	-I00	-I00	-40	870	-350	-360	-I20	0	-I90	-I20	-30	60	-480
						1965 г.							
a X	56.3	49.I	57.7	I3.2	25.9	43.5	67.8	78.6	95.I	79.2	52.7	96.8	7I6
b $У_{пов}$	258	233	293	I553	555	326	258	286	327	359	299	258	50I0
c $У_{подз.}$	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	72.0
d пр	320	288	357	I572	587	376	332	370	428	444	358	36I	5800
	2.5	I.0	4.0	3.0	7I.I	78.2	96.0	64.2	58.0	64.3	I2.8	2.0	457
e $У_{ст}$	398	357	383	789	I0I0	587	286	276	230	300	375	389	5380
f ст	400	358	387	792	I080	665	382	340	288	364	388	39I	5840
	-80	-70	-30	780	-490	-290	-50	30	I40	80	-30	-30	-40
						1966 г.							
a X	58.6	32.9	79.4	67.7	3I.6	32.3	67.9	86.9	II4	74.I	48.2	40.2	734
b $У_{пов.}$	226	204	256	I060	I360	3I9	256	288	484	535	329	262	5580
c $У_{подз.}$	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	72.0
d пр	290	243	34I	II30	I400	357	330	38I	604	6I5	383	308	6390
	I.0	I.0	4.0	9.0	27.I	7I.0	95.0	I03	59.0	22.0	I4.9	9.8	4I7
e $У_{ст.}$	3I9	27I	337	352	I300	926	425	368	285	453	508	398	6000
f ст.	320	272	39I	36I	I330	997	520	47I	344	475	523	408	6420
	-30	-30	-50	770	70	-640	-I90	-90	+260	I40	-I40	-I00	-30

a - precipitation; b - surface inflow into the lake; c - subsurface inflow; d - total input; e - outflow from the lake; f - outflow plus evaporation. Between d & e evaporation figures are given. Last line is net water loss or retention.

Table 2 (cont'd)   Т а б л и ц а 2 (продолжение)

	Составляющие components	I	П	Ш	IУ	У	УI 1967 г.	УП	УШ	IX	X	XI	XП	Годовая yearly
a	X	4I.I	39.7	83.7	49.7	48.7	62.9	57.7	68.0	I6.4	I48	64.8	72.9	753
b	$У_{пов.}$	226	228	372	I286	470	272	2I0	238	240	433	3I3	252	4540
c	$У_{подз.}$	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	72.0
d	пр.	278	274	462	I342	525	34I	274	3I2	262	587	384	33I	5360
		I.0	2.0	I0.0	26.5	56.6	90.5	II4	67.5	70.0	33.2	29.6	3.0	504
e	$У_{ст.}$	322	282	232	936	878	55I	330	275	262	I43	344	438	4990
f	ст	323	284	242	962	935	64I	444	343	332	I76	374	44I	5490
		-50	-I0	220	380	-4I0	-300	-I70	-30	-70	4I0	I0	-II0	-I30
					Four-year averages	Средние за 4 года								
a	X	54.6	38.0	57.7	39.8	33.5	39.8	6I.6	72.2	82.6	85.9	53.2	7I.4	690
b	$У_{пов.}$	242	227	304	I346	758	305	237	269	350	432	3I0	280	5060
c	$У_{подз.}$	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	72.0
d	пр.	303	27I	368	I392	798	35I	304	347	439	524	369	357	5820
		I.9	I.4	5.I	I0.2	47.9	82.0	I0I	80.5	59.4	36.7	I8.4	4.2	449
e	$У_{ст.}$	366	322	338	682	I042	666	336	289	344	360	399	398	5540
f	ст.	368	323	343	692	I090	748	437	369	403	397	4I7	402	5990
		-65	-52	25	700	-295	-398	-I32	- 22	35	I28	-48	-45	-I70

observed in summer; in winter it is higher--around 0.7 m^3/sec. Spring spate produces quite a sharp rise. Its maximum fluctuates between 3.1 - 6.5 m^3/sec. (average for 4 years - 4.66 m^3/sec.; M - 57 1/sec. km^2). In spite of the small size of the catchment basin, which means that the water takes a short time to run in, the abatement of the spate takes a month after the snow melting is over. This is explained by the fact that the subsurface drainage (mainly soil and sub-soil drainage) is considerably greater than the surface run-off in supplying the Strannitsa river. Rain floods which occur in summer but do not reach great extent are superimposed on the curve of the abatement of the spate. The autumn months are usually 121
a time of extensive flooding. Subsurface drainage also plays a decisive role in floods, but the surface run-off from the field part of the catchment area is an important factor, particularly after heavy downpours. The average yearly run-off from the Strannitsa river basin is 372 mm (in mm of layer on the surface of the basin), which corresponds to a run-off factor of 0.54.

In the years 1966--1967, occasional observations of the remaining tributaries were made to assess the general inflow into Lake Krasnoye. The results obtained in this way reflected differentiated monthly correlations between the discharge from the tributaries and the discharge from the Strannitsa river (Table 3).

The total water discharge from the small tributaries equals half of the discharge from the Strannitsa river, even though the catchment area of the latter approximately equals that of the remaining tributaries. The reason for this is, probably, that the Strannitsa river drains deep water-bearing levels which are fed not only from the territory of its surface catchment basin but also from the neighbouring territories.

Т а б л и ц а 3

Отношение общего притока в оз.Красное к притоку по р. Страннице

I	П	Ш	IУ	У	УI	УП	УШ	IX	X	XI	XП
I.IO	I.IO	I.25	2.75	I.70	I.55	I.I5	I.I5	I.30	I.35	I.20	I.IO

Table 3

Relation of the total inflow into Lake Krasnoye to the inflow from the Strannitsa river.

This is indicated by the small fluctuation range of discharge: the average maximum exceeds the minimum by less than 10 times. According to the data obtained from preliminary investigation, intensive stratal discharges of ground water containing an abundance of characteristic vegetation occur at the foot of the slopes of the deep canyon-like Strannitsa river valley which cuts several tens of meters into the central plateau of the Karelian Isthmus. Stream No. 23, with its absence of deep subterranean supply, sharply differs from the Strannitsa river. At the beginning of spring the discharge from this stream is even bigger than the discharge from the Strannitsa river, but in summer the stream almost completely dries up.

The relation of the total inflow into Lake Krasnoye to the inflow
from the Strannitsa river varies from month to month (Table 3). Because 122
of the uneven distribution of discharge within a year, the relation of the total inflow into the lake to the inflow from the Strannitsa river is different in different years, thus: in 1964 = 1.52, in 1965 = 1.54, in 1966 = 1.49 and in 1967 = 1.42. For the 4 years the average quantity of inflow into Lake Krasnoye is 5060 mm (in a water layer in the lake), or, correspondingly, 275 mm in the water layer on the surface of the catchment basin; the run-off factor is 0.40.

E.L. Greiser and V.A. Zhuravlev (1967) have calculated the subterranean inflow into Lake Krasnoye using the method of electrohydrodynamic analogy. It must be noted that subterranean influx into the tributaries of the lake plays a decisive role. But the amount flowing directly into the lake is small, amounting to 70 mm a year. Since there are no data on the dynamics of subterranean inflow, it is assumed to be 2 mm per ten-day period.

Thus the incoming part of the water balance, comprising precipitation, surface and subterranean inflow, is 5820 mm.

We shall now calculate the elements of the outgoing part of the water balance--evaporation and run-off from the lake. Evaporation was calculated according to the formula of A.P. Braslavsky and Z.A. Vikulina:

$$E = 0.13(e_0 - e_{200})(1 + KW) \text{ мм/сутки},$$

where $\bar{\bar{e}}_o$ = absolute humidity (in mb) calculated from the water temperature in the central part of the lake. This temperature was determined from the graph correlating the data obtained from the survey at the 'Bui' station and from the region of the water gauging post (L.G. Kuzmenko, in this book). The water temperature at both these posts is practically the same; $\bar{\bar{e}}_{200}$ = absolute humidity (in mb) is calculated from the data provided by the meteorological post on the lake ("lower"); W = wind velocity at a height of 10 m at the upper post; k = factor taking into account the effect of wind velocity on evaporation. k is defined as the product of two factors, k_1 and k_2, with k_1 = 0.72 calculated for the wind at a height of 2 m above the open surface of the lake, and k_2 = 1.39 is a transitional factor for calculating wind velocity over the lake at a height of 2 m, in accordance 123
with the data for wind velocity at the upper station at a height of 10 m;

$(k = k_1; k_2 = 0.72 \cdot 1.39 = 1)$.

Quantities of evaporation for 10-day periods were calculated for the time of unfrozen water. Evaporation from the snow surface during the freeze-up was determined from the graph by B.V. Poljakov and was accepted as constant for a month. The average quantity of evaporation for the 4 years is 450 mm.

It was quite difficult to determine the run-off from the lake. Until September 1964 the Krasnaya river was dammed and the speed of its flow was smaller than the initial rotation speed of a current meter. The speed of flow was also very low later at the time of low-water level and also at the time of the highest water level of the lake, when the back-water effect from Lake Pravdinskoye was felt. Therefore the run-off from the lake in the years 1964 - 1965 was considered as the remaining term of the equation of the water balance. In the years 1966--1967 when the remains of the dismantled bridge at the mouth of the Krasnaya river ceased to affect its water level there came an opportunity to measure directly the water discharge. The curve showing the dependence of discharge on the levels was drawn in accordance with the data for 1967. (Fig. 3). The run-off calculated with the help of this curve differs by 10% from the run-off calculated by the equation of the water balance. The discrepancy between these two quantities for 1966 was even more significant. Because of the already mentioned difficulties in measuring the run-off from the lake the discrepancy in the water balance was attributed to the run-off itself.

The total quantities of the balance for the 4 years (Table 4) were
rounded off to the nearest 10 mm (the level was measured correct to 1 cm). 124
The difference between the levels at the beginning and the end of the

Таблица 4

Баланс оз.Красного за 4 года

Приходная часть 1	мм (mm)	%	Расходная часть 2	мм (mm)	%
Осадки 3	690	II.9	Испарение 7	450	7.7
Приток поверхностный 4	5060	86.9	Сток 8	5410	92.3
Приток подземный 5	70	I.2	Приращение уровня 9	-40	-
Итого: 6	5820	I00	Итого: 10	5820	I00

Table 4

Balance of Lake Krasnoye for the 4 years

1 - Incoming part; 2 - Outgoing part; 3 - Precipitation; 4 - Surface inflow; 5 - Subterranean inflow; 6 - Total; 7 - Evaporation; 8 - Outflow; 9 - Increase in the level; 10 - Total.

period, for which the balance has been calculated, is 68 cm. This difference is due to hydrometeorological factors as well as to changing conditions of the run-off from the lake, which resulted in the fall of the water level by 50 cm in 1964. This quantity we have excluded from the final variant of the balance: for 1964 the run-off from the lake decreased by 500 mm. The remaining part of the difference in the levels (18 cm) can be explained by the fact that in 1967 precipitation was below the long-term norm. The balance of the lake in the long term could have been determined without an increase in the level. But since the observations lasted only 4 years, the increase in the level was 45 mm on average each year (40 mm rounded off), or 0.7% of the incoming part of the balance.

The calculations show that the surface inflow (86.9%) plays the basic role in the incoming part of the balance; precipitation (11.9%) plays a smaller role; the subterranean inflow is 1.2%. These quantities are caused by the fact that the lake has quite a large catchment basin, whose area is 18.4 times bigger than that of the lake itself. Accordingly, the

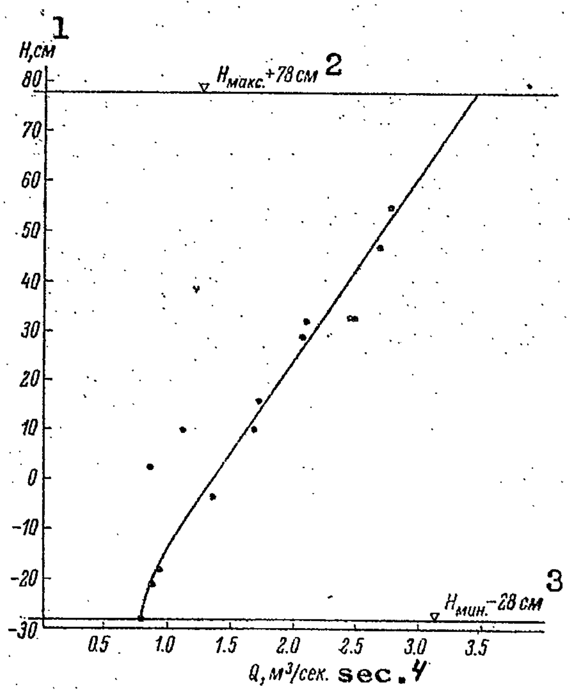

Рис. 3. Fig. 3

Кривая зависимости расходов от уровней р.Красной за 1967 г.

Fig. 3

Water-level — water-discharge curve for the Krasnaya river for 1967.

1 - H, cm; 2 - $\nabla H_{maximum}$ + 78 cm; 3 - $\nabla H_{minimum}$ - 28 cm; 4 - Q, m^3/sec.

run-off from the lake plays the essential role in the outgoing part of the balance, being 92.3%; evaporation is only 7.7%. The water volume of Lake Krasnoye is totally renewed every 1.14 years, or, approximately, every 14 months.

A four-year period of observations is too short to evaluate the changeability of the elements of the water balance. The considerable part played in supplying the lake by the deep subterranean inflow helps smooth 127
the fluctuations of the inflow due to heavy precipitation. The run-off from the lake fluctuates even more smoothly. In the course of a year the

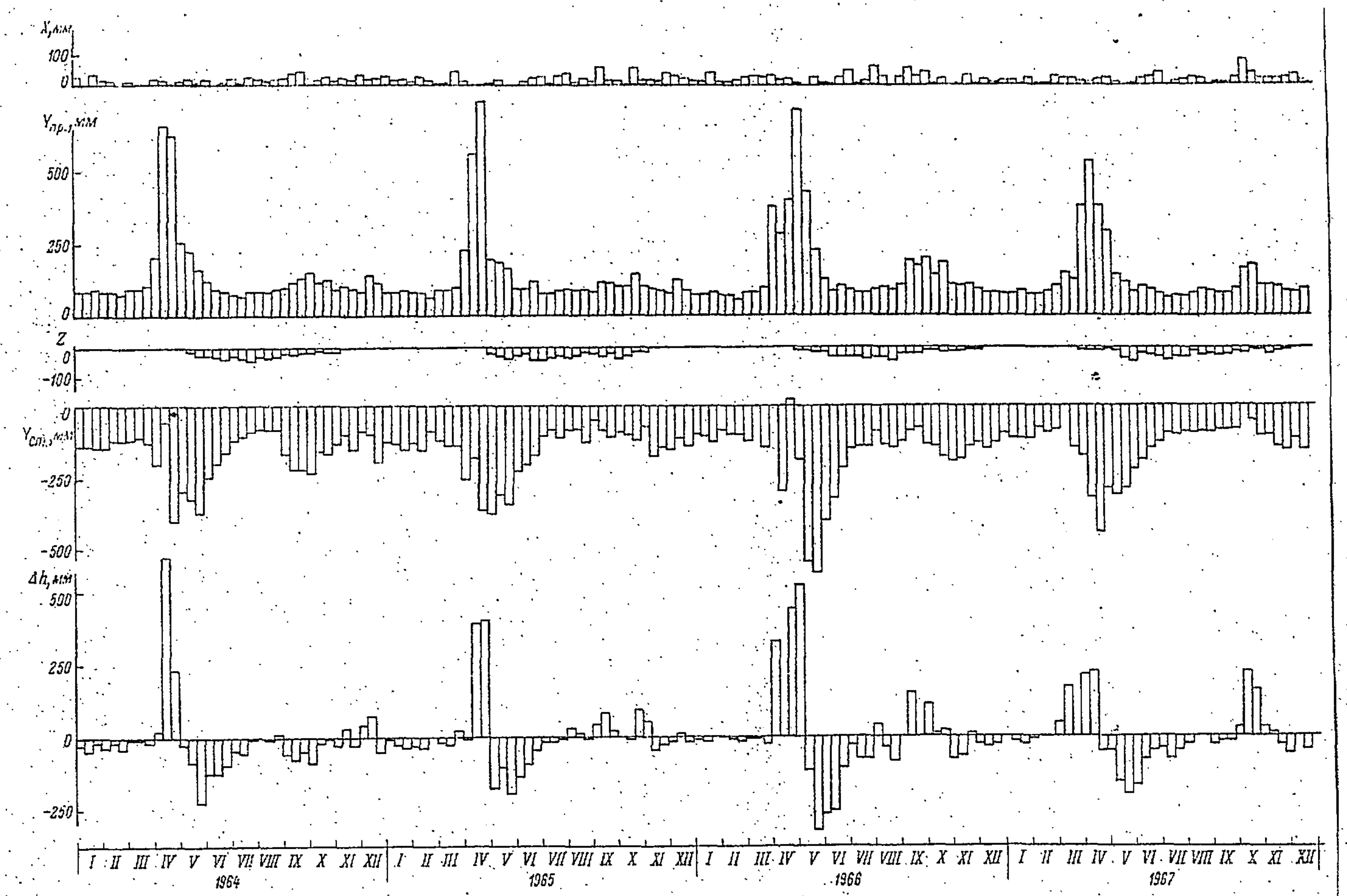

Рис. 4.

Ход составляющих водного баланса оз. Красного за 1964–1967 гг.

Fig. 4

The pattern of the components of the water balance of Lake Krasnoye for 1964 – 1967.

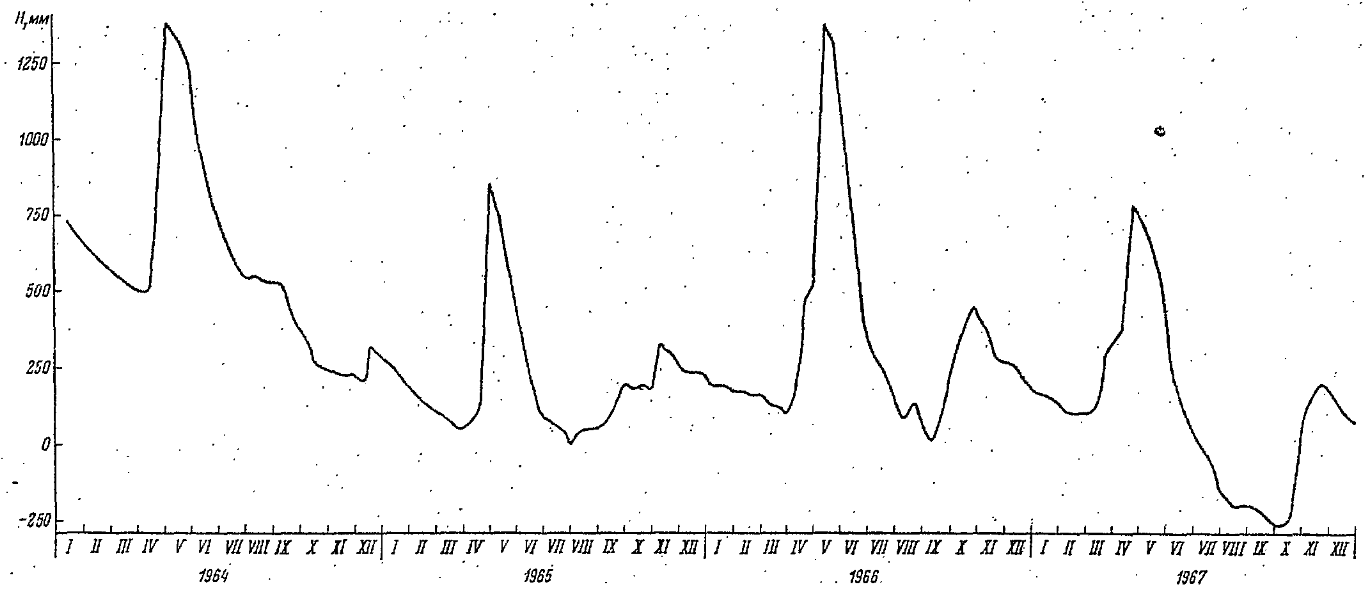

Рис. 4 (продолжение).

Fig. 4 (continuation).

elements of the water balance also undergo smooth changes (Fig. 4). Maximal monthly inflow observed in April surpasses the minimal inflow in July by no more than 6 times. Fluctuations of the elements of the water balance, particularly inflow and run-off, cause the changes in the level of the lake. The high level throughout most of 1964 was caused by the backwater effect, but in other years the course of the run-off can be considered as having been natural. The average maximal level for the 3 years (1965 - 1967), which was observed in the first days of May (100 cm) exceeds the minimal (July - August) by 109 cm. The absolute maximum of the level was observed on 10 - 12 May, 1966; it was 138 cm and was caused by a high flood of that year. The absolute minimum of the level (-28 cm) occurred from September 30 to October 5, 1967; it was caused by the small amount of precipitation which fell during the preceding month (16.4 mm). The average level of the lake with its natural regime is 21 cm for the 3 years (1965 - 1967).

The data for the 4 years are, obviously, insufficient to characterize the long-term water balance. However, it is worth noting that during the last three years precipitation did not essentially differ from the norm. The average precipitation for the 4 years (690 mm) is practically equal to the average precipitation calculated at the Sosnovo weather station in the years 1951 - 1967 (691 mm). This suggests that the balance which we have calculated does not differ substantially from the long-term balance.

This research provided us with a notion of the water balance of Lake Krasnoye.

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