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Regularities in the Space and Time Flow Variations in the Near-Mouth Reach and Delta of the Lena R.

D. V. Magritsky[a, *], **D. N. Aibulatov**[a], **and A. V. Gorelkin**[b]
[a]*Moscow State University, Moscow, 119991 Russia*
[b]*OOO InzhGeo, Moscow, 101000 Russia*
**e-mail: magdima@yandex.ru*

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Abstract—Lena flow showed considerable, mostly climate-induced, changes in the recent 30–40 years. The character of these changes at the river watershed–sea border somewhat differs from that in the basin outlet station because of flow transformations in the near-mouth reach and, especially, in the delta. The new stationary and occasional expedition observations were used to improve the estimates of the major characteristics of the discharges of water, suspended sediment, and heat in the Lena outlet section and to identify the features and causes of their long-term and seasonal variations. Another important result is the estimation of flow characteristic in the reach downstream of the basin outlet station, at delta head, and on its coastline. New data are given on the present-day distribution of water and suspended sediment discharges between the major delta branches, their long-term variations, and the character of inundation of the near-head delta area during spring floods.

Keywords: river, delta, flow, variations

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INTRODUCTION

The Lena R. and its unique delta play a specific role in the natural complex and economic activity in the Central and Northeastern Siberia. Lena flow is the main component of the regional hydrological cycle and an important factor that has an effect on the natural conditions on the arctic coast; mouth and marine hydrological processes; local, and, maybe, regional climate. The river and its tributaries are the major water transport lines in the Republic of Sakha (Yakutia), important sources of hydroelectric power, and the habitat of many aquatic organisms, including fishes. In the recent 30–40 years, river flow and hydrological regime changed significantly [2, 7, 8, 19, 24]. Integrated studies of the present-day space and time variations of the major flow characteristics in the Lower Lena, its regularities, and causes were not studied in recent years. There are also no reliable estimates of river flow characteristics downstream of the basin outlet gauge. Flow transformation is a key factor to be taken into account for correct estimation of river water inflow into the Laptev Sea, as well as the export of river sediments, dissolved substances, and heat into this sea. Such estimates are of importance for correct interpretation of hydrological processes in the delta and nearshore mouth areas. The Lena Delta, the largest in area in Russia (~30 thous. km^2 [33]), has complex morphology and a unique number of water bodies and streams (~6 thousands of streams with a total length of 14.6 thousand km and area of 7.3 thousand km^2, 29.5–59 thousands of lakes with an area of 3.2–6.2 thousand km^2 [13, 33]). The delta is of great ecological value and transport significance (the “sea-gate” of Yakutia). The results of long-term studies given in this article answer many questions, unresolved so far, and enable formulating important new research lines.

AVAILABLE KNOWLEDGE. MATERIALS AND METHODS

The earliest hydrological observations at Lena near-mouth reach and delta were carried out in 1919–1921. By the near-mouth reach we mean the terminal segment of Lena lower reach between the basin outlet gauge section (OS) and delta head (DH); in some publications, it is referred to as near-delta reach, which is incorrect in accordance with the commonly accepted (according to V.N. Mikhailov) zoning of river mouth areas and, in particular, Lena mouth area [20]. In 1934, observations were started at the furthest downstream gage and at Lena OS. In the early 1950s, Ust’-Lenskaya Hydrological Expedition of the Arctic and Antarctic Research Institute (AARI), established permanent and temporal gages within the delta and collected a large hydrological data array. Stationary polar station Stolb (Fig. 1), established in 1950, has been monitoring water level H, discharge Q, and temperature T, and ice phenomena at the source of Bykovskaya Branch and water discharges in the main channel; since 1968, turbidity s and suspended sediment discharge R have been also measured. Note, that, first, the Main Channel in the Lena Delta is taken to be the river reach between DH and Stolb Isl. and, second, transit branches in the Lena Delta are referred to as *protokas* (a local term accepted in many Siberian deltas). In 1948, Tit-Ary level gage was established at a settlement with the same name (near DH); in 1953, Malysheva Isl. polar station was established on Ispolitova Branch; in 1961, Sagyllakh-Ary polar station was established at the mouth of Trofimovskaya Branch. The results of expedition studies and network observations underlay first important generalizations of hydrological observation data on Lena lower reaches and delta, given in [3, 4, 11, 12, 21, 25].

The new stage of studies of delta hydrological regime and field hydrometric observations started in the mid-1970s. Since 1973, Tiksi TsHMS has been carrying out episodic measurements of Q and R at the sources of Trofimovskaya, Tumanovskaya, and Olenekskaya branches; these measurements became systematic since 1977; in the early 1980s, several episodic measurements were carried out in some other branches. Ust'evaya Field Party of the Integrated Erosion–Channel Expedition, Geographic Faculty, Moscow State University, was working in the delta in 1979–1981. The results of stationary and expedition measurements of water and suspended sediment discharge in the near-mouth reach and delta branches are given in [8, 10, 13, 14, 17, 20].

Almost all level gages in the delta have been closed by 1991. After 2007, systematic measurements of Q and R in the near-head delta part were ceased; in OS, full-scale measurements of Q and R were ceased after 2003. At the same time, many measurements of Q and R, as well as other hydrological and morphological characteristics of delta watercourses were carried out in the delta under Russian–German Project "Natural System of the Laptev Sea" in 2001–2006 [5, 6, 26]. New estimates of the flow characteristics of water, sediments, and heat in the Lena R. and some results of the examination of their time variations are given in [2, 15, 16, 24]. In addition to the important results of previous studies and monitoring data at the gages mentioned above, an information base for the study included, first, long-term observation series (1926–2013) at some other gages in the lower reaches of the main river and its tributaries; second, measurement data on air temperature and precipitation depth at weather stations [30]; third, data on the amounts of economic use of river water and groundwater for each year from 2001 to 2013 [9]; and additional special data from official sites of the major participants of water utilization system in the Lena basin.

The main methods for processing and analysis of source data were standard hydrological and balance calculations, statistical analysis methods, including tests of major statistical hypotheses for the series (at 5% significance level): homogeneity and stationarity hypotheses checked with the use of Dixon, Fisher (F-test), Student (t-test), and Mann-Whitney (U-test) tests, applied to time-correlated and asymmetric series of hydrological characteristics; independence hypotheses, checked with the use of Andersen test and the test of the number of series; trend hypothesis, checked with the use of Spearmen test (Spearmen RCC – r_s), etc. In the course of the study, various empirical relationships and chronological plots were constructed, and their closeness and reliability were evaluated. Part of statistical analysis was carried out using Gidroraschety software (NPO Gidrotekhnologii), Excel (Microsoft), and Statistica (StatSoft). The heat flux W_T was evaluated as

$$W_T = c_p \rho T W, \tag{1}$$

where c_p is water specific heat, kJ/(kg °C); ρ is water density, kg/m^3; T is ten-day mean water temperature, °C; W is ten-day water runoff volume, m^3. In addition, comparative analysis of many-year variations of hydrological and meteorological characteristics was carried out, the curves of along-channel transformations of various hydrological characteristics were plotted, etc.

FLOW CHARACTERISTICS IN THE BASIN OUTLET RIVER SECTION

The basin outlet section is the gage at Kyusyur ($F =$ 2430 thousand km^2), situated before the river enters the Lenskaya truba, 145 km upstream DH and 315 km from the sea (from the mouth of the Bykovskaya Branch), and at the distance of 2220 km from the Vilyuiskaya HPP–1, 2. In 1927–2013, the mean annual value of Q at Kyusyur was 17200 m^3/s, and the annual runoff volume W_a = 543 km^3/year (Table 1) (data of 1927–1934, recalculated using Tabaga gage data). Because of lateral inflow and positive water balance in the huge delta, the value of W_a increases toward the sea by about 10 km^3. The comparison of this value with the maximal water-management load ΔW_man, including the total water withdrawal and runoff losses due to evaporation, suggests no appreciable effect of economic activity from reservoirs either on the annual Lena inflow into the sea or on its long-term variations [9, 24, 32]. In 2001–2013, $\Delta W_\text{man} \approx 1.25$ km^3/year (or 0.23%), W_a = 553 km^3/year (or 0.28%), $W_{\text{a},95\%}$ = 447 km^3/year. Actually, this effect is even less (~0.35 km^3/year), if we take into account only consumptive water use and additional evaporation from the surface of all reservoirs in the Lena Basin. It increases only in some years with year-to-year runoff

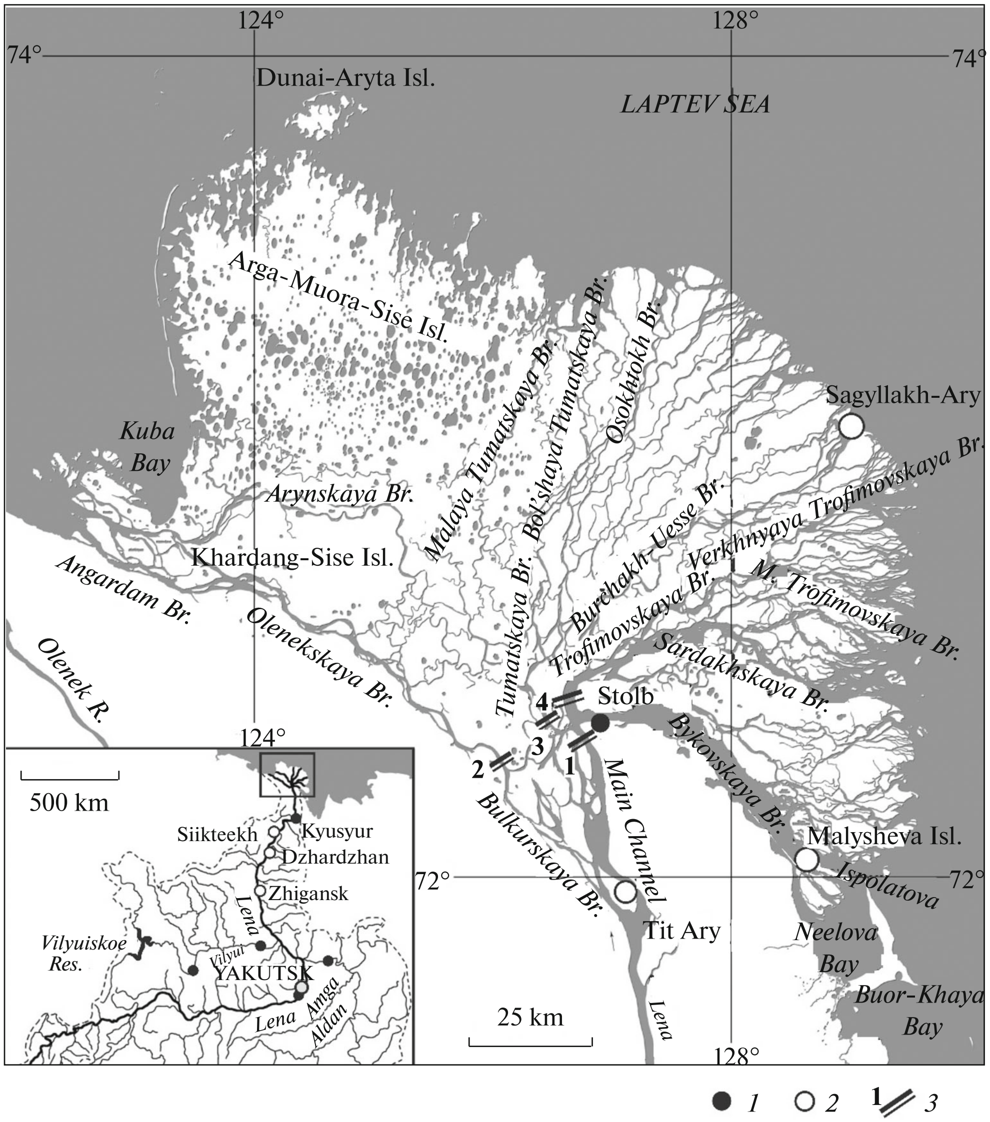

Fig. 1. Schematic map of Lena basin and delta with layout of major (*1*) discharge and (*2*) level gages, and (*3*) permanent delta hydrometric sections. Sections: (1) 4.7 km upstream Stolb Isl., (2) Olenekskii, (3) Tumatskii, (4) Trofimovskii.

variations and the withdrawal of a large volume of river water for the initial filling of two Vilyui reservoirs.

The year-to-year variations W_a are relatively small, and the autocorrelation coefficient (0.36) is statistically significant, as is common for very large rivers. The long-term variations of W_a in the Lena, first, show alteration of periods with different water abundance and duration (Fig. 2). High-water periods are 1927–1938 (the average module coefficient over the period is $K_{av} = 1.04$) and 2004–2013 ($K_{av} = 1.13$), and a low-water period is 1939–1957 ($K_{av} = 0.91$), the period 1958–2003 show medium water abundance ($K_{av} = 0.99$). Second, long-term variations of W_a show a statistically significant ascending trend ($r_s = 0.37$). In 1980–2014, W_a was 563 km^3/year, exceeding W_a in 1935–1979 by 42 km^3/year. The beginning of the second period corresponds to the start of climate warming in the basin [19]. In this increase, 45% are due to the greater water volume of the spring flood (May–July), 12 and 43% are due to the summer–autumn and winter seasons. Third, the value of W_a shows a complex response to climate warming. The relationship between W_a and the mean annual air temperature (by data of 11 major weather stations), averaged over 5-year periods, contains positive trend and harmonic components.

Seasonal variations of water flow at OS correspond to East Siberian type of water regime. The spring flood, which is taking place, on the average, from May 18 to July 31, accounts for ~60% of the annual runoff volume (3.9 in May, 36.2 in June, and 19.4% in July).

Table 1. Major streamflow characteristics of the Lower Lena (Kyusyur gage)

Characteristic	Period	Streamflow			$C_v(C_s/C_v)$
		mean*	maximal date	minimal date	
Mean annual water discharge, m^3/s	1927–2013	17200 (2.0)	23100 1989	12700 1986	0.13 (4.0)
Maximal water discharge, m^3/s	1935–2012	135000 (3.0)	220000 June 4, 1989	78000 June 6, 1935	0.18** (5.5)
Minimal winter water discharge, m^3/s	1935–1979 1980–2012	992 (7.5) 1950 (5.3)	2920 April 30, 2007	366 April 27, 1940	0.22 (–2.5) 0.23 (0)
Minimal summer–autumn water discharge, m^3/s	1935–2011	17500 (4.5)	26800 August 22, 1983	9800 September 20, 1964	0.25 (2.5)
Mean annual suspended sediment discharge, kg/s	1936, 1944, 1960–2010	712*** (9.4)	1700 2005	240 1984	0.43 (3.5)
Heat flow, 10^{12} kJ/year	1935–2012	15590 (2.2) 16590****	22320 1938	10620 1986	0.19

* The number in parentheses is the relative root-mean-square error, %, of the mean annual value.

** For the set of exceedance probability values <50%, the best result was obtained with the use of Kritskii–Menkel distribution at $C_V = 0.22$ and $C_s/C_V = 3.5$.

*** With reconstructed values over 7 years.

**** The number below the line is the value corrected for water temperature underestimation because of the effect of Ebitiem R. cold water.

Flood peak shows annual maximums of Q with an average date of June 7. The summer–autumn hydrological season with rainfall floods accounts for 32.8% of the annual runoff volume (throughout the observation period): 13.4 (August), 12.2 (September), and 7.2% (October); the stable winter low-water season (starting from the late October), accounts for 7.7% and shows minimal annual Q.

Large-scale climate changes in the basin along with the operation (since 1974) of the single large Vilyui Reservoir, which added ~700 m^3/s to winter runoff, appreciably improved the hydrological conditions of winter low-water season over a long reach in the Lower Lena [17, 19, 31] and in the delta. The runoff volumes in OS in November–April increased from 34.1 (in 1935–1979) to 51.5 km^3/year (in 1980–2012), i.e., by 51%, while minimal Q increased from 992 to 2000 m^3/s (Fig. 2; Table 1). The first considerable increase in runoff began in 1978–1979, and the second, in 2004. The contributions of natural and anthropogenic factors in this process were almost equal. This disturbed the stationarity of runoff characteristics of winter low-water season and increased the share of winter months by ~2.7%. The dates of the start of winter low-water season showed almost no changes. The analysis of the series of other characteristic Q (mean annual, maximal annual, minimal over summer–autumn season, mean monthly from June to October) showed them to keep stationary. The minimal values of Q for summer–autumn increased from 17000 to 18200 m^3/s, and the maximal Q of the spring flood, conversely, decreased from 136 to 133 thousand m^3/s, while the volume of spring flood runoff increased from 315 to 330 km^3/year, i.e., the flood wave became flatter.

Suspended sediment load in the Lower Lena is small, because the erosion processes in the basin and the input of erosion products into the river network are limited by the considerable duration of the period with air temperature below zero, the location of the basin in the permafrost zone, a considerable portion of lowland and forested areas, the passage of spring flood in the period when soils have not fully thawed, etc. [16, 22]. The mean annual suspended sediment turbidity s in OS is ~40 g/m^3. Within a year, it varies from maximal values during spring flood (on the average, 35–90 g/m^3) and the period of summer–autumn floods (35–65 g/m^3) to minimal values in winter low-water season (1.5–4.5 g/m^3). In periods between floods, it decreases to 20–30 g/m^3. The small s is compensated for by the huge water flow; therefore, the suspended sediment runoff W_R in the Lena is relatively large and equals 22.5 million t/year (Table 1). The suspended sediment runoff in DH is about the same as in OS, because the lateral inflow of ~0.32 million t/year is compensated for by sediment accumulation (because of decreasing water surface slope and flow velocity) at

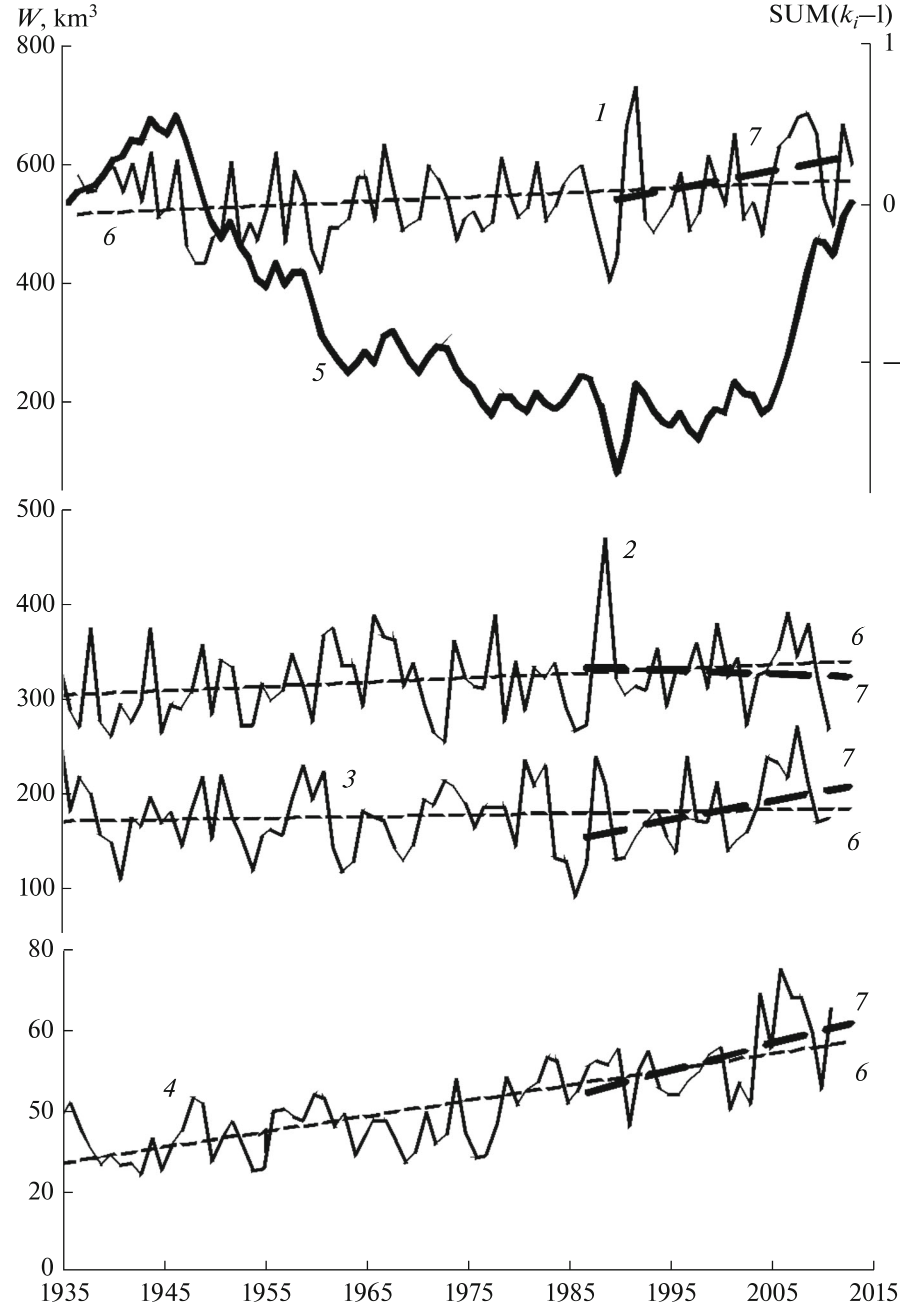

Fig. 2. Long-term runoff variations in the Lower Lena (Kyusyur gage). (*1*) Annual runoff, (*2*) runoff volume over spring flood period, (*3*) runoff over summer–autumn low-water-season–flood period, (*4*) runoff over winter low-water season, (*5*) differential–cumulative curve of annual runoff, (*6*) linear trend over period 1935–2013, (*7*) linear trend over period 1988–2013.

the exit of the river from Lenskaya truba. Bed-load sediments are also transported into the delta (~17.0 million t/year) [8]. Suspended sediment runoff into the boundary delta branches from the local watershed can reach 125 thousand t/year.

Long-term variations of W_R show some correlation with water flow variations and two long-term tendencies: a decrease in W_R before1986–1987 and its subsequent increase (Fig. 3), which coincides with an increase in river water abundance. Only U-test shows the W_R series to be not stationary, while other tests do not. The low correlation between variations of the annual values of water and sediment runoff ($r \approx 0.5$) is attributed to the dependence of W_R not only on the water runoff in a year, but also on the within-year distribution of water flow, the number and magnitude of rain floods, and the effect of other factors [17]. In the case of mean monthly values, the correlation between

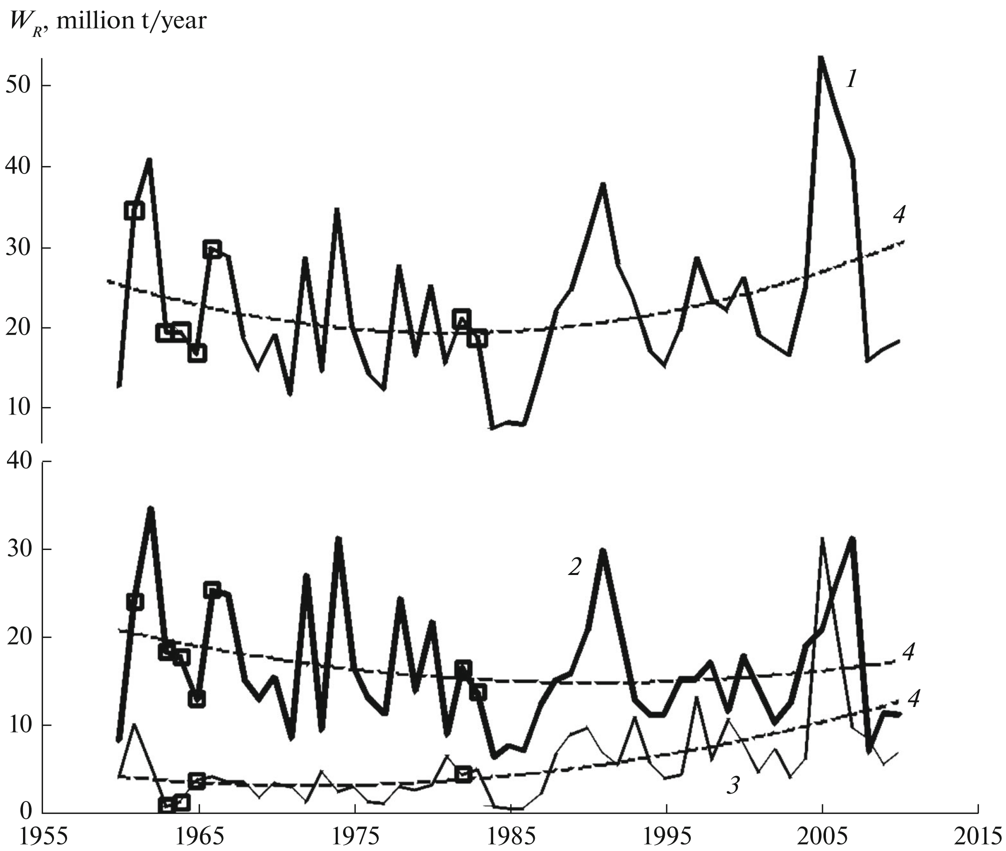

Fig. 3. Long-term variations of suspended sediment runoff in the Lower Lena (Kyusyur gage). (*1*) Annual sediment runoff, (*2*) sediment runoff over spring flood period, (*3*) sediment runoff over runoff over summer–autumn low-water-season–flood period, (*4*) polynomial trends. Squares show years for which data were reconstructed.

Q and R is greater, though the relationship itself is nonlinear and different for periods before and after 1988. The increase in the annual sediment runoff is mostly due to the summer–autumn season. The result is that the share of runoff in this season increased from 16.8 to 34.9% (since 1988, inclusive); the homogeneity of the series of summer–autumn R was disturbed in terms of both variance and mean. Anthropogenic contribution to these changes was not identified.

The heat runoff of the Lena R. at OS is very high (Table 1), notwithstanding the relatively low values of water temperature (all over the observation period: $T_{\text{June}} \sim 5.1°\text{C}$, $T_{\text{July}} \sim 14.2°\text{C}$, $T_{\text{Aug}} \sim 12.6°\text{C}$, $T_{\text{Sep}} \sim 6.1°\text{C}$) and the short period of the year with $T \geq 0.2°\text{C}$ (on the average, from June 4 to October 13). This phenomenon is facilitated by the huge river water runoff and the higher water abundance in this season with high T. The leading role of water flow can also be seen from the close correlation between it and W_T ($r \approx 0.73$). Even closer correlation was obtained with the inclusion of water temperature in the equation ($R \approx 0.85$):

$$W_T\left(\text{kJ} \times 10^{15}\right) = 0.028W_{\text{a}} + 1.416\overline{T}_{\text{VI–IX}} - 12.9, \quad (2)$$

where $\overline{T}_{\text{VI–IX}}$ is average water temperature over period from June to September. However, the value of W_T (Table 1) may be an underestimate because of the poor representativeness of data on T. This issue is discussed in detail below.

The amount of heat transported by the river is maximal in summer: 23.7 (June), 39.7 (July), and 24.9% (August); September and October account for 10.9 and 0.8; and May, for 0.1%. At the many-year scale, the heat transport in the Lena increases under the effect of increasing water abundance and T (Fig. 4). Before 1980, the mean annual W_T was 15.26×10^{15}; and in 1980–2012, it was 16.04×10^{15} kJ. W_T increased mostly due to summer months ($\Delta W_T \approx 0.76 \times 10^{15}$ kJ). At the same time, the duration of the period with $T \geq 0.2°\text{C}$ increased by 8 days. The changes in the thermal state in the Lena near-mouth reach can also be due to the operation of Vilyui reservoirs [15].

WATER RUNOFF DISTRIBUTION IN THE DELTA

The spatial distribution of Lena flow begins in DH, near the head of Tit-Ary Isl. The flow here is distrib-

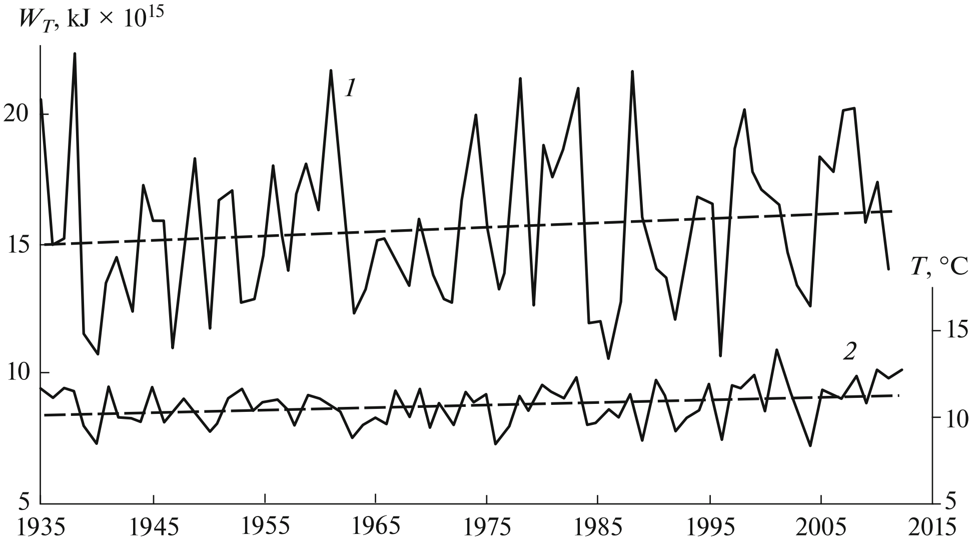

Fig. 4. Long-term variations of the (*1*) annual heat runoff and (*2*) summer-season-averaged water temperature in the Lower Lena (Kyusyur gage) with linear trends.

uted between the continuation of the river, i.e., its Main Channel, and the small Bulkurskaya Branch, separating from it to the left (Fig. 1). The character of this distribution can be assessed based on long-term observation data at a gage 4.7-km upstream of Stolb Isl., as well as several measurements of Q at the mouth of the Bulkurskaya Branch in the summer and autumn of 2004–2006, given in [5]. Data processing showed that at water discharges at OS $Q_K <$ 45 thous. m^3/s, the Bulkurskaya Branch receives less than 1% of river runoff at DH (Table 2), while at $Q_K <$ 20–25 thous. m^3/s, it receives no water at all. As water abundance in the Lena increases, the share of water flow in the Bulkurskaya Branch abruptly increases (up to 6% and more). These estimates are close to data in [14]; however, they reflect the changes in the channel flow (without the floodplain component). The water regime of the Bulkurskaya Branch shows not only the effect of river water abundance, but the position of level surface in the Olenekskaya Branch, and ice phenomena. Over a long time, the share of Main Channel flow was found to increase with a rate of ~0.9%/10 years, suggesting its increasing activity and the decay of lateral watercourses in this part of the delta. This trend became even more pronounced after the passage of an extremely high water discharge in 1989 ($Q_{\max}$ = 220 thousand m^3/s).

The comparison of total water discharges through the Bulkurskaya Branch and the Main Channel Q_{DH} with water discharges at Kyusyur gage Q_K shows these discharges to be different in most cases (Table 2). Note that, as water abundance in the river increases, the negative $\Delta Q = Q_{DH} - Q_K$ give place to positive values. This disagreement has several causes: insufficient number and accuracy of measurements, especially, at very large Q; the effect of ice phenomena; the regulating role of floodplain, etc. [13, 17]. In fact, ΔQ is greater when the redistribution of part of the flow in favor of the floodplain part that is inundated in spring is taken into account.

Three levels of floodplain—the old, mature, and young—are identified in the Lena delta along with various channel forms that expose during low-water season [5, 28]. The height of these floodplains above the mean low-water-season water level in the branches averages 10 (up to 12 m), 3–5, and less than 3 m, respectively. At an annual water level rise at Tit-Ary gage during spring flood by more than 10–11 m, the low and medium floodplains are always inundated, while land areas with higher elevations are inundated only in 80% of years. The result is that, during spring flood and at maximal Q, part of river water passes between the Bulkurskaya Branch and the Main Channel (Fig. 5). The right-bank floodplain is inundated only over several hundred meters. Floodplain flow is almost not subject to stationary measurements, though it can be approximately evaluated by the discrepancy. In addition, upsets of channel water balance can be due to melting snow and ice, which accumulates in large amounts on the delta floodplain. That is why, strictly speaking, the value of Q entering the delta cannot be evaluated either by water discharge in the Main Channel, or by the total discharve in the branches.

At Stolb Isl., the flow of the Main Channel is distributed between the branches of Bykovskaya, Trofimovskaya, Tumatskaya, and Olenekskaya (Fig. 1). Continuous measuremetns at their sources (at gages Olenekskii, Tumatskii, and Trofimovskii, as well as at polar stations Stolb Island or Khabarova in the source

Table 2. Distribution of water discharges in the upper part of the Lena Delta in ice-free period. Based on data of stationary measurements in 2001–2007 (mean daily, regular) and expedition measurements of the Arctic and Antarctic Research Institute and St. Petersburg State University in summer seasons of 2004–2006 in the Bulkurskaya Branch (the data do not cover the period of spring flood rise; here and in Table 3, dash means no data available or unreliable data; data in italic are very approximate, especially for under-ice period, because of the ambiguity of relationship)

Lena R.		Delta head			Main branching point						
Basin outlet section—Kyusyur gage		Main channel, gage 4.7 km upstream of Stolb Isl. *	Bulkurskaya Branch, mouth	discrepancy of ΣQ_i with respect to Q at Kyusyur gage	source of the Bykovskaya Branch, Stolb Isl. gage (Khabarova)		source of the Trofimovskaya Branch	source of the Tumanskaya Branch	Olenekskaya downstream of the confluence point with the Bulkurskaya Branch	discrepancy of ΣQ_i with respect to Q at gage (with rounding)	
										Kyusyur V.	4.7 km upstream of Stolb Isl.
Q, m^3/s	H, cm	Q_i, m^3/s	Q_i, m^3/s	%	Q_i, m^3/s	H, cm	Q_i, m^3/s	Q_i, m^3/s	Q_i, m^3/s	%	%
10000	360	9000	*~0*	*–10*	2000	120	6800	200	400	–6	4.5
20000	620	19000	*~0*	*–5.0*	4800	267	13000	825	1040	–1.5	3.5
30000	828	28800	*100*	*–3.5*	7500	370	18900	1670	1800	–0.5	3.5
40000	1025	38600	*320*	*–2.5*	10200	445	24200	2640	2680	–0.5	3.0
50000	1200	48500	*950*	*–1.0*	13500	518	30000	3800	3750	2.0	5.5
60000	1360	57500	*1900*	*–1.0*	16800	578	35300	4890	4880	3.0	7.5
80000	1640	76000	*5000*	*1.0*	23500	685	46500	7700	7800	7.0	12.5
100000	*1930*	*92500*	–	–	*29500*	*805*	*55500*	*10700*	*10800*	*6.5*	*15.0*
120000	*2240*	*108000*	–	–	*34300*	*900*	*63000*	*13300*	*13900*	*4.0*	*15.5*
140000	*2560*	*122500*	–	–	*39000*	*990*	*70000*	*15000*	*16200*	*0*	*14.5*
160000	*2840*	*136000*	–	–	*45000*	*1050*	*77000*	–	–	–	–

* By relationship with Kyusyur gage with a travel time of 1–3 days taken into account.

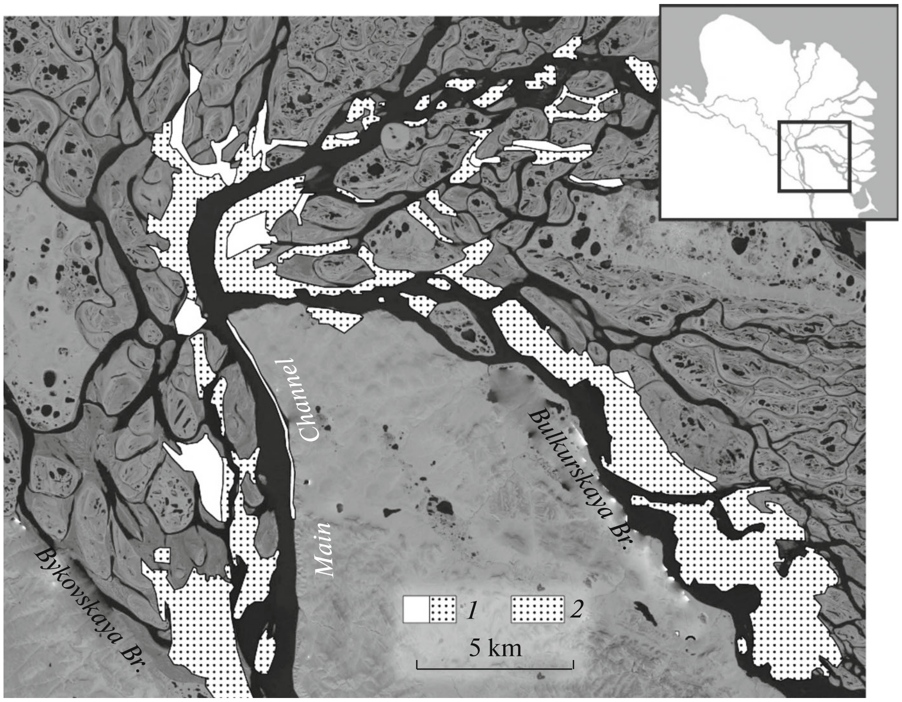

Fig. 5. Schematic map of areas in Lena Delta inundated in 2008: (*1*) during flood peak of May 30; (*2*) during its recession on June 24.

of the Bykovskaya Branch) were being carried out from 1977 to 2007. If we compare Q in each branch with their sum ΣQ_i under median water conditions of the summer–autum season, then the flow share is ~25.1 for the navigable Bykovskaya Branch (in 1977–2007), 62.3 for the Trofimovskaya Branch, 6.2 for the Tumatskaya Branch, and 6.4% for the Olenekskaya Branch (along with the flow of the Bulkurskaya Branch (Table 2). Thus, the major portion (>90%) of river water enters the northeastern part of the delta.

Within a year, because of seasonal flow variations and different response of flow resistances of the branches and their systems, this proportions change: the share of the Trofimovskaya Branch decreases from 72.3 (at Q_K = 10 thousand m^3/s) to <50% (at Q_K = 140 thousand m^3/s); while the flow in the Bykovskaya, Tumatovskaya, and Olenekskaya branches, conversely, increases from 21.3, 2.1, and 4.3 to 27.8, 10.7, and 11.6%, respectively (Table 2). On the average, the shares of flow during spring flood (May–July), in August–October, and in winter are 56.9, 64.5, and 77.5 in the Trofimovskaya Branch, 26.8, 24.7, and 19.4 in the Bykovskaya Branch, 8.1, 5.1, and 0.9 in the Tumatskaya Branch, and 8.1, 5.8, and 2.2% in the Olenekskaya Branch, respectively. The within-year variations of water flow in the largest Trofimovskaya and Bykovskaya branches is similar to that at OS, while in the Olenekskaya and, especially, Tumatskaya branches, the share of flow during spring flood is much greater (70 and 73.5% compared with 55 in the Trofimovskaya and 62.2% in the Bykovskaya branches), and the flow of the winter low-water season is small (2.6 and 1.2%) or zero.

At large Q, large ice jams, and, accordingly, high water levels, part of the flow runs over the floodplain. This flow is almost completely neglected in measurements at gages. The inundation of the left-bank floodplain of the Bykovskaya Branch begins at water levels >240 cm (2.24 m BS) at Stolb Isl. gage, while at levels above 600 cm, the Bykovskaya Branch merges with the neighboring Trofimovskaya Branch to form a common water area up to several tens kilometers in width (Fig. 5). For the floodplain of 2008 and based on the processing of Landsat-7 space photographs [31], the relationship between water levels at Stolb Isl. gage H_{St} and the inundated area in the near-head part of the delta F_{in} can be approximately described by the empirical formula $F_{\text{in}}(\text{km}^2) = 0.71H_{\text{St}}(\text{cm}) + 70$. The width of floodplain flows for the Olenekskaya and Tumatskaya branches is minimal.

If we compare the present-day runoff distribution with that in 1951–1953 [3, 13], we will find that the flow shares in the Bykovskaya and Trofimovskaya branches have increased by 0.7; that of the Tumatskaya, by 0.6; and that of the Olenekskaya, conversely decreased by 2%. However, long-term (1977–2007) data on the annual runoff of these branches show the rate of changes in runoff share of the Trofimovskaya Branch is –0.23%/10 years, and those of the Bykovskaya, Olenekskaya, and Tumatskaya are ~0, 0.07, and 0.14%/10 years, respectively. This may reflect errors in the field measurements of Q and, in general, the stability of runoff distribution in this branching node.

Downstream of the main delta branches, river water distributes among thousands of watercourses of different size. Full-fledge data on this transformation are few, and the available data are the results of occasional (in summer seasons of individual years) expedition studies. According to incomplete data [14], water flow in the Olenekskaya Branch upstream of its separation from the Angardamskaya Branch (to the left) almost does not change (~100%). Further downstream Q decreases by 53% (at $Q_{\rm DH}$ ~34 thousand m^3/s). Downstream of the Ardynskaya Branch (from the right), the runoff of the Olenekskaya Branch increases again (to 75% of its previous value), again decreases further downstream, and amounts to ~65% at its mouth. The increase in the share of the Angardamskaya Branch to 65–75% by the 2000s (at $Q_{\rm DH}$ ~30 thousand m^3/s) and the cessation of navigation in the Olenekskaya Branch suggest the gradual decay of its end reach [5, 26]. In the Tumatskaya Branch, only 6% of its flow at the entry reached its mouth: 59% of its water passed into the Arynskaya Branch, and a considerable portion, into the system of the Vasil'evskaya Branch [14]. In the early July 2006, during a flood at spring flood recession and at $Q_{\rm DH}$ ~60 thousand m^3/s, water discharges in the Bol'shaya Tumatskaya and Oskhotokh branches at a distances of 51, 91, 114, and 148 km from the source of the Tumatskaya Branch were 20, 29, 25, and ~15% of the value at the source [5]. Up to 90% of flow persisted at a distance of 25 km from the source of the Trofimovskaya Branch [14]. Further downstream, the flow was distributed between the Bol'shaya Trofimovskaya and Sardakhskaya branches in proportion of 41 to 49%. The Bol'shaya Trofimovskaya Branch yielded part of its flow to the Baarchakh Branch (22%) and into the Malaya Trofimovskaya and Davyda branches (the total of 12%). The Bykovskaya Branch yielded a part of its flow to the Kyuryuellekh and Byrdaktaakh branches (the total of 40% at $H_{\rm St}$ = 600 cm) and to Sinitsyna and Gerasimova branches, which enter into Neelov Bay (10%) [13, 14]. Only ~33% reached the mouth of the Bykovskaya Branch, where it is called Ispolatova Branch.

Unfortunately, the above estimates of the along-channel flow transformation may not reflect the present-day situation because of the transformations of deltaic watercourses, and the points of branching and confluence. An example of such instability is the distribution of runoff in the large Sardakhskii branching point. In the early 1980s, the Bol'shaya Trofimovskaya Branch, according to archive materials of the Tiksi TsGMS, received 900, 2000, 4500, and 7300 m^3/s at Q in the Trofimovskaya Branch of 2500, 5000, 10000, and 15000 m^3/s, respectively). The rest of the flow entered the Sardakhskaya Branch. According to [5], in 2001–2002, water discharges decreased to 700, 1600, 3600, and 5850 m^3/s. This was due to the active channel transformations in the Sardakhskii branching point. In addition, we have to emphasize that the expedition measurements were commonly made at a single water discharge of the river, were neither universal nor synchonized even for the elements of a small system of branches. Thus, now we have no reliable data on the distribution of Q over numerous deltaic watercourses downstream of the major branching points, even for the conditions of medium water abundance.

A partial solution of the problem of the lack of actual data (for deltas as large and multibranching as that) can be found by the incorporation of indirect calculation methods, for example, the method of indication hydrology [1, 23]. This method relates the mean characteristics of river flow with the mean width of the watercourse, as the width of the channel depends primarily on Q. The only exception is the seacoast watercourses in the zone of strong influence of periodic and aperiodic variations of sea level. Watercourse width can be readily and accurately determined by maps and space photographs. Measured discharges can be used to test the obtained relationships. Such study was carried out for Lena delta and 75 largest elements of its channel network with the participation of one of the authors [1].

TRANSFORMATION OF SEDIMENT RUNOFF IN THE DELTA

The regime and distribution of suspended sediment runoff in the near-head part of the delta can be assessed using the results of long-term observations at the gage 4.7 km upstream of Stolb Isl. and expedition measurements in the Bulkurskaya Branch. As the gage is located 70–80 km from the river exit from Lenskaya truba, part of river sediments accumulates in this reach and the sediment load decreases. Compared with OS, the sediment load in the Main Channel during spring flood recession (July) is about 17.5% less; in August–September, it is 42% less; and the mean annual s is 14.5% less. During spring flood rise and a major portion of its duration, s shows almost no changes from OS to the gage 4.7 km upstream of Stolb Isl. As the result, W_R of the Main Channel is ~79% of its value at OS. However, these estimates may contain errors inherited from the source data. The role of the Bulkurskaya Branch is relatively small (the share of its sediment load is less than 1% at $Q_{\rm DH}$ < 50–55 thousand m^3/s). This share increases exponentially with an increase in Q in the river (Table 3). The long-term variations of the annual W_R in the gage 4.7 km upstream of Stolb Isl. shows largely the same regularities as in OS, in particular, a considerable increase since 1988 (by 6.9 million t/year compared with 1951–1953 and 1967–1987). This increase disturbed the pre-

Table 3. Present-day distribution of suspended sediment discharge in the upper part of the Lena Delta by data of stationary measurements in ice-free period and expedition measurements of the Arctic and Antarctic Research Institute and St. Petersburg State University in the Bulkurskaya Branch in summer seasons of 2004–2006

Delta head			Main branching point			
Main channel, 4.7 km upstream of Stolb Isl.		Bulkurskaya Branch, mouth	source of the Bulkurskaya Branch	source of the Trofimovskaya Branch	source of the Tumatskaya Branch	Olenekskaya Branch downstream of the confluence point with the Bulkurskaya Branch
Q, m^3/s	R, kg/s	R_i, kg/s	R_i, kg/s	R_i, kg/s	R_i, kg/s	R_i, kg/s
10000	60	*~0*	*20*	*50*	*5*	*5*
20000	300	*~0*	65	200	10	20
30000	800	*0.5*	155	630	60	55
40000	1450	*2.5*	290	1100	140	95
50000	2250	*12.5*	500	1650	250	145
60000	3150	*60*	755	2150	400	205
80000	4900	–	1290	3150	800	345
100000	*6900*	–	*1950*	*4200*	*1380*	*510*

viously existed at this gage relationship between Q and R and caused an upward shift of the curve reflecting this relationship. The spring flood now accounts for 77% of the annual W_R, the summer season accounts for 22, and the winter low-water season, for 1%.

The total runoff of suspended sediments at the sources of major delta branches was 109% of the value of W_R at the gage 4.7 km upstream of Stolb Isl. and 88% of W_R at Kyusyur gage. The access of the sediment runoff in the branches over its value in the gage at the 4.7 km can be explained by the fact that, during floods of river water, bypassing the gage at the 4.7 km through floodplain and floodplain branches, a part of suspension is recorded in observations at gages in the sources of main branches. Converted to a many-year period, the mean turbidity is 36.5 g/m^3. It decreases on the average 1.5–2.5 times toward the delta coastline. The result is that the total losses of suspended sediments in the delta are ~40–65%, rather than 83–90%, as given in [29]. The estimates of the losses were improved, in particular, based on the results of new expedition measurements from [14, 26, 27] and the fuller use of the data of stationary observations in the delta. An indirect confirmation of the lesser decrease in W_R in the delta, compared with earlier estimates, is the authors' analysis of changes in the characteristic of spectral brightness of water surface on space photographs of the Lena Delta. The spectral brightness decreases by 20–40% toward the sea. The decrease is maximal for smallest watercourses. In the main channels, the decrease in brightness is maximal only at the nearshore, as can also be seen from field measurement data [10, 27]. In some reaches of the watercourses, changes in the brightness correspond to the local increase in suspended load because of the erosion of delta deposits. In the downstream segments of delta watercourses, the regime of suspended load is disturbed by periodic and aperiodic sea level variations. All the transported deposits, as well as the deposits transported by river ice, accumulate in the Lena Delta and near its nearshore.

The distribution of suspended load between main channels under median water conditions in summer–autumn season is as follows (in percent of the total W_R at the entries of the main branches) (Table 3): 17.2 for the Bykovskaya Branch, 70 for the Trofimovskaya Branch, 6.7 for the Tumatskaya Branch, and 6.1% for the Olenekskaya Branch (downstream of the inflow of the Bulkurskaya Branch). This distribution varies with changes in river water discharge and, accordingly, within a year. Notwithstanding the increase in the absolute values of W_R, the share of sediment load in the Trofimovskaya Branch decreases from 68 at $Q_{4.7\text{ km}}$ = 20 thousand m^3/s) to 56.4% (at $Q_{4.7\text{ km}}$ = 80 thousand m^3/s), while the share of sediment load of the Tumatskaya Branch increases from 3.4 to 14.3%. Changes in the shares of sediment load of the Bykovskaya and Olenekskaya branches show now distinct

Table 4. Water temperature variations along the downstream reach and in the delta of the Lena R. (over period 1962–1991) and the mean monthly air temperature at weather stations at different geographic latitudes

Gage	Watercourse	Distance, km	Mean monthly water temperature, °C			
			June	July	August	September
Zhigansk	Lena R.	0	10.2	17.0	14.6	7.2
Dzhardzhan*	Lena R.	242	7.7	14.6	12.2	4.5
Siikteekh	Lena R.	386	7.1	15.6	13.7	6.3
Kyusyur V.**	Lena R.	543	4.7	13.7	12.7	6.0
Tit-Ary	Main channel	702	5.2	13.5	12.5	5.5
Stolb	Bykovskaya Branch	754	5.6	14.7	14.0	7.7
Malysheva Isl.	Ispolatova Branch	838	4.5	13.8	12.9	6.9
Sagyllakh-Ary	Antipinskaya Branch	887	2.6	10.5	8.4	3.2
Ebetem	Ebitiem R.	–	3.7	9.6	8.4	2.8
Weather station	**Water object**	**Coordinates**	**Mean monthly air temperature, °C**			
			June	July	August	September
Zhigansk	Lena R.	66°46′; 123°24′	11.7	16.0	12.1	3.5
Dzhardzhan	Lena R.	68°73′; 124°00′	10.3	14.8	11.0	2.8
Kyusyur	Lena R.	70°41′; 127°24′	7.6	12.4	9.4	1.8
Tiksi	Tiksi Bay	71°35′; 128°55′	2.8	7.3	6.9	1.4

* The thermal regime is disturbed by the effect of colder water of the Dzhardzhan R.

** The thermal regime is disturbed by the effect of colder water of the Ebitiem R.

trends. Thus, the response of R and Q to an increase in river water runoff is different in different branches, especially, in the case of the branches of Olenekskaya and Tumatskaya, which are similar in size (Tables 2, 3). The Trofimovskaya Branch, during spring flood, in August–October, and in winter, accounts, on the average, for 60.7, 70.1, and 84.7% of the total W_R at the entries of main branches, i.e., much more than that for water flow; the respective values are 22.1, 18.5, and 12.9% for the Bykovskaya, 11.7, 6.4, and 0.3% for the Tumatskaya, and 5.5, 5, and 2.1% for the Olenekskaya branches. The considerable increase in sediment load in the Lena R. starting from 1988 has disturbed the earlier relationships of the form $R = f(Q)$ and made the data over the period before 1988 unusable for the analysis of the present-day suspension distribution in this and other delta branching points.

SPATIAL VARIATIONS OF WATER TEMPERATURE AND HEAT DISCHARGE

Water temperature T in the Lower Lena, with its flow directed northward along the meridian (Table 4), steadily decreases toward its mouth. Nevertheless, the river plays a warming role down to the Laptev Sea, as river water temperature never drops below 0°C and is higher that air temperature in July–October.

The data of stationary measurements of T show a considerable effect of local factors, including the colder water of Lena tributaries, flowing not far from gages. The temperature measured near the bank and in the surface water layer does not reflect its distribution over river depth and width and, accordingly, its average value over the flow cross section. According to [21], the mean conversion factor from the value of T, measured at the bank to its weighted mean over the flow was 1.22 in 1936 at Kyusyur V.

Despite these problems, the available data can be used to derive some conclusions. First, the value of water temperature measured at OS is less than the real value because of the disturbance of river thermal regime near the gage due to the effect of colder waters of the Ebitiem R. (Table 4) on the average by 1°C in June and less than 0.5°C in July–August. Therefore, the actual heat flow W_T, is likely ~1000 × 10^{12} kJ/year greater than the value in Table 1, calculated only based on official data of T measurements. An even greater value of W_T can be obtained with the use in calculations of T averaged over the flow. Second, the rate of T decrease along the flow (over the single observation period from 1962 to 1991) is maximal in the lower reach of the river, and reaches 0.6–0.8°C/100 km. In other months, it varies within the range of 0.25–0.35°C/100 km.

In the delta branches of the systems of the Bykovskaya and Olenekskaya branches, which have a latitudinal direction, T variations are generally minor. Conversely, in the branches of the systems of the Tumatskaya and Trofimovskaya branches, which flow northand northeastward (Fig. 1), T keeps decreasing with even greater rate (1.4°C/100 km in June and 1.5–2.5°C/100 km in other months), then in the lower reaches of the river. These estimates based on stationary observations are supported by materials of expedition measurements [5]. The cause is the distribution of water flow between numerous branches, a decrease in flow rates (2–4 times) and depths, an increase in the water area, hence faster water cooling under the conditions of further air temperature drop, a decrease in solar energy inflow, considerable heat expenses to warm frozen rocks and melting of river ice, which stays every year in large amounts in the delta, in shallows, and on the floodplain.

W_T in the reach OS–DH is subject to the effect of two opposite processes: an increase because of heat inflow from the lateral watershed (~120 × 10^{12} kJ/year—this value was derived from the regional relationship in [15]) and its decrease because of decreasing T. As the thermal regime in the reach at Kyusyur gage is disturbed, the effect of the second factor was not identified. Therefore, W_T of the Lena R. at DH can be estimated at 15.6–16 × 10^{15} kJ/year. At the delta coastline, considering the regularities in the water flow distribution between the systems of delta branches, its annual distribution, and longitudinal variations of T, we estimate W_T at ~11.75 × 10^{15} kJ/год. Thus, ~25% of W_T is lost in the delta at its head. This is close to the estimate of 10 × 10^{15} kJ/year in [4]. The Laptev Sea receives 21.4 of the total annual W_T at delta coastline in June, 43.9 in July, 25.2 in August, and 9.3% in September. The rest of that is received in May and October.

CONCLUSIONS

According to new estimates, water runoff of the Lena R. at the OS, DH, and DC over period 1927–2014 is 543, 547, and 553 km^3/year, respectively. In the same sections, suspended sediment runoff is 22.5, ~22.5, and ~7.9–13.5 million t/year; a very approximate estimate of bed load runoff is 17.0, 17.0, and 0 million t/year, respectively. The heat runoff is estimated at 16.6 × 10^{15}, 15.6–16 × 10^{15}, and ~11.75 × 10^{15} kJ/year, respectively. Thus, the vast and multibranched arctic delta of the Lena retains 40–65% of the incoming (at DH) suspended sediment runoff, almost all transported deposits, and ~25% of heat runoff. Water runoff shows a minor increase.

The value and regime of Lower Lena runoff changed significantly in the recent 30–40 years, responding to climate factors, Water runoff at the near-mouth Lena reach increased in all hydrological seasons, and its annual total increased by 42 km^3/year, compared with its values in 1935–1979; sediment runoff increased by 5.85 million t/year since 1988; and heat runoff increased by 0.8 × 10^{15} kJ/year; water temperature was also found to increase. The major increase in runoff has been observed since the late 1980s. The greatest increase was recorded in the runoff of winter low-water period (with a disturbance of the stationarity of the series) and the runoff of suspended sediment in summer–autumn season.

Water consumption and the construction of two Vilyui reservoirs have nearly no effect on river water resources ($\Delta W_{\text{econ}} \approx -0.35$ km^3/year) but disturbed the natural conditions of winter low-water season. The effect of economic activity on other river runoff components was not found.

The distribution of Lena runoff in the near-head branching point and at Stolb Isl. is relatively stable; the proportions between runoff values at the sources of major branches and in the heads of branching points, derived from stationary-monitoring data, in most cases do not keep constant. At Stolb Island, i.e., in the main branching point in the delta, the share of water runoff through the Bykovskaya Branch in 2001–2007 was about 25.1% of the total runoff volumes at the sources of major branches; the same shares were ~62.3 for the Trofimovskaya Branch, ~6.2 for the Tumatskaya Branch, and ~6.4% for the Olenekskaya Branch. Because of seasonal variations of river water abundance, these proportions also change: with an increase in Q_{Kyusyur} from 10 to 140 thousand m^3/s, the share of runoff of the Trofimovskaya Branch decreases from 72.3 to 50% and less, while the runoff volumes of the Bykovskaya, Tumatskaya, and Olenekskaya branches, conversely, increase from 21.3, 2.1, and 4.3% to 27.8, 10.7, and 11.6%, respectively. At larger Q, large ice jams, and high water levels, a part of flow passes over the floodplain and floodplain branches, i.e., bypasses the major gages. Suspended load is distributed between the branches in the following proportions: 17.2 for the Bykovskaya Branch, 70 for the Trofimovskaya Branch, 6.7 for the Tumatskaya Branch, and 6.1% for the Olenekskaya Branch. These proportions change with changes in Q in the river.

In the reach from the Stolb Isl. to Lena delta coastline, the runoff is distributed between ~6 thousand watercourses. The distribution in small delta nodes is unstable because of channel processes. Accurately describing this distribution with the use of standard field measurements is impossible and inexpedient. The problem of monitoring runoff transformation in the delta can be solved with the use of methods of indication hydrology and materials of satellite sounding of the Earth.

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