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Features and Evaluations of Spatial and Temporal Changes of Water Runoff, Sediment Yield and Heat Flux in the Lena River Delta

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Abstract: In the last 30 to 40 years, the water runoff, sediment yield and heat flux of the Lena River have undergone significant changes due to, mainly, climatic factors. Features of these changes at the marine margin of the Lena River delta are different compared to changes in the delta head area. The reason for this disparity is the transformation of river runoff in the large and multi-branched delta. New data and research results not only clarified the values of water flow, suspended sediment yield, and heat flux at the basin outlet station of the Lena, but also estimated the river runoff into the Laptev Sea. The data offering current distribution of water flow, suspended sediment discharges between the main deltaic branches, their long-term changes, and the character of the spring flooding within the upper part of the Lena River delta are presented in the article. Features and causes of long-term and intra-annual fluctuations of water flow, sediment yield, and heat flux of the Lena River have been studied in detail. The accuracy of the hydrological observations used and role of anthropogenic factors have also been evaluated.

Zusammenfassung: In den letzten 30 bis 40 Jahren haben sich Wasserabfluss, Sedimentfracht und Wärmetransport der Lena erheblich verändert, verursacht im Wesentlichen durch klimatische Faktoren. Die Muster dieser Veränderungen sind am meerseitigen Rand des Lenadeltas deutlich anders als im landseitigen Deltabereich. Grund für diese Verschiedenheit ist der Übergang vom reinen Flusstransport zu einem Flussverlauf in einen großen und vielverzweigten Deltabereich. Neue Daten und Ergebnisse haben nicht nur zur Klärung und Einschätzung von Wasserströmung, suspendierter Sedimentfracht und Wärmetransport beim Eintritt des Lenaflusses in das Lenadelta geführt, sondern erlauben auch eine Abschätzung des Flusseintrags in die Laptewsee. Die Untersuchung präsentiert Daten zur aktuellen Verteilung der Wassermassen und des suspendierten Sediments in den größeren Stromzweigen des Deltas, auf ihre langfristigen Veränderungen sowie auf den Charakter der Frühjahrsfluten in landseitigen Deltateilen der Lena. Im Detail wurden die Merkmale und Ursachen der langfristigen und jahreszeitlichen Veränderungen der Wasserströmung, der Sedimentfracht und des Wärmetransports der Lena untersucht. Kritisch abgeschätzt wurde die Genauigkeit der hydrologischen Beobachtungen und Daten sowie die Rolle der anthropogenen Faktoren.

INTRODUCTION

The parameters of the Lena River runoff (such as sediment concentration, heat fluxes, contents of dissolved and contaminating agents, and biological substances) change between the basin outlet station, the head, and the marine margin of the Lena Delta. These parameters have significant impact on the environment of river valleys, Arctic shelf circulation with associated heat and biogeochemical fluxes, and freshwater budget of the Arctic region (e.g. Yang et al. 2005, Dmitrenko et al. 2008, Morison et al. 2012, Fofonova et al. 2016). Therefore, quantitative estimates and understanding of regularities, causes of the longitudinal transformation of flux characteristics, and estimation of the total value and seasonal variability of the Lena River runoff at the mouth area are of utmost importance. However, these important tasks still represent a great scientific challenge.

The Lena Delta area is ~30,000 km^2 (Schneider et al. 2009) and represented by a considerable number of freshwater channels, with over 6,000 in total. More than 30,000 lakes and a multitude of islands also constitute components of the delta, a considerable part of the eastern delta can be submerged by the Lena water during floods. Despite the large number of observations in the delta head and at several hydrological stations upstream, there are gaps in knowledge of discharge characteristics such as heat fluxes and organic and inorganic material concentrations in the mouth and marine margin of the delta. These characteristics experience complex changes within the delta due to the processes of dispersion and redistribution of river flow. These processes are initiated by a large amount of bifurcations in the riverbed, coastal erosion, hydraulic interaction between river and sea water, and chemical and biological transformations of substances contained in the water. The channels in the delta have different geomorphologic structures and regime of functioning, and the concentration of passive and active substances (organic and inorganic materials, phytoplankton and zooplankton species), and heat fluxes do not follow water discharges, known for main channels and some sub-channels in the area (Ivanov et al. 1983, Magritsky 2001, Bolshiyanov et al. 2013, Fedorova et al. 2009).

The main objective of the current study includes calculation and analysis of the river runoff characteristics as water runoff, sediment load and heat fluxes at the gauging section of the river, at the head and marine margin of the delta, and in the main channel systems. The calculation demanded a study of the features and factors of longitudinal transformation of the river runoff characteristics. The current research also provides

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Keywords: Long-term data series, Laptev Sea, spatio-temporal variability, discharge characteristics

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and examines causes and trends of long-term fluctuations of the runoff characteristics in the Lena River.

The statement of the main results of the study precedes the sections with information on the data and materials used and the methods and approaches of their processing, analysis and generalization. The first subsection of the "Results and discussion" section contains relevant estimates of the water runoff, suspended sediment concentration (SSC) and suspended sediment load or discharge (SSL), water temperature and heat fluxes at the basin outlet station of the Lena River, and the results of the detailed analysis of features and reasons for their long-term variability. The next three subsections, for each of the components of the river runoff, provide the obtained results about spatial transformation of the water runoff, sediment load and heat fluxes from the main stream station to the delta and the Laptev Sea.

MATERIALS AND METHODS

Long-term observational data, their measurement techniques and accuracy

The base of the current research is represented by the long-term observational data on the Lena River water levels (H), water temperatures (θ), water discharges (Q) and SSC (C_s)/SSL (Q_s) at the hydrological gauging stations with daily, 10-day, and monthly averaging. In addition, air temperature and precipitation data from the meteorological stations, which are in direct access on the RIHMI-WDC portal (web source), and data on the total water consumption in the basin of the Lena River in 2001–2013 (State Water Cadaster 2004–2014) were used.

Data on water levels and temperatures are taken at gauges Kyusyur (for the period from 1935 to 2013) and Tit-Ary (1948–1990), polar stations Yu.A. Khabarova (previously called Stolb) at the Bykovskaya branch (1951–2012), Malyshev Island (1953–1989) and Sagyalah-Ary (1962–1991). Water temperature data from eight Lena gauges upstream from Kyusyur station and from gauges on the Vilyuy River, Ebitiem River, and Eremeyka River were additionally used. The data on water discharges and SSL are taken at gauges Tabaga (1927–2014), Kyusyur (1934–2012, 2014), "4.7 km upstream of the Stolb Island" (1951–2007), and Yu.A. Khabarova (1950–2007), as well as at the hydrometric sections at the sources of the main branches of the delta (1977–2007), at gauges Khatyryk-Homo and Verhoyanskiy Perevoz at the lower reaches of Vilyuy River and Aldan River (1935–2014) correspondingly.

According to the standard procedures for hydro-meteorological observations in Russia and former USSR the water level and stream temperature measurements were carried out twice a day. The water temperature observations were made near the river bank with flowing water deeper than 0.3-0.5 m. Water temperature was measured with a water thermometer with an accuracy of 0.1 °C. The measurements of temperature were not carried out during the winter months, when the rivers are frozen. The reliability of these measurements will be partly analyzed below. In the national hydrological year-books the stream temperature data were averaged for three intervals of about 10 days in length: from beginning of month to the 10th, from 11th to 20th, and from the 21st to the end of each month.

The SSL at hydrological stations were determined from the SSC daily measurements and measured or calculated water flow rates (using $Q = f(H)$ curve). The SSC was measured at gage point of the gauge located near the river bank. At gauge Kyusur, this gage point was at a distance of 1680 m from the right bank until the late 1980s, then it was moved much closer to the bank. Such shifting also took place at other considered gauges approximately at the same time or later. This could affect the homogeneity of a long-term data series, because SSC in the coastal zone is influenced by even streamlet tributaries upstream, local coastal erosion and strong mixing processes acquired in shallow zones. SSC is calculated by the formula: SSC (mg/l, g/m^3) = SSM (mg, g)/V (l, m^3), where SSM is the mass of suspended sediments contained in the water sample and remaining on the paper filter (after filtering the water sample), V is the volume of the water sample with sediments collected at gage point (usually from 1-6 liters). The content of organic material in the water sample is approximately 7-25 % at gauge Tabaga, 12-22 % at Verkhoyanskiy Perevoz and 5-15 % at Kyusyur. SSC at the gage point is recalculated into the mean SSC for the hydrometric cross-section using multiplying coefficient, which varies from 0.7 to 1.0. Since 1990s, the number of SSC measurements has been reduced. After 2003, SSC measurements at gauge Kyusyur have been ceased altogether, at gauge Verkhoyanskiy Perevoz since 1999, at gauge Khatyryk-Homo since 2010. Since 1981, SSL data for the winter months at gauge Kyusyur have not been published. When SSC at gage point is not measured, the daily SSL is determined from the previously estimated dependence $Q_s = f(Q)$. Note, that at the gauges in the Lena Delta area SSL was nearly almost calculated in this way. The SSL data errors are a composition of errors in the measurements of water discharges and SSC, where errors in the discharge measurements play dominant role. The maximum errors in SSC measurements are estimated by Roshydromet at the level of 15-20 %.

The main sources of water discharges and SSC/SSL values are the national hydrological year-books (Hydrological Yearly Bulletin 1950–1983, State water cadaster 1984–2016), reference books with long-term hydrological data series (Shestakova 1967, 1975, Shestakova & Egorova 1979, State water cadaster 1987) and the archival data of the regional departments of the Roshydromet. According to these and other sources there are errors in the water discharges measured and calculated using the curve $Q = f(H)$ due to:

1. lack of full-scale measurements of the water discharges, which are more than 100,000 m^3/s and the significant extrapolation of the curve $Q = f(H)$ (valid for gauge Kyusyur);
2. impact of huge ice dams and ice hummocking on the quality of the water level measurements;
3. poor quality of discharge measurements during the winter low-water period under high ice thickness conditions, very low stream velocities and the high congestion of the river channel with sludge;
4. ignoring a floodplain runoff during the high-water period (valid for gauges Yu.A. Khabarova and "4.7 km upstream of the Stolb Island", to a lesser degree for gauge Tabaga where floodplain runoff is about 5 % of maximum flow rate ($Q_{\max}$));
5. ignoring a flow over the ice cover (valid for gauges Yu.A. Khabarova and "4.7 km upstream of the Stolb Island");

6. intensive river bed deformations and an extremely unstable form of the long-term curve $Q = f(H)$ (valid for Tabaga, where was a radical reformation of the river bed in 2006, and for Khatyryk-Homo gauges);
7. shallowing of the river bed in the summer-autumn low-water period and hydraulic backwater from the Lena River (valid for gauge Khatyryk-Homo) (Chistyakov 1964, Hydrological Yearly Bulletin 1950-1983, Magritsky 2001, Shestakova 1975, Shestakova & Egorova 1979, State water cadaster 1987, State water cadaster 1984–2016).

The quality of the data was worse during the first years of the considered gauge operation when the measurements covered only 60-80 % of the range of H and Q fluctuations. Also, the field measurements were not performed in all years, for example for the period 1947–1959 there were no discharge measurements at Kyusyur gauge. As the result, the Roshydromet estimates the possible and maximum overestimation of $Q_{\max}$, which exceed 100,000 m^3/s, by 30-50 % before the beginning of the 1960s compared to the true discharges and by 10-30 % in the subsequent years for all considered stations (Shestakova 1975, Shestakova & Egorova 1979). The winter runoff is, on the contrary, underestimated up to 1.5-2.5 times according to the measurement data in the first years of the gauges operation, and up to 15-20 % in the subsequent years. There is no information on the measurement errors at the permanent deltaic hydrometric sections at the sources of the Olenekskay, Tumatskaya and Trofimovskaya branches.

Due to the fact that there are no more reliable data on network observations, the authors and other researchers are forced to use the materials contained in the official hydrological reference books. At the same time, firstly, a comparison of the observed water discharges and the data, derived from GRACE (Gravity Recovery and Climate Experiment) and reanalysis, at gauge Kyusyur shows their good consistency, especially for the summer-autumn season, compared to other large rivers of Siberia, and the underestimation of the mean discharges during winter (Syed et al. 2007). Secondly, estimates of discharge become increasingly well constrained from daily to monthly and to annual averages (McClelland et al. 2004).

Methods for data processing and analyzing

The primary methods used for processing and analyzing available data were the calculation of the mean values, variation and skewness coefficients, building empirical and theoretical (probabilities distribution by Kritsky-Menkel and Pearson of type III) frequency curves, evaluation of extreme value probability of water discharge, and statistical analysis methods for testing data series for major statistical hypotheses (significance level 0.05): (a) homogeneity and stationarity using the Dixon and Smirnov-Grubbs criteria, Fisher's (F-test), Student's (t test) and the Mann-Whitney (U-test) tests applied to the time-correlated and asymmetric hydrological information and (b) the presence of a trend using the Spearman criterion (Spearmen RCC or SRCC) and Student's statistics for regression coefficient, slope of the trend line ($t_k = k/\sigma_k$). Statistically significant rejection or acceptance of the "null" hypotheses is indicated in the text by the symbols «+» and «-» correspondingly. They were preceded by the data reliability verification and recovering of the missing values in data series.

In addition to the mathematical statistics tools, different water balance methods and systems of linking the water and sediment balance were applied along the length of the river channels and in deltaic branching knots (Magritsky 2000, 2001, 2009, 2010, Mikhailov 1998, Mikhailov et al 2006). Accuracy and adequacy of various empirical dependencies and chronological charts were evaluated against the adjusted r^2 and F.
Calculation of the 10-day heat flux ($W_{\theta,10}$) was completed using the formula $W_{\theta,10} = c_p\rho\theta_{10}W_{10}$ (1)
where c_p is water specific heat (kJ/(kg °C)), ρ is water density (kg/m^3), θ_{10} is 10 day mean water temperature (°C) and W_{10} is sum water runoff over 10 days (m^3).

Seasonal and yearly heat flux values ($W_{\theta,y}$) were calculated as sum of $W_{\theta,10}$. Part of the methods, which were developed by authors, will be considered below.

In addition to the sources mentioned above, the results of the previous studies (Alexeevsky et al 2014, Alexeevsky 2007, Magritsky 2000, 2001, 2009, 2010, Magritsky & Mikhailov 2006), the conclusions and estimates obtained by other experts, and the materials of expeditionary studies in the lower reaches and the delta of the Lena River (Reynberg 1938, Antonov 1960, 1967, Ivanov 1963, 1964, Tasakov 1965, Ivanov et al. 1983, 1995, Korotaev et al. 1990, Gukov 2001, Bolshyianov et al 2006, 2013, Fedorova et al 2009, 2015) were also considered.

RESULTS AND DISCUSSION

Features and reasons for long-term variability of water run-off, sediment load, and heat flux at the basin outlet station of the Lena River

Kyusyur is usually considered to be the basin outlet station (main stream station) of the Lena River. It is situated at the entrance of the river to the "Lenskaya Truba" ("Lena pipe"), 145 km upstream from the head of the delta and 315 km from the sea (from the mouth of the Bykovskaya branch), at a distance of 2,220 km from the Vilyuy Hydroelectric Station-1, 2. The gauging station encloses a catchment area of about 2,430,000 km^2. The mean annual water discharge of the Lena River at Kyusyur is 17,200 m^3/s, and the annual water runoff volume (W_y) is 543 km^3 (Tab. 1) for the period from 1927 to 2014 (with the data restored based on observations at Tabaga gauge for the period from 1927 till 1935). Due to the lateral inflow (from the catchment area of 27,900 km^2) and the positive water balance in the huge delta, W_y increases by approx. imately 10 km^3 towards the sea.

The comparison of this value to the maximum value of anthropogenic pressure (ΔW_{he}) (which consists of total water intake and runoff losses due to evaporation from the reservoirs) indicates the lack of noticeable influence of water management activity on the Lena River's annual runoff into the sea and on its long-term variability (Adam et al. 2007, Georgiadi et al. 2011, Magritsky 2008, 2015, State Water Cadaster 2004–2014). During 2001–2013, ΔW_{he} was approximately 1.25 km^3/year. It is 0.23 % of mean annual runoff volume (1927–2014) at the marine margin of the delta or 0.28 % of the runoff volume of 95 % probability (447 km^3/year). This influence is

Feature	Period	Value of the characteristics			C_v (C_s/C_v)
		Mean (1)	Maximal year	Minimal year	
Mean annual flow discharge, m^3/s	1927–2014	17,200 (2.0)	23,100 1989	12,700 1986	0.13 (4.0)
Maximum flow discharge, m^3/s	1935–2014	135,000 (3.0)	220,000 06/04/1989	78,000 06/06/1935	0.18 (2) (5.5)
Minimum winter flow discharge, m^3/s	1935–1979 1980–2014	992 (7.5) 2,000 (5.3)	2,920 04/30/2007	366 04/27/1940	0.22 (-2.5) 0.23 (0)
Minimum summer-autumn flow discharge, m^3/s	1935–2011	17,500 (4.5)	26,800 08/22/1983	9,800 09/20/1964	0.25 (2.5)
Mean annual suspended sediment discharge, kg/s	1936, 1944 1960–2010	*712* (3) (9.4)	1,700 2005	240 1984	0.43 (3.5)
Heat flux, 10^{12} kJ/year	1935–2012	15,590 (2.2) *16,590* (4)	22,320 1938	10,620 1986	0.19

Tab. 1: Main characteristics of water flow, sediment load, and heat flux of the Lena River (gauge Kyusyur). Notes: (1): the mean square relative (%) error of calculation of the average long-term value is given in the brackets; (2): the truncated Kritsky-Menkel distribution when $C_v = 0.22$ and $C_s/C_v = 3.5$ gives the best result for a set of values of <50 % probability; (3): taking into account the values restored for 7 years; (4) : denominator contains a value adjusted for a decrease in water temperature at gauge Kyusyur due to the influence of cold waters of the Ebitiem River and other mountain right-bank tributaries.

Tab. 1: Die wesentlichen Charakteristika des Abflusses, der Sedimentfracht und des Wärmeflusses der Lena am Kyusyur Pegel. Beachte: (1): In Klammer der mittlere quadratische relative Fehler (%). (2): die verkürzte Kritsky-Menkel Verteilung. (3): unter Berücksichtigung der wiederhergestellten Werte für 7 Jahre. (4): enthält einen bereinigten Wert für abnehmende Wassertemperatur am Pegel Kyusyur wegen des Einflusses von kaltem Wassers aus dem Fluss Ebitiem und anderer rechtseitiger Zuflüsse aus dem Gebirge.

actually even less (~0.35 km^3/ year), taking into account only the irrevocable water consumption and additional evaporation from the surfaces of all the reservoirs in the basin of the Lena River. The impact of the Viluysk reservoir on the annual water runoff of the lower Lena is statistically insignificant. Even in the years of initial filling (1966–1972) of the Viluysk reservoir, when the water runoff losses reached ~8-10 km^3/year, the total impact is less than 1.5-2.0 % of the annual runoff at gauge Kyusyur. This conclusion is confirmed by the simulation results provided in Adam et al. (2007), but it is in a contrast with the conclusions given in the articles McClelland et al. (2004) and Ye et al. (2003). However, we should note that the Viluysk reservoir impact is significant if we consider seasonal redistribution of the water runoff and its long-term variability, this question will be addressed below.

The inter-annual variability of W_y (gauge Kyusyur) is rather low ($C_v \approx 0.13$), while the autocorrelation coefficient $r(1)$ is high and statistically significant ($r(1) = 0.36$; $t(A) = 3.5$ (+), and $t(u) = 1.98$ (+) $> t_{NormalDistr}(\alpha/2) = 1.96$), which is natural for very large rivers. According to the dendrohydrological reconstruction data from MacDonald et al. (2007) and the results of transient simulations with the coupled atmosphere–ocean circulation model ECHO-G from Wagner et al. (2011) the fluctuations of the annual water runoff of the Lena River over a significantly longer period include the cycles of about 80 years (from 60 to 100 years) and 1.5-2 thousand years duration. However, within the last 60-100 years, statistically significant cycles were not found, we can only highlight the statistically insignificant cycles with the durations of 7.8, 5.7, 14.3 and 43 years (Magritsky 2015). The long-term fluctuations of W_y contain a statistically significant increasing trend ($SRCC = 0.23$ (+) ($p = 0.035 < \alpha = 0.05$) and $t_k = 2.5$ ($t_{k,95\%} = 2.0$) for 1927–2014; $SRCC = 0.37$ (+) ($p = 0.0007$) and $t_k = 3.6$ for 1935–2014), particularly evident since 1988.

In 1980–2014, W_y at Kyusyur gauge was 563 km^3/year and exceeded W_y in 1935–1979 by 41.7 km^3/year. The fact of present-day increasing the flow of the Lena River is shown in a variety of studies (Alekseevskiy et al. 2004, 2007, Berezovskaya et al. 2005, Fedorova et al. 2009, Georgiadi et al. 2011, Magritsky 2015, Peterson et al. 2002, Shiklomanov et al. 2013, Wagner et al. 2011, Ye et al. 2003, etc.). Wagner et al. (2011) consider that the current increasing in the annual water discharges of the Lena River is unprecedented over last ~9 thousand years. According to ECHO-G model results the increasing annual water runoff from mid-Holocene (7 ka BP) until preindustrial time (around 200 years ago) is estimated at 3.05 % (±1.04 %), and in the industrial period at 13.07 % (±2 %). Especially tremendous ascent has been obtained since the second half of the XX century. About 24.5 km^3/year of this growth is due to an increase in the water runoff of the rivers in the upper part of the catchment area closed by Tabaga gauge ($F_{Tb} = 897{,}000\ km^2$); 13.2 km^3/year belongs to the Aldan River ($F_{VerkhPer} = 696{,}000\ km^2$); 7.95 km^3/year is attributed to the Vilyuy River ($F_{KhatHomo} = 452{,}000\ km^2$). In the context of seasonal structure of long-term annual runoff changes, 45 % of its growth is due to an increase in runoff during the spring-summer high water period (May–July), while 12 % and 43 % accrue to the summer–autumn (August–October) and winter seasons, respectively.

The value of W_y has a complex response to climate warming. The relationship between the annual water runoff and the average annual air temperature, averaged for 5-year periods, shows a positive trend and a harmonic component (Fig. 3). The air temperatures were calculated and averaged for 11 main meteorological stations in the basin (Fig. 1). Moreover, the amplitude of fluctuations grows with the increase in air temperature (t). Note also that the sharp increase in the air temperature at the end of the 1980s and in the mid-2000s coincides with the behavior of the annual Lena River runoff during these years (Magritsky 2015). The dependence between the

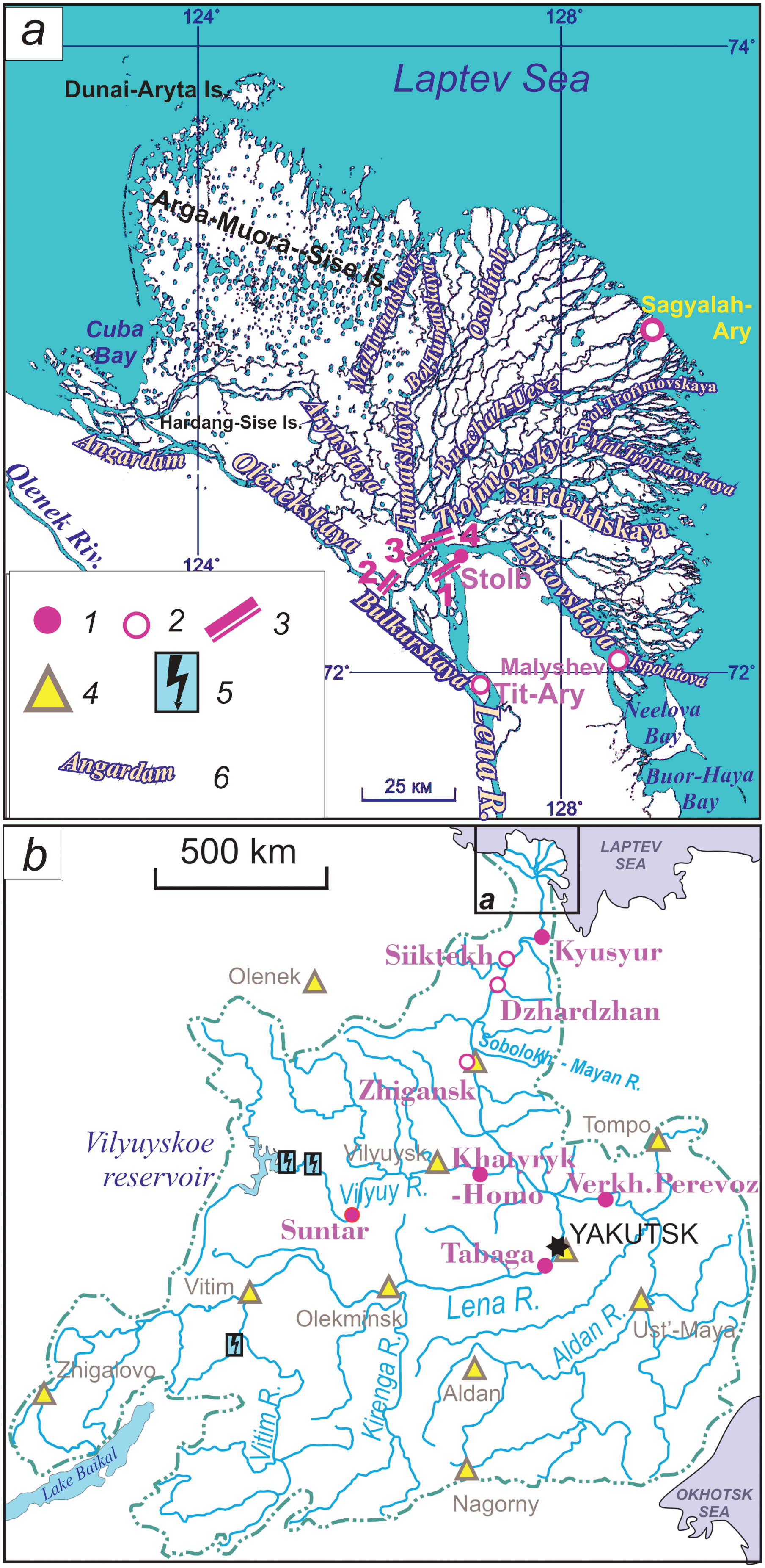

Fig. 1: Maps of the Lena River basin (b) and its delta (a), showing the location of (1): main discharge and (2): water level hydrological gauges; (3): constant deltaic hydrometric cross-sections; (4): meteorological stations in the Lena basin (data of which were used for Fig. 3); (5): hydropower plants; (6): major river branches of Lena Delta; red (1): "4.7 km upstream the Stolb Island"; red (2): at the source of the Olenekskaya branch; red (3): at the source of the Tumatskaya branch; red (4): at the source of the Trofimovskaya branch.

Abb. 1: Karten des Einzugsgebietes der Lena (b) und des Lena Deltas (a) mit Lage der verschiedenen Stationen. (1): Haupt-Abflusspegel; (2): Messung des Wasserspiegel; (3): permanente hydrometrische Stationen im Delta; (4): Meteorologische Stationen im Einzugsgebiet der Lena; (5): Staudämme und Wasserkraftwerke im Lena Einzugsgebiet; (6): größere Flussarme im Lena Delta; (rote 1): Pegel 4,7 km stromauf der Insel Stolb; (rot 2): Pegel am Beginn des Olenekskaya Kanals; (rot 3): Pegel am Beginn des Tumatskaya Kanals; (rot 4): Pegel am Beginn des Trofimovskaya Kanals.

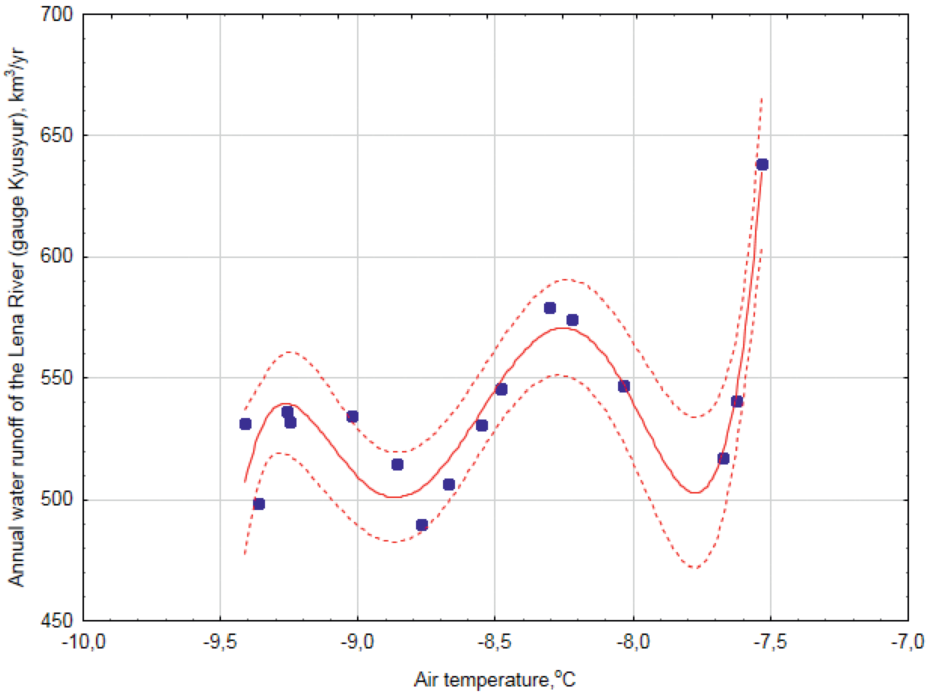

Fig. 3: Scatterplot with the quintic polynomial curve and 95 % confidence limits between the annual water runoff of the Lena River (gauge Kyusyur) and the average annual air temperature over the catchment area (stations Zhigansk, Vilyuysk, Olenek, Vitim, Zhigalovo, Yakutsk, Aldan, Ust'-Maya, Nagorny, Olekmisk and Tompo), averaged for 5-year periods.

Abb. 3: Streudiagramm (quintische Polynomfunktion mit 95 % Konfidenz) des jährlichen Wasserabflusses der Lena (Kyusyur Pegel) und der durchschnittlichen Jahrestemperatur im Einzugsgebiet der Lena an den Stationen Zhigansk, Vilyuysk, Olenek, Vitim, Zhigalovo, Yakutsk, Aldan, Ust'-Maya, Nagorny, Olekmisk und Tompo (vgl. Abb. 1b), gemittelt über 5-Jahresabschnitte.

annual water runoff and the average annual air temperature is nonlinear and is a composition of several functions. It does not contradict the conclusions about a reliable relation between precipitation, or effective precipitation, and water runoff of the Lena River (Berezovskaya et al. 2005, Serreze et al. 2003) and about the absence of correlation between air temperature and annual water runoff (Yang et al. 2002). It reflects the complexity of the reaction of runoff forming conditions in the river basin to climate changes. The thawing of permafrost and melting of ground ices due to increasing of the air temperature can also contribute to an increase in the river runoff in the permafrost zone (Davydov 2011, Dzhamalov & Potekhina 2010, Serreze et al. 2003, Zhang et al. 2003, Yamazaki et al. 2006, Yang et al. 2002). Davydov (2011) considers that the thawing of 1 cm of permafrost within the Kolyma lowland is able of producing 3 mm of water. The contribution of these water is equal to 5 % of the summer precipitation value. Zhang et al. (2003) estimated the addition to the annual runoff of the Lena River due to the changes in active layer thickness +10, +20 and +30 cm as 1.3-1.6 km^3/yr, 2.6-3.2 km^3/yr and 3.9-4.8 km^3/yr respectively. The water addition owing to the thawing the ground ices, the changes of permafrost talicks (channels in permafrost) increases the role of permafrost degradation in changes of Arctic rivers runoff. But there is also another opinion with respect to the effect of permafrost thaw on the river flow (McClelland et al. 2004).

The high-water season, lasting on average from mid-May to the end of July, takes 59.5 % of the annual water runoff (4.1 % in May, 36.1 % in June and 19.3 % in July), showing the maximum water discharge on 7 June, which is the average date corresponded to the high-water season peak. The summer–autumn hydrological season with rain floods accounts for 32.7 % of the annual water runoff, in particular, 13.3 %, 12.2 % and 7.2 % occurs in August, September, and October, respectively. The steady winter low-water period, starting on the third 10-day period of October, has 7.8 % of annual runoff and the minimal water discharges.

The large-scale climatic changes in the basin and the operation of the large Vilyuy Reservoir (which provided an additional discharge volume of ~700 m^3/s for the Lena River in winter (Magritsky 2015)) considerably improved the hydrological conditions of winter low-water in the lower reaches of the Lena River (Adam et al. 2007, Berezovskaya et al. 2005, Magritsky 2001, 2008, 2015, Ye et al. 2003) and in the delta. According to the new data, the water runoff over the period from November to April increased from 34.1 (in 1935–1979) to 51.5 km^3/year (in 1980–2014), i.e. by 51 %. The minimum water discharges increased from 992 to 2,000 m^3/s (Fig. 2, Tab. 1). The first significant increase occurred in 1978–1979, and the second in 2004. The contribution of the anthropogenic factor to this process exceeds the role of climate-induced rising in the winter runoff. As a result, the stationarity of winter low-water runoff in the lower reaches of the Lena River was violated (*F-test* (+), *U-test* (+)). Apart from that, the proportion of winter months increased approximately by 2.7 %. The starting dates of winter low-water season have not almost changed (Magritsky 2015).

The stationarity of the average annual, maximal, summer–autumn minimal, and average monthly (from June to October) flow discharges are confirmed. The minimum summer–autumn discharges increased from 17,000 to 18,200 m^3/s and have a close relation to the average annual flow discharges (r^2 = 0.47). The maximum water discharges, on the contrary, slightly decreased in particular from 136,000 to 135,000 m^3/s, which is significantly less than the possible measurement errors, whereas the runoff increased from 315 to 334 km^3/year over the high-water period. The high-water wave became flatter. The peak water discharges showed a tendency of being reached on average 3 days earlier (the significance value was 0.01) over the period of 1935–2014. Because of strong Vilyuy Reservoir regulation the spring, summer and autumn discharge long-term changes and trends do not always represent natural changes and variations (Adam et al. 2007, Magritsky 2001, 2015, McClelland et al. 2004, Ye et al. 2003).

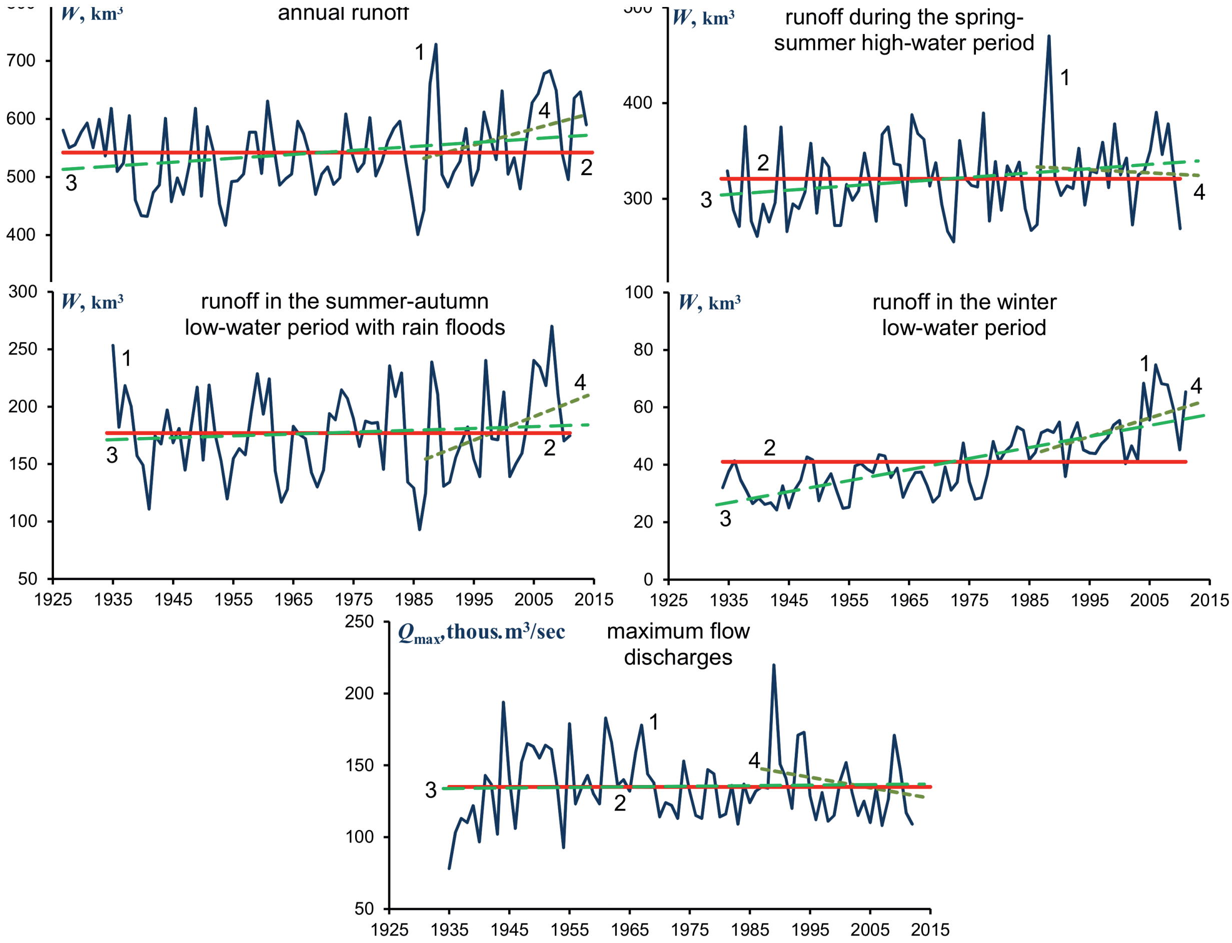

Fig. 2: Long-term behavior of water runoff characteristics in the lower Lena (Kyusyur gauge). 1 – long-term fluctuations of runoff, 2 – long-term average of runoff characteristic, 3 – linear trend for the entire period of observations, 4 – linear trend for the period of 1988-2014.

Abb. 2: Langzeitliches Verhalten der Abfluss-Charakteristika im Unterlauf der Lena (Kyusyur Pegel). 1: langzeitliches Abflussverhalten; 2: langzeitlicher Abfluss-Durchschnitt; (3): linearer Trend über Gesamtzeit der Messungen; 4: linearer Abfluss-Trend für die Zeit 1988–2014.

Erosion processes in the basin and the intake of erosion products to the river network are limited by a high duration of negative air temperatures, the location of the basin in the permafrost zone, a considerable number of plains and forested areas, as well as spring and main high-water wave passing in the period of slightly thawed soils, etc. (PROTASIEVA 1972, KARAUSHEV 1977, MAGRITSKY 2010). According to the new data, the mean annual SSC at the Kyusyur station is equal to ~40 g/m³. Within a year it changes from the maximum values during the high-water period (on average 35-90 g/m³) and the period of summer–autumn floods (on average 35-65 g/m³) to the minimum values in the winter low-water period (on average 1.5-4.5 g/m³). The SSC decreases between rain floods (on average 20-30 g/m³). The maximum measured SSC was 790 g/m³ (18.08.2004). But perhaps it is the result of incorrect measurements. In June 1974 and August 2005 measured SSC reached 400 g/m³. The relatively low SSC is compensated by a large water runoff, therefore the annual SSL ($W_{s,y}$) of the lower Lena is quite high and equals 22.5 million tons (Tab. 1). The value of $W_{s,y}$ at the delta head is approximately the same as at mainstream station, as the lateral inflow of ~32.000 t/year is compensated by the intensive sediment accumulation at the outfall of the river from the "Lenskaya truba" (ANTONOV 1960). The bed load is transported to the delta too. In accordance to the research results from CHALOV et al. (2000) and TANANAEV & ANISIMOVA (2013) the annual bed load yield at Kyusyur gauge is 14.9-17.5 10^6 t. Bed material transport occurs mostly during snowmelt floods (78.5 %). This is followed by rain-induced events (19.5 %) and the summer low-flow period (2 %) (TANANAEV & ANISIMOVA 2013). The intake of SSL to the border of the delta branches from the local catchment area can reach 125,000 t/yr; the local inflow of bed load yield is probably higher. Thus, the total sediment yield in the Lena River delta could reach up to 40 10^6 t/yr, and the share of delta- and channel-forming fractions are very high. This explains why the delta is so large and, at that, is on the open seacoast. However, there are also other factors involved in the formation of the delta of the such topography (BOLSHYIANOV et al. 2013, KOROTAEV et al. 2007).

As for the long-term changes of $W_{s,y,}$ a certain coincidence to the fluctuations of water runoff and two long-term tendencies are observed. The first tendency is a decrease in $W_{s,y}$ until 1986–1987, and the second is an increase in $W_{s,y}$ in the subsequent years (Fig. 4). The low correlation between the fluctuations of annual water runoff and SSL ($r \approx 0.5$) is explained by the dependency of $W_{s,y}$ not only on total annual water runoff, but also on the distribution of water discharges during the year, on the number and the power of rain-caused floods, and also by the influence of other factors (MAGRITSKY 2001), including

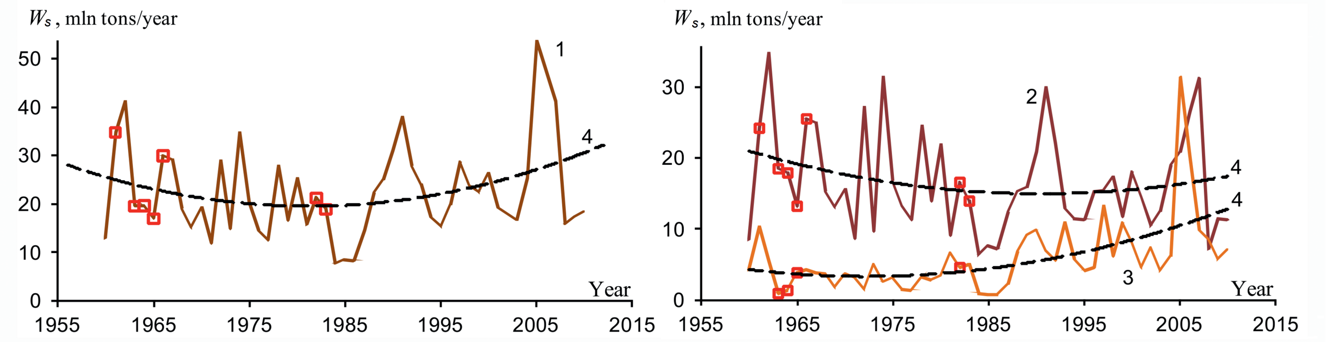

Fig. 4: Long-term changes of suspended sediment yield in the lower reaches of the Lena River (gauge Kyusyur). 1: annual sediment yield; 2: sediment yield averaged over snow-melt flood season; 3: sediment yield averaged over summer–autumn season, 4: the squares show the years, for which the data have been restored.

Abb. 4: Langzeitliche Wechsel der suspendierten Sedimentfracht im Unterlauf der Lena (Kyusyur Pegel). 1: jährliche Sedimentfracht; 2: Sedimentfracht gemittelt über die Saison der Schneeschmelze; 3: Sedimentfracht gemittelt über die Saison Sommer–Herbst; 4: rote Quadrate stehen für die Jahre, für welche die Daten wiederhergestellt worden sind.

errors of field measurements. The correlation ratio between monthly values of Q and Q_s is higher compared to the correlation ratio between annual water runoff and SSL, especially for the ice-free period.

The dependency between monthly Q and Q_s can be characterized as nonlinear ($Q_s \approx aQ^b$) and changes after 1987. In 1960–1987, $a = 9.65 \cdot 10^{-7}$, b = 1.98 ($r^2 = 0.78$) for the period of May–June, and $a = 1.56 \cdot 10^{-9}$, $b = 2.6$ ($r^2 = 0.80$) for the months of July–October (Magritsky 2015). In 1988–2010, $a = 5.35 \cdot 10^{-6}$, $b = 1.8$ ($r^2 = 0.92$) for the period of May–June and $a = 1.09 \cdot 10^{-6}$, $b = 2.02$ ($r^2 = 0.60$) for the period of July–October.

The increase of the $W_{s,y}$ is mainly attributed to the summer–autumn season (Fig. 4b). This tendency can be explained by the fact, that during this season the SSC in permafrost zone is sensitive not only to an increase in the amount of precipitation and water discharges, but also to the increase of air and river water temperatures. This results in the weakening of hardness of frozen soils and the development of erosion processes (Costard et al. 2003). The intensity of such processes increases with the growth of volumetric ice content of perennially frozen rocks and the presence of buried ices, which is a distinctive feature of the banks of the lower Lena (Protasieva 1972). Therefore, according to the field measurement data, the high values of SSC and its increase along the lower Lena are observed downstream the mouth of the Aldan River and especially the Vilyuy River (Rachold et al. 1995, Charkin et al. 2009, Magritsky 2015). Another confirmation of our findings and conclusions is the results of the study dedicated to the long-term dynamics of the islands near the Yakutsk city by (Gautier et al. 2011). The authors compared satellite images for the period 1967–2002 and showed that since 1992 the abrasion rate of the shores of islands in the middle part of the Lena riverbed has increased by 29 %, and of the islands near the bank of the Lena River has increased by 21-22 %. The SSL at the Kyusyur station has increased by 30 % since this period of time (Magritsky 2015). At the same time, it was in the late 1980s when the final shifting of the SSC measurements position took place.

As a result, the share of the high-water period in annual SSL decreased from 82.7 % in 1936, 1944 and 1960–1987 to 64.8 % in 1988–2010, and the share of the summer–autumn season increased from 16.8 to 34.9 %. The data series homogeneity of summer–autumn SSL has been disrupted since 1988 both for dispersion (*F-test* (+)) and for the average value (U-*test* (+)). The anthropogenic contribution to the long-term changes of sediment flux of the lower Lena is negligible small.

The annual heat flux ($W_{\theta,y}$) of the Lena River is very high (Tab. 1) despite the rather low values of stream temperatures (θ_{VI} ~5.1, θ_{VII} ~14.2, θ_{VIII} ~12.6 and θ_{IX} ~6.1 °C for 1935–2012) and the fact that the period of the year with $\theta \geq 0.2$ °C (on average from June 4 to October 13) is very short. A huge water runoff and the increased relative water runoff particularly during the season with high values of water temperature (θ) enables this phenomenon. The leading role of water runoff is also indicated by the close relation between W_y and $W_{\theta,y}$ ($r \approx 0.73$). A still more reliable correlation can be obtained by entering the mean water temperature ($r \approx 0.85$) into the equation:

$$W_{\theta,y}(kJ \cdot 10^{15}) = 0.028W_y + 1.416\bar{\theta}_{\mathrm{VI-IX}} - 12.9. \qquad (2)$$

where $\bar{\theta}_{\mathrm{VI-IX}}$ is the average water temperature over the period from June to September. Note that there is a stable relation ($r \approx 0.81$) between $\bar{\theta}_{\mathrm{VI-IX}}$ and the corresponding air temperatures ($\bar{t}_{\mathrm{VI-IX}}$):

$$\bar{\theta}_{\mathrm{VI-IX}}(\mathrm{Kyusyur}) = 0.584\bar{t}_{\mathrm{VI-IX}}(\mathrm{Zhigansk}) + 0.231\bar{t}_{\mathrm{VI-IX}}(\mathrm{Kyusyur}) + 1.19. \quad (3)$$

This relation (and similar dependencies for separate months) is much more reliable and precisely than shown in the paper (Liu et al. 2005).

However, the calculated value of $W_{\theta,y}$ (Tab. 1), is, perhaps, understated in view of the insufficient representativeness of data on θ. This issue is covered in detail below.

The highest heat flux is naturally for the summer months, 23.7 %, 39.7 % and 24.9 % of the total annual heat flux are attributed to June, July and August respectively. 10.9 % and 0.8 % accrue in September and October, respectively and 0.1 % accrues in May. In the long-term scale, heat flux of the Lena River increases (Fig. 5) with increased water runoff and stream temperature (Alexeevsky 2007, Evseeva et al. 2004, Magritsky 2009, Fofonova et al. 2016, Liu et al. 2005). During the observation period the water temperature in June and August increased by

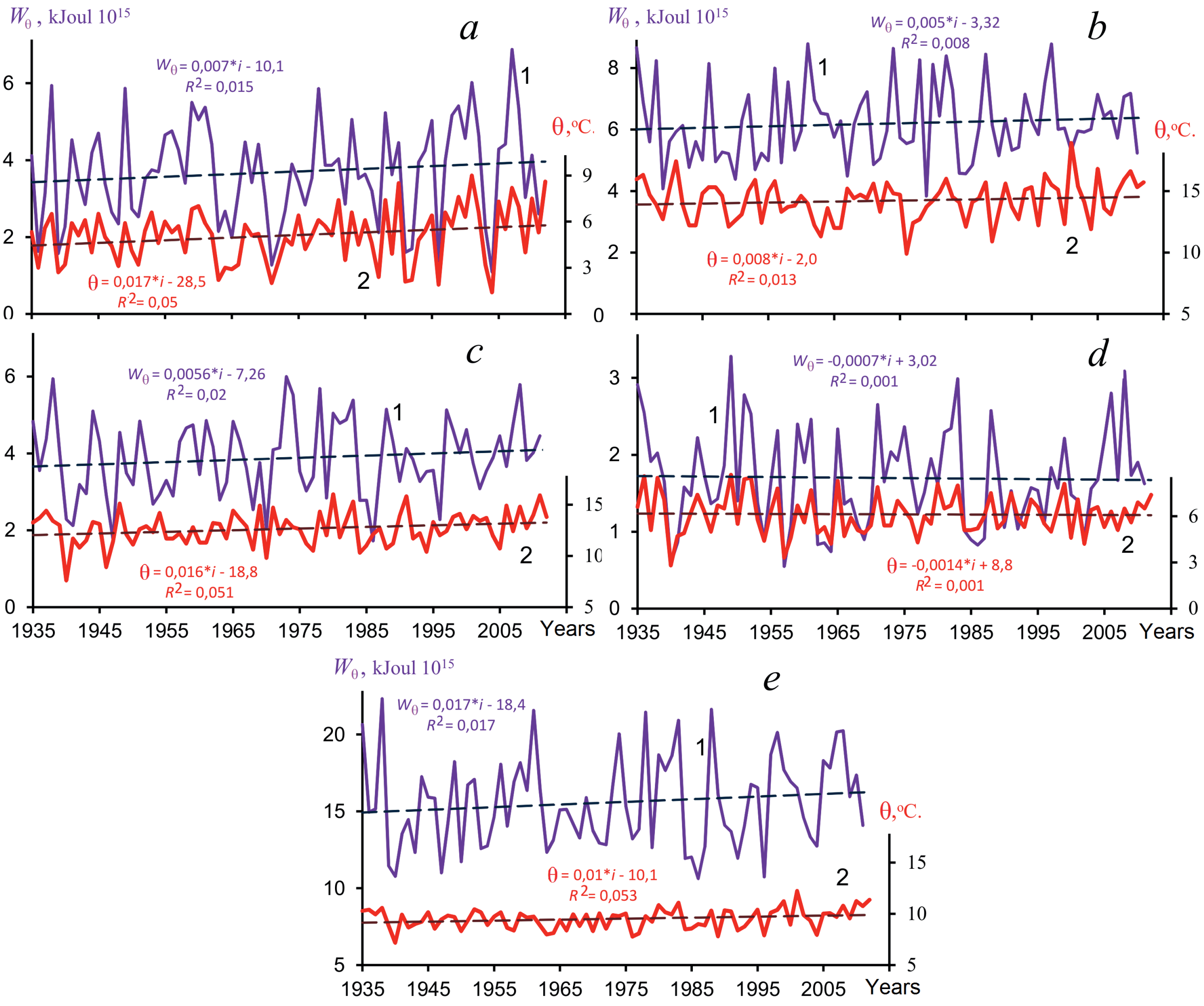

Fig: 5: Long-term changes of the heat flux (1) and mean water temperature (2) of the lower Lena (gauge Kyusyur) with the linear trends and a trend equation for: *a*. June, *b*: July, *c*: August, d: September, and *e*: year (1) and navigable season VI–IX (2).

Abb. 5: Langzeitliche Wärmefluss-Schwankungen (1) und mittlere Wassertemperatur (2) der unteren Lena (Pegel Kyusyur) mit linearen Trends für *a*: Juni; *b*: Juli; *c*: August; *d*: September; *e*: Jahr (1) und schiffbare Zeit Juni bis September.

1.33 and 1.25 °C (Fig. 5a, c). In September, October the water temperature decreased by approximately 0.1 °C (Fig. 5d). The decrease of September and October mean temperature was also found at gauges Verkhoyanskiy Perevoz and Tabago in the lower reaches of the Olenek River.

Before 1980, the value of $W_{\theta,y}$ according to gauge measurements and their processing by the authors, had been $15.26\cdot10^{15}$ kJ, and in 1980–2012, $W_{\theta,y}$ increased to $16.04\cdot10^{15}$ kJ, mainly due to summer months impact. At the same time, the duration of the period with $\theta \geq 0.2$ °C increased by 8 days.

The thermal state of the river changes noted in the lower reaches of the Lena River may be related to the operation of the Vilyuy reservoirs (Evseeva et al. 2004, Magritsky 2015), mainly, due to the change of the water regime of the lower Vilyuy. The maximum contribution of anthropogenic heat flux changes of the lower reaches of the Vilyuy River to the total and long-term changes of the heat flux of the Lena River lower stream can reach 85 % in June, 20-25 % in July–August and 18 % for annual values. These estimates were obtained by comparing values of heat flux of the Vilyuy River for 1947–1957 (I), 1973–1980 and 1988–1992 (II). These two periods have similar climatic and hydrological parameters with respect to the Vilyuy River basin. Therefore, changes in the heat flux at the mouth of the Vilyuy River, obtained as a difference between the heat flux values for these periods, maximally represent the magnitude of the anthropogenic impact. However, the heat flux balance for the section from the mouth of the Vilyuy River to the basin outlet station of the Lena River was not calculated.

Distribution of water runoff over the channel network of the delta

The main transformation of water runoff in the Lena River delta is caused by its distribution over the branches and in the form of floodplain streams. The distribution of the river runoff begins at the delta head – near the Tit-Ary Island. It is distributed between a small Bulkurskaya branch that flows off to the left and the Main channel of the Lena River. The features of this distribution can be assessed by the continuous monitoring at the hydrometric cross-section "4.7 km upstream the Stolb Island" (at the end of the Main channel) and four measurements of Q in the mouth of the Bulkurskaya branch (Fig. 1).

The latter measurements were performed in the summer and the autumn of 2004–2006 by the participants of the project "The Natural System of the Laptev Sea" (Bolshiyanov et al. 2013, Fedorova et al. 2009). The data processing showed that less than 1 % of water runoff at the delta head comes to the Bulkurskaya branch with the discharges <45,000 m^3/s at Kyusyur gauge (Q_K) (Tab. 2). When Q_K <20,000-25,000 m^3/s, the branch stops functioning at all. With an increase in the water runoff of the Lena River the percentage of the Bulkurskaya branch increases sharply (to 6 % and above). These estimates are close to the previous assessments (Korotaev et al. 1990), but reflect the changes of the channel runoff only, i.e. without the floodplain component. The water regime of the Bulkurskaya branch is influenced, apart from the water runoff, by the water level in the Olenekskaya branch and ice phenomena. In the long-term, the increase in the share of the Main channel flow, calculated as ~0.9 %/10 years (Fig. 6), points to its intensification and to the gradual destruction of lateral streams in this part of the delta. This tendency enhanced after the passage of extremely high flow discharge in 1989 (Q_{max} = 220,000 m^3/s).

The comparison of the total flow discharge of the Bulkurskaya branch and the Main channel (Q_{HD}) with the discharge at the Kyusyur station (Q_K) shows that in most cases, the values of these discharges are unequal (Tab. 2). Moreover, with an increase in discharge in the river, the negative values ΔQ (= Q_{HD}-Q_K) are replaced by positive ones. There are several reasons for this discrepancy; for example, the insufficient quantity or accuracy of measurements, especially with very

Lena River		Head of delta			Main delta branch point						
Kyusyur gauge		Main channel, 4.7 km upstream Stolb Island **	Bulkurskaya branch, mouth	Discrepancy ΣQ_i (towards Q at Kyusyur gauge)	Bykovskaya branch source, polar station Yu.A. Khabarova (Stolb)		Trofimovskaya branch source	Tumatskaya branch source	Olenekskaya branch downstream the confluence with Bulkurskaya branch	Discrepancy ΣQ_i (towards Q at gauge), rounded off	
										Kyusyur	4.7 km upstream Stolb Island
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	%	%
open channel period*											
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*	–	–	–	–
freezing-over period											
1000	*170*	900	–	-10	220	*55*	850	*0*	*0*	*7.0*	*19.0*
2000	*250*	1800	–	-10	310	*70*	1500	*0*	*0*	*-9.5*	*0.5*
3000	*340*	2700	–	-10	510	*100*	2150	*~0*	*~0*	*-11.5*	*-1.5*
4000	*415*	3750	–	-6	700	*140*	2850	*20*	*60*	*-9.0*	*-3.0*
5000	*505*	4400	–	-12	900	*170*	3200	*60*	*110*	*-14.5*	*-3.0*
7000	*655*	6600	–	-6	*1500*	*280*	4600	*190*	*270*	*-6.5*	*-0.5*
10000	*750*	10000	–	0	*2450*	*350*	6850	*400*	*480*	*2.0*	*2.0*
15000	***	15500	–	3	*3750*	–	*10400*	*730*	*840*	*5.0*	*1.5*
20000	–	22000	–	10	*5400*	–	*14400*	*1100*	*1250*	*11.0*	*0.5*

Tab. 2: Distribution of flow discharges in the Lena River delta head area based on the data of the stationary measurements performed in 2001–2007 (from Hydrological Year-books, PANGAEA, web source, Bolshiyanov et al. 2006, 2013, Fedorova et al. 2009). Notes *: data not be applied to the period of high-water wave rise; **: for the relation to gauge Kyusyur and taking into account a time lag of 1 to 3 days; ***: dashed figures mean lack of data or their unreliability. Very approximate data, especially for the freezing period, in view of the ambiguity of relation, are put in italics.

Tab. 2: Verteilung der Abflussmenge im landseitigen Bereich des Lena Delta auf der Basis von Pegelmessungen von 2001 bis 2007 (aus Hydrologischen Jahrbüchern, Weltdatenzentrum PANGAEA, Bolshiyanov et al. (2006, 2013), Fedorova et al. 2009). Beachte: * Daten gelten nicht für die Zeit der Hochwasserwelle; ** im Vergleich zum Pegel Kyusyur unter Berücksichtigung einer zeitlichen Verzögerung von 1 bis 3 Tagen; *** Gedankenstrich markiert fehlende oder unrealistische Daten; *kursiv* dargestellt sind ungefähre Daten, was speziell für die Frostperiode gilt.

high Q, the influence of ice phenomena, the regulating role of the inundated floodplain, etc. (Ivanov et al. 1983, Magritsky 2001). There are three levels of floodplain in the Lena River delta: the old, the mature and the young one, and also various channel forms bared during the low-water period (Korotaev et al. 2007, Bolshiyanov et al. 2013). The heights of these floodplains over the mean low-water level in the branches are 10 (to 12 m), 3-5 and less than 3 m, correspondingly. With the annual water level rise at Tit-Ary gauge station during the high-water period of more than 10-11 m the low and middle floodplains are flooded, and the higher land areas are flooded in 80 % of years. As a result, part of the river waters is flows through the floodplain of the Bulkurskaya branch and the Main channel (Fig. 7). Only a few hundred meters of the right bank floodplain are flooded. The floodplain runoff is hardly involved in gauge measurements, though it can be roughly estimated in accordance with discrepancy value. Furthermore, the disruption of channel water balance may be due to the snow melting and a large amount of ice accumulating on the delta floodplain (Antonov 1960, 1967, Ivanov et al 1983, 1995). Therefore, strictly speaking, neither the water discharge in the Main channel, nor the total discharge of the branches can be taken as the Q coming to the delta.

The water runoff of the Main channel at the Stolb Island is distributed among the Bykovskaya, Trofimovskaya, Tumatskaya and Olenekskaya branches (Fig. 1). The continuous measurements at their sources were performed during the period from 1977 to 2007. Comparing the Q of each of the branches to their sum ($\sum_{i=1}^{4} Q_i$), the current proportion of runoff of the navigable Bykovskaya branch for the average conditions of summer–autumn navigable season is about 26.2 % (1990–2007), Trofimovskaya 58.8 %, Tumatskaya 7.4 %, Olenekskaya (together with the runoff of the Bulkurskaya branch) 7.6 % (Tab. 3). Thus, the greater part of river waters comes to the eastern part of the delta.

This ratio changes due to the intra-seasonal fluctuations of Q of the Lena River and the differences in the reaction of hydraulic resistance of the branches and their systems to these fluctuations. The share of the Trofimovskaya branch decreases from 72.3 % of $\sum_{i=1}^{4} Q_i$, (with Q_K =10,000 m^3/s) to <50 % (with Q_K=140,000 m^3/s), whereas the share of the Bykovskaya, Tumatskaya and Olenekskaya branches, on the contrary, increases from 21.3 %, 2.1 % and 4.3 % to 27.8 %, 10.7 % and 11.6 % respectively (Tab. 2). The intra-annual distribution of mean seasonal water discharges in the largest

Hydrometric section	Spring–summer high water season (V-VII)			Summer–autumn season (VIII-X)			Winter season (XI-IV)			Navigable season (VI-IX)			Year		
	%_Yr	%_Kyus	%_ΣQ_i	%_Yr	%_Kyus	%_ΣQ_i	%_Yr	%_Kyus	%_ΣQ_i	%_Yr	%_Kyus	%_ΣQ_i	%_Yr	%_Kyus	%_ΣQ_i
1977 – 1989															
Kyusyur gauge	59.6	100		32.2	100		8.2	100		81.5	100		100	100	
Main channel, 4.7 km upstream Stolb Is.	57.3	85.4		33.8	93.2		8.9	97.1		81.3	88.7		100	88.9	
Bykovskaya branch source	61.1	24.3	26.8	32.4	23.9	24.8	6.5	19.0	19.9	84.8	24.7	26.3	100	23.7	25.5
Trofimovskaya branch source	54.6	52.1	57.3	35.0	61.8	64.3	10.4	72.5	75.7	79.6	55.6	59.1	100	56.9	61.2
Tumatskaya branch source	72.4	7.3	8.0	26.4	4.9	5.1	1.2	0.9	0.9	92.4	6.8	7.2	100	6.0	6.5
Olenekskaya branch downstream confluence with Bulkurskaya branch	67.4	7.2	7.9	28.5	5.6	5.8	4.1	3.2	3.4	89.1	7.0	7.4	100	6.4	6.8
1990 – 2007															
Kyusyur gauge	59.0	100		31.7	100		9.3	100		78.3	100		100	100	
Main channel, 4.7 km upstream Stolb Is.	57.7	92.5		33.2	98.8		9.1	92.1		78.5	94.8		100	94.5	
Bykovskaya branch source	62.4	26.9	26.7	31.2	25.0	24.8	6.4	17.5	19.4	82.1	26.7	26.2	100	25.4	25.5
Trofimovskaya branch source	55.4	57.0	56.7	33.7	64.6	64.1	10.9	70.8	78.2	77.1	59.8	58.8	100	60.7	60.9
Tumatskaya branch source	73.5	8.3	8.3	25.3	5.3	5.3	1.2	0.9	1.0	88.3	7.5	7.4	100	6.6	6.7
Olenekskaya branch downstream confluence with Bulkurskaya branch	71.3	8.3	8.3	27.0	5.9	5.8	1.7	1.3	1.4	87.3	7.7	7.6	100	6.9	6.9

Tab. 3: The relative distribution of flow discharges in the lower Lena and Lena River delta head during the year (%_Yr) in comparison with the discharges at Kyusyur gauge (%_Kyus) and in the delta head (%_ΣQ_i).

Tab. 3: Die relative jährliche Verteilung des Abflusses (%_Yr) in der unteren Lena und im Lena Delta im Vergleich mit dem Pegel Kyusyur (%_Kyus) und dem Kopf des Deltas (%_ΣQ_i).

Trofimovskaya and Bykovskaya branches are close to the distribution at Kyusyur gauge station (Tab. 3).

The differences between the data presented in Table 2, which characterize the distribution of water runoff in 2001–2007, and the data presented in (Ivanov et al. 1983, 1995, Korotaev et al. 1990, Magritsky 2001) that were calculateed for the period up to 1990 should not be considered high: for the Trofimovskaya and Bykovskaya branches, the relative difference between the values is on average +1.5 to +5 %; for the Tumatskaya and Olenekskaya branches it varies from -4 to +20 %.

Due to high flow discharges and huge ice jams, and therefore high-water levels, a part of the water runoff passes through the floodplain. This particular runoff is badly taken into account by the measurements at hydrometric cross-sections. The inundation of the Bykovskaya branch's left-bank floodplain starts at the water level over 240 cm at gauge station Yu.A. Khabarova, and at levels over 600 cm the Bykovskaya branch in fact merges with the neighboring Trofimovskaya branch, forming a continuous flooded area up to ten kilometers wide (Fig. 7). For the high-water period of 2008, and according to processed satellite images of "Landsat-7" retrieved from the U.S. Geological survey (web source) the relation between the water levels at Yu.A. Khabarova gauge (H_{St}) and the flooding area in the near-to-head part of the delta (F_{fl}) is approximately described by the empirical formula:

$$F_{fl}(km^2) = 0,71*H_{St}(cm)+70 \qquad (4)$$

The widths of floodplain streams of the Olenekskaya and Tumatskaya branches are minimal.

Comparing the present-day water runoff distribution (Tab. 2) to that of 1951–1953 (Antonov 1960, 1967, Ivanov et al. 1983), we see that the runoff shares of the Bykovskaya and Trofimovskaya branches have increased by 0.9 % and 0.4 % (with $Q_K(p = 50\ \%) = 31{,}600\ m^3/s$), the Tumatskaya branch by 0.6 %, while the Olenekskaya branch, on the contrary, decreased by 1.9 %. However, very low rates of the long-term water runoff redistribution were obtained analyzing the long-term fluctuations of annual runoff in these branches over the more reliable period of continuous observations from 1977 till 2007 (Fig. 6). Note that the discharge measurements were episodic in 1953–1955 and it is reliably unknown where they were carried out. A change in runoff share of the Trofimovskaya branch in the period from 1977 till 2007 is only 0.27 % per 10 years (*SRCC* = -0.20 (–) with $p = 0.2\ 6 > \alpha = 0.05$), and the Bykovskaya, Olenekskaya and Tumatskaya branches have about +0.01 (*SRCC* = -0.04 (–), $p = 0.83$), +0.09 (*SRCC* = 0.18 (–), p = 0.33) and +0.17 % per 10 years (*SRCC* = 0.2 (–), $p = 0.12$) respectively. On the contrary, the long-term fluctuations of W_y in the considered branches for the period from 1977 till 2007 have statistically significant linear trends (Fig. 6).

The redistribution of water runoff between the branches in the delta of the Lena River, taking into account its enormous size and location, can be due to not only hydro-morphological causes, but also to the movements of the earth's crust (Are & Reimnitz 2000, Bolshiyanov et al. 2013, Polyakova et al. 2009). In the last 9,000 years, neotectonics had a high impact on an increase of the role of some branches and a temporary decrease of the role of others (Polyakova et al. 2009). Additional possible factor of influence is a periodic dredging activities in the navigable Bykovskaya branch.

The waters of the main delta branches are distributed among thousands of streams of different sizes in the mouth area. There is a little information on this spatial transformation, and the available data are the result of episodic field studies. According to such data as (Korotaev et al. 1990), the water runoff in the Olenekskaya branch upstream from the site where the Angardam-Uese branch flows off (to the left; Fig. 8a) does not almost change (~100 %). Downstream the discharges decrease by 53 % (with Q_{HD} ~34,000 m^3/s). However, after the influx of the Ardynskaya branch (on the right) the runoff of the Olenekskaya branch increases again (up to 75 % of the

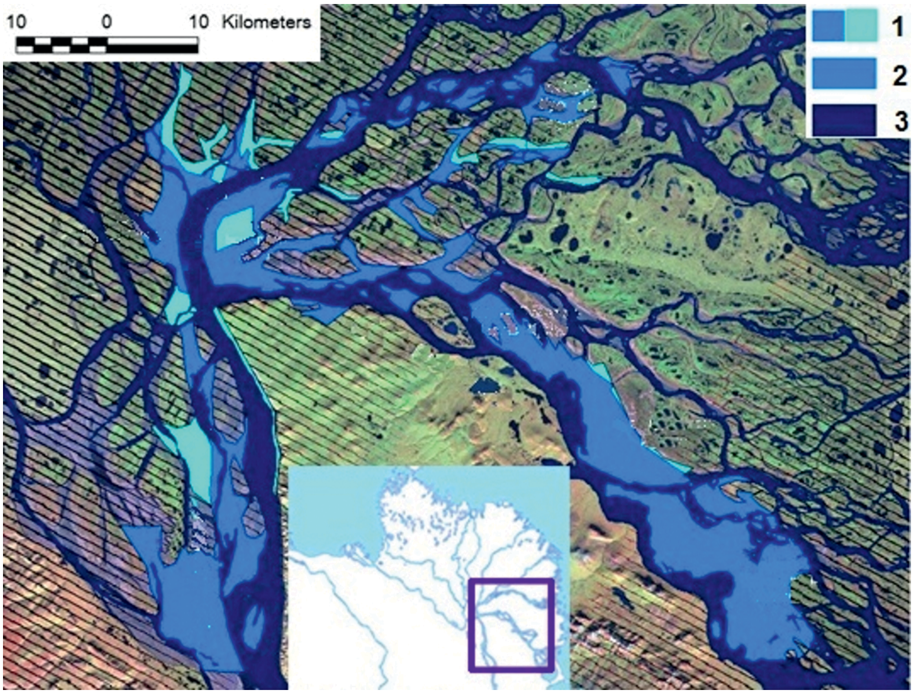

Fig. 7: A schematic map of flooded areas at the peak (1: 05/30/2008) and fall (2: 06/24/2008) of snowmelt flood wave; 3: indicates channel borders during the low-water period.

Abb. 7: Schematische Karte überfluteter Gebiete zum Höhepunkt (1: 30. Mai 2008) und Ende (2: 24. Juni 2008) der Flutwelle der Schneeschmelze; 3: markiert die Flussarme während der Niedrig-Wasser-Periode.

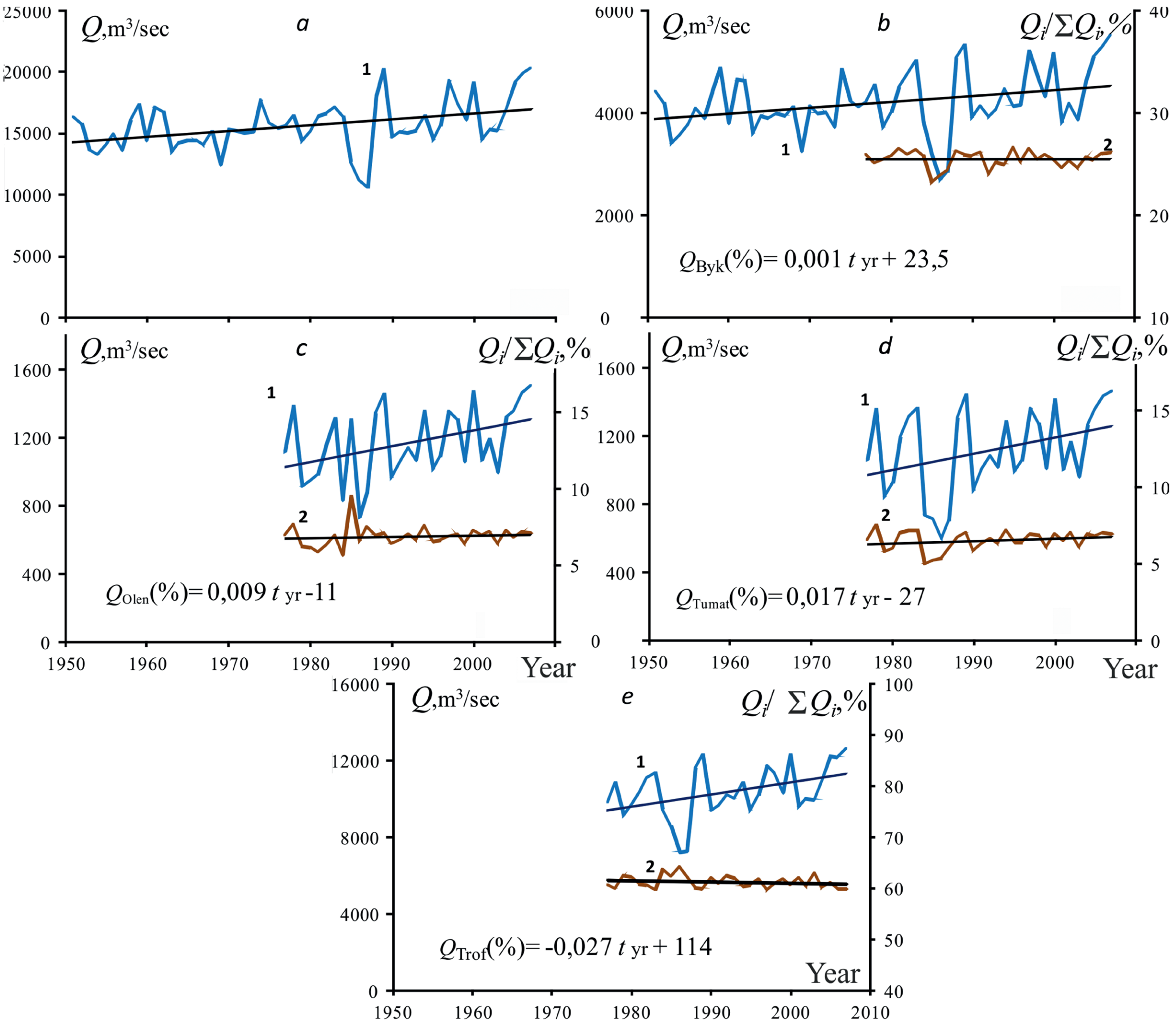

Fig. 6: The long-term changes of the absolute (1) and relative (2) values of the water runoff in the Main channel (a), at the sources of the Bykovskaya (b), Olenekskaya (c), Tumatskaya (d) and Trofimovskaya (e) branches of the delta with linear trends and a trend equation (in case of change of proportion of the branch runoff).

Abb. 6: Langzeitliche Veränderungen der absoluten (1) und relativen (2) Werte des Abflusses im Hauptkanal (a), am Beginn des Bykovskaya Kanals (b), des Olenekskaya Kanals (c), des Tumatskaya Kanals (d) und des Trofimovskaya Kanals (e) im Delta mit linearen Trends einer Trendgleichung (für den Fall einer Änderung der Verhältnisse im Abflusses des Deltakanals).

previous value). Downstream it gradually decreases again and is equal to ~65 % in its mouth. The increase in the share of the Angardam-Uese branch up to 65-75 % by the year 2000 (with Q_{HD} ~30,000 m³/s) and practically the termination of navigation in the Olenekskaya branch indicates the stepwise withering away of its end section (FEDOROVA et al. 2009, BOLSHIYANOV et al. 2013).

In the past, only 6 % of the runoff from the source of the branch reached the mouth of the Tumatskaya branch; it gave 59 % of its water to the Arynskaya branch and a considerable part to the system of the Vasilyevskaya branch (KOROTAEV et al. 1990). At the beginning of July, 2006, during a rain flood at the fall of high-water wave with Q_{HD} ~60,000 m³/s, the discharges in the Bol'shaya Tumatskaya and the Osokhtoh branches at a distance of 51 km, 91 km, 114 km and 148 km from the source of the Tumatskaya branch were equal to 20 %, 29 %, 25 % and ~15 % of the initial value (BOLSHIYANOV et al. 2013; see Fig. 8b).

About 90 % of the water runoff remained 25 km from the source of the Trofimovskaya branch (KOROTAEV et al. 1990). Downstream, it was distributed between the Bol'shaya Trofimovskaya and the Sardakhskaya branches at a ratio of 41 % and 49 %. Bol'shaya Trofimovskaya branch gave part of the runoff to the Burchah (22 %), Malaya Trofimovskaya, and the Davyda branches (12 % in total) (see Fig. 8c).

The Bykovskaya branch gave part of the water runoff to the Kyuryuyollekh and the Byrdaktaakh branches (40 % in total with H_{St} = 600 cm), and also to the Sinitsyna and the Gerasimova branches flowing into the Neelova Bay (10 %) (Ivanov et al. 1983 KOROTAEV et al. 1990). Only about 33 % reached the mouth of the Bykovskaya branch, where it is called the Ispolatova branch (see Fig. 8d).

Unfortunately, the above-obtained estimates of water runoff transformations along the channel from the sources of the main branches to their mouths provide rough clues to the actual

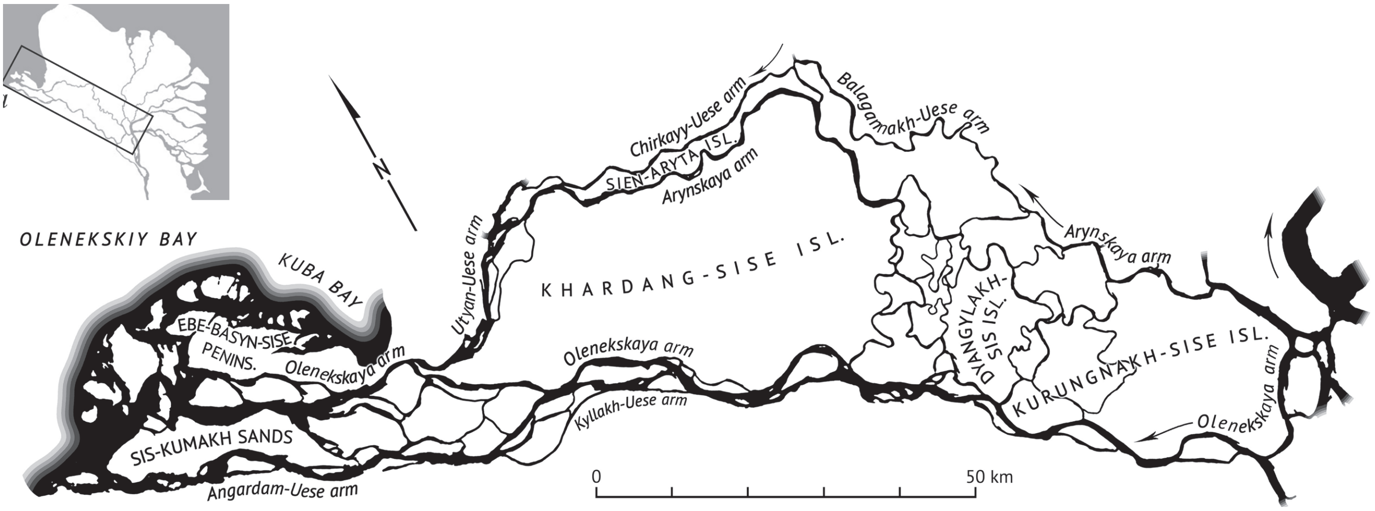

Fig. 8a: Detailed scheme of river channel systems of Oleneksky deltoid branch.

Abb. 8a: Ausführliches Schema des Flussverlaufes im Bereich des Oleneksky Kanals.

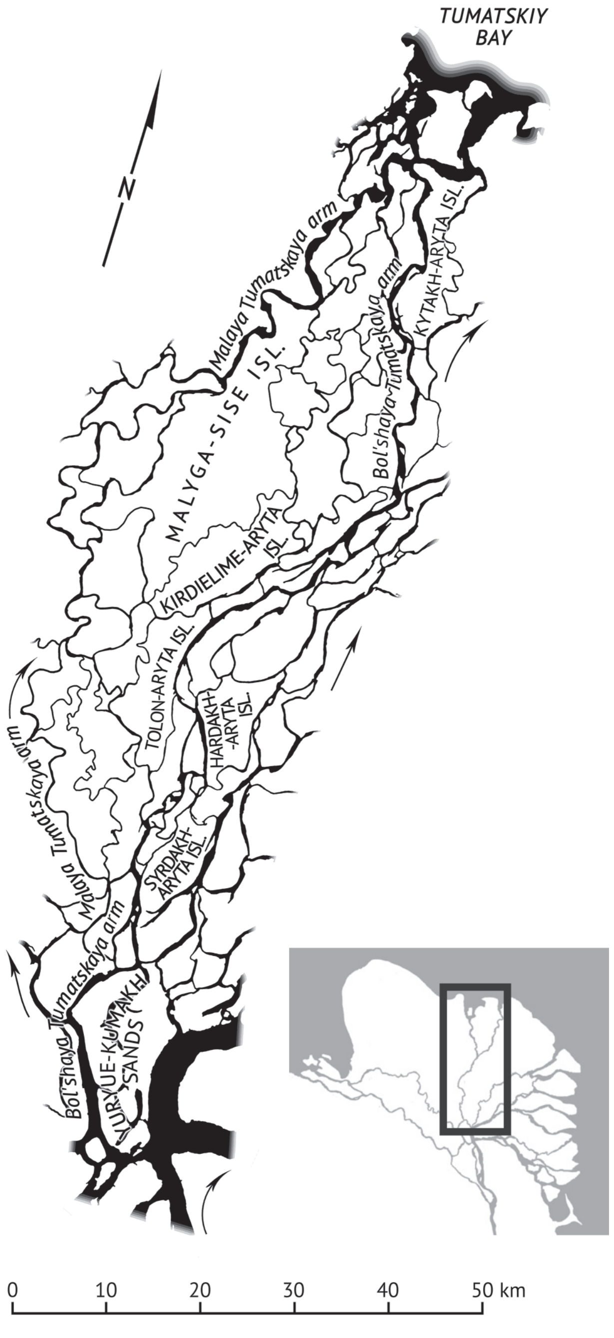

Fig. 8b: Detailed scheme of channel systems of Tumatsky deltoid branch.

Abb. 8b: Ausführliches Schema des Flussverlaufes im Bereich des Tumatsky Kanals.

conditions because of the active change in delta watercourses, in its bifurcation and merge points (Fig. 9). The expeditionary measurements, usually performed upon the same water discharge only once, were neither broad in scope nor well synchronized even for the elements of a small branch system. The water runoff distribution in the large Sardakhskaya branch point is an example of the instability of runoff distribution between the branches. In the first half of the 1980s, between 35 and 50 % of the runoff of the Trofimovskaya branch (with its *Q* from 1500 to 20,000 m^3/s) (Fig. 10) discharged to the Bol'shaya Trofimovskaya branch, according to the fund materials of the Tiksi Center of Hydrometeorology and Monitoring of Environment. The other part discharged into the Sardakhskaya branch. In 2001–2002, the share of the Bol'shaya Trofimovskaya branch reduced to 30-40 % (Bolshiyanov et al. 2006), which was caused by active channel reformation in the Sardakhskaya branch point (Bolshiyanov et al. 2006, 2013, Fedorova et al 2015, Korotaev et al. 1990, (Fig. 9)).

The solution to this problem for such large and braided deltas is seen in the wide use of indirect calculation methods. For example, the duct width can be an indicator of the flow rate considering additionally easily accessed information about the water discharge in the delta head and conditional order of the watercourses. An exception is the seaside channels in the area of strong influence of periodic and non-periodic fluctuations of sea level. The stream width is easily and precisely determined using maps and satellite images. This work has been performed for the Lena River delta and 75 largest elements of its channel network (Alexeevsky et al. 2014). Another example is an approach presented in Ivanov & Piskun (1995) and Krylova et al. (2014), it is based on solving Saint-Venant equations in one-dimensional approximation using representation of the Lena Delta system of the channels as a "tree"-type graph and assuming some morphology characteristics of the channels and behavior of the elevation.

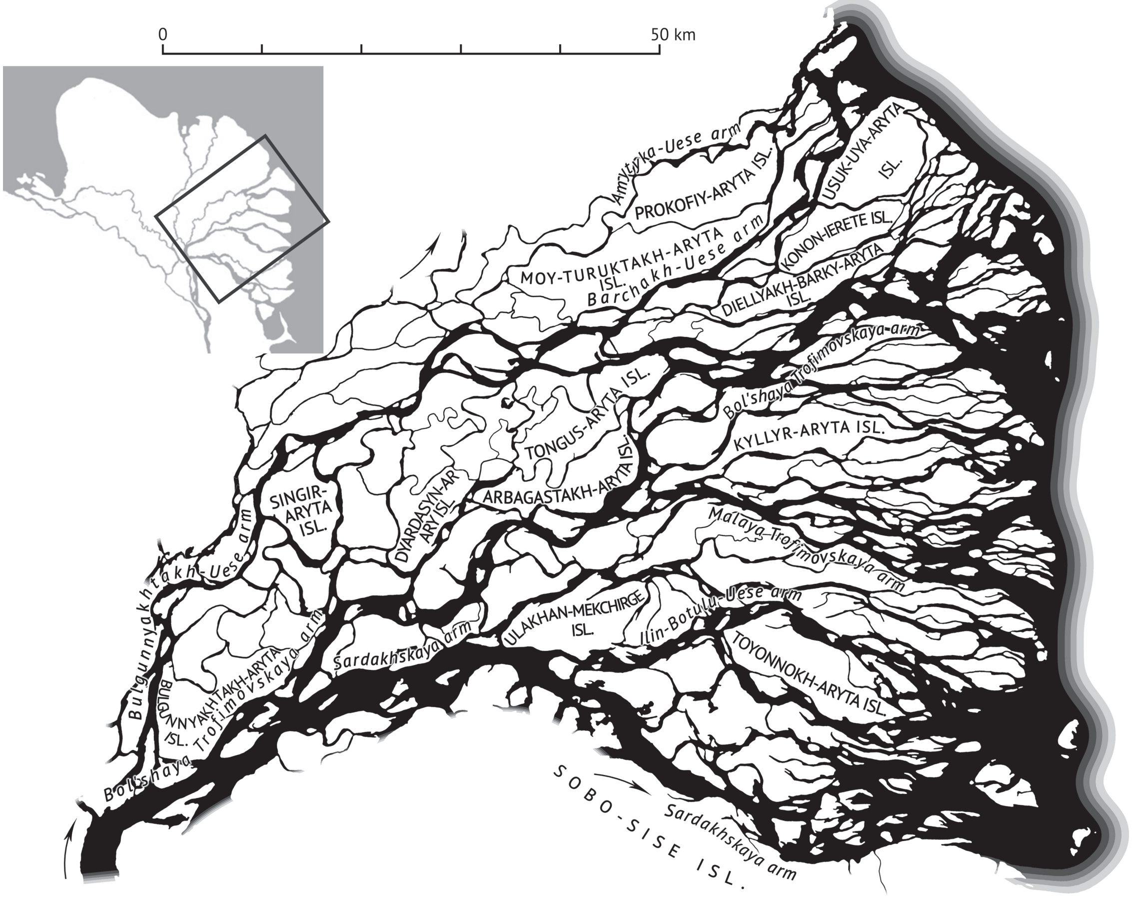

Fig. 8c: Detailed scheme of channel systems of Trofimovsky deltoid branch.

Abb. 8c: Ausführliches Schema des Flussverlaufes im Bereich des Trofimovsky Kanals.

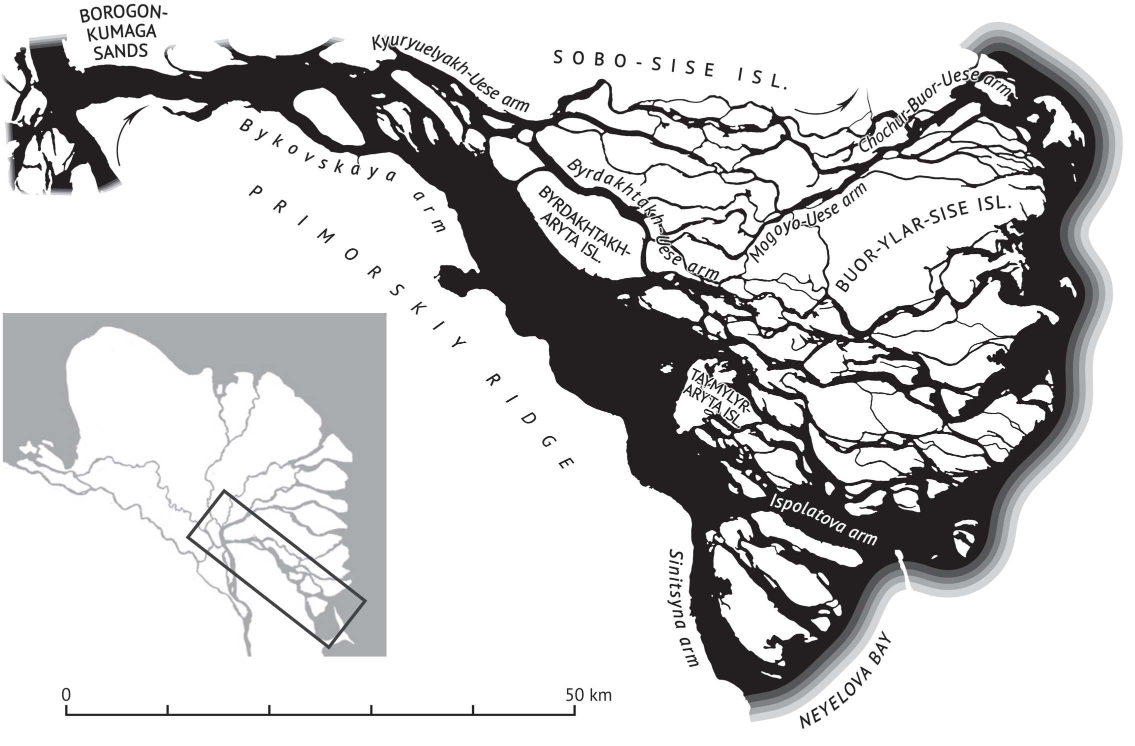

Fig. 8d: Detailed scheme of channel systems of Bykovsky deltoid branch.

Abb. 8d: Ausführliches Schema des Flussverlaufes im Bereich des Bykovsky Kanals.

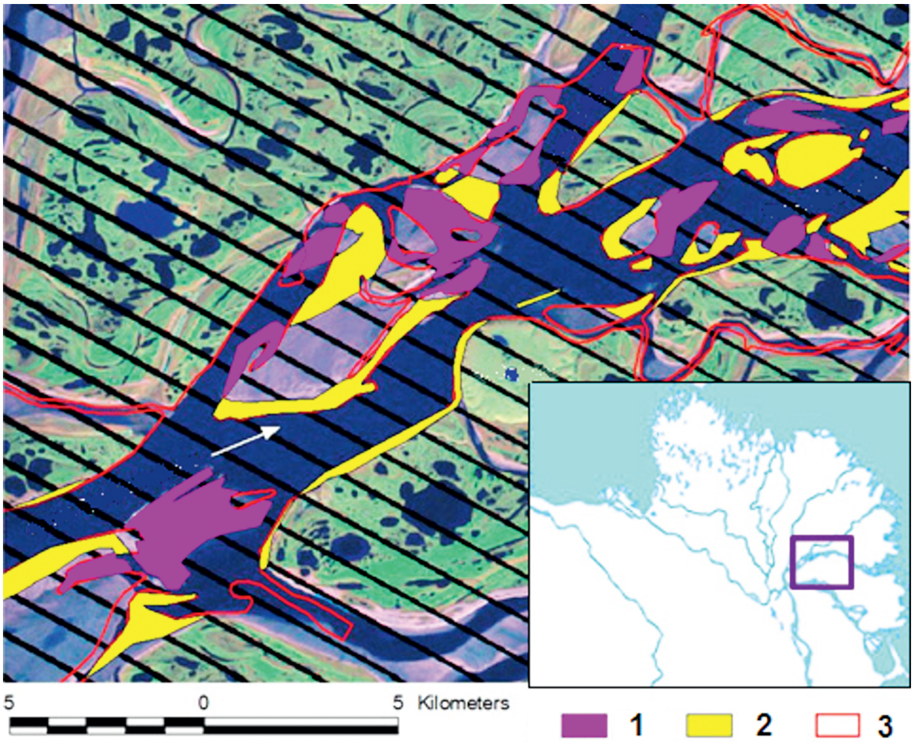

Fig. 9: Channel reformation in the Sardakhskaya branch point over the period of 1981–2007. 1: areas of sediment accumulation; 2: areas of erosion of the banks and islands, 3: channel border in 1981.

Abb. 9: Neugestaltung der Flussarme im Delta am Sardakhskaya Kanal in der Zeit 1981–2007. (1): Bereiche mit Sediment-Akkumulation; 2: Gebiete mit Erosion von Sandbänken und Inseln; 3: Uferlinie im Jahr 1981.

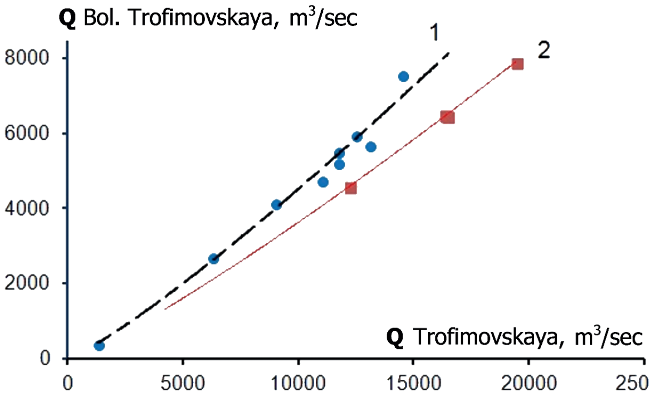

Fig. 10: Changes of water runoff distribution of the Trofimovskaya branch between the Bol'shaya Trofimovskaya and the Sardakhskaya branches. 1: 1982–1985; 2: 2001–2002.

Abb. 10: Veränderung des Wasserabflusses im Trofimovskaya Kanal zwischen dem Bol'shaya Trofimovskaya und dem Sardakhskaya Kanal in den Jahren (1): 1982–1985 und (2) 2001–2002.

Spatial transformation of sediment yield in the delta

Results of long-term observations at the hydrometric cross-section "4.7 km upstream the Stolb Island" (or "4.7 km") and expeditionary measurements in the Bulkurskaya branch demonstrate the specific features of the regime and distribution of SSL in the near-to-head part of the delta. As the hydrometric cross-section is located 70-80 km from the place of the river outfall from the "Lenskaya truba", part of the suspended sediments is deposited on the way. Therefore, SSC on the high-water wave fall (in July) is about 17.5 % less than that at Kyusyur gauge, and in August–September it is 42 % less and the average annual SSC is 14.5 % less. At the rise and at the peak of the high-water wave, the SSC value between Kyusyur and "4.7 km" remains almost the same. As a result, the annual SSL in the Main channel is ~79 % of its value at Kyusyur gauge. The role of the Bulkurskaya branch is relatively low. The share of its sediment load does not exceed 1 % with Q_{HD} <50,000-55,000 m^3/s. It increases under the exponential law with an increase of Q in the river (Tab. 4). The long-term fluctuations of the SSL in the section "4.7 km" have the same regularities as at Kyusyur gauge. For example, it has significantly increased since 1988: by 6,900,000 tons per year in comparison with 1951–1953 and 1967–1987. This growth provided the disruption of the former dependence $Q_s = f(Q)$ and the upward move of the curve. Within a year, currently 77 % of annual SSL account for the share of high-water period in the Main channel, 22 % of the share of summer-autumnal season and 1 % is the share of the winter low-water period.

The total annual SSL in the sources of the main deltaic branches was 109 % in average of the value of annual SSL at the hydrometric section "4.7 km", and 88 % of the value of annual SSL at Kyusyur gauge. The part of the sediment that bypasses the hydrometric section "4.7 km" along and across the floodplain and its channels during the spill of the river waters is perhaps "caught" by observations in the sources of branches. The average annual SSC of river waters was equal to 36.5 g/m^3 at the hydrometric section "4.7 km". It decreases by 1.5-2.5 times towards the marine margin of the delta. As a result, the total losses of SSL in the delta are about 40-65 %, but not 83-90 % as cited by Alabyan et al. 1995 and not 70 % as cited by Korotaev 1991. Rachold et al. 2000 also doubt the numbers about total losses of SSL in the delta given in Alabyan et al. (1995) and Korotaev (1991), but confirm conclusions about absence of natural levees along the delta branches and noticeable mud deposits on the floodplain near the riverbeds. The update of estimation of losses was provided by the results of new expeditionary measurements (Charkin et al. 2009, Fedorova et al. 2009, Gukov 2001, Korotaev et al. 1990) and a more complete use of the data received from stationary observations in the delta by the authors of this paper. The indirect confirmation of decrease in SSL in the delta is provided by the analysis of index change in water surface spectral brightness, performed by the authors upon the satellite images of the Lena River delta. The values of spectral brightness decrease by 20-40 % towards the sea.

For the main branches, the reduction of brightness reaches maximum at the estuarine coastal area, which is also confirmed by the data of field measurements (GUKOV 2001, CHARKIN et al. 2009). The changes in brightness in some sections of streams correspond to the local increase in SSC because of erosion of delta deposits. In the lower sections of delta streams, the SSC regime is disrupted under the influence of periodic and non-periodic fluctuations of the sea level. The bed load, as well as the sediments transferred by river ice, remains complete in the Lena River delta and near its marine margin.

Between the main branches, the SSL is distributed under the average values of water discharges of summer–autumn season in the following shares (Tab. 4): the Bykovskaya branch 17.2 % of the sums of SSL values in the sources of the main channels (i.e. at the Stolb Island), the Trofimovskaya branch 70 %, the Tumatskaya branch 6.7 %, the Olenekskaya branch (downstream the influx of the Bulkurskaya branch) 6.1 %. With the change in water discharges in the river within a year, this ratio changes. Despite the increase in the absolute values of SSL, the share of SSL of the Trofimovskaya branch decreases from 68 % (with $Q_{4.7km}$ = 20,000 m^3/s) to 56.4 % (with $Q_{4.7km}$ = 80,000 m^3/s) whereas the share of SSL at the Tumatskaya branch increases from 3.4 % up to 14.3 %. The Bykovskaya and Olenekskaya branches do not show any specific tendency. Thus, despite the fact that the Olenekskaya and Tumatskaya branches have the same size in a water discharge term (Tab. 2, 4), the response of Q_s to the increase in the water discharges differs in these channels. A part of these differences is explained by the errors in the data of field measurements and their processing. On average, in the period of high-water, August–October and in winter 60.7 %, 70.1 % and 84.7 % respectively (of the SSL sums in the sources of the main channels)go to the Trofimovskaya branch, i.e. considerably more as compared to the water runoff; 22.1 %, 18.5 % and 12.9 % to the Bykovskaya branch, 11.7 %, 6.4 % and 0.3 % to the Tumatskaya branch, 5.5 %, 5% and 2.1 % to the Olenekskaya branch. The significant increase in the suspended sediment load of the Lena River has caused the disruption of initial dependence of the type of $Q_s = f(Q)$ since 1988. Therefore, it is impossible to use the data from the period prior to 1988 for the analysis of the current distribution of SSL in the mentioned and other delta branch nodes. A similar conclusion is given in FEDOROVA et al. (2009, 2015). The distribution of the SSL at the Sardakhskaya branch node, according to the measurements of the Tiksi Center of Hydrometeorology and Monitoring of Environment in 1983 and 1985, occurred approximately with the same ratio as the water runoff. New measurements (since 2000) do not provide any additional information on the distribution of Q_s as they have not been synchronized. For other delta branches and nodes the data on SSC and the SSL can be found in (BOLSHIYANOV et al. 2013, FEDOROVA et al. 2009, GUKOV 2001, KOROTAEV et al. 1990).

Spatial changes of water temperature and heat flux

The water temperature (θ) of the Lena River naturally decreases along the lower reaches, the direction of which is meridional and northern. The intensity of θ decrease along the stream (for the common period of observations 1962–1991) is maximal in the lower reaches of the river in June and is 0.6-0.8 °C per 100 km (Tab. 5). In other months, it changes in the range of 0.25-0.35 °C per 100 km. But the river (up to the Laptev Sea) keeps its heating function as the temperature of river waters does not fall below 0 °C and exceeds the air temperature in July–October (Tab. 5; Fig. 11).

However, the regularity of water temperature reduction from the South to the North is regularly significantly disrupted

Head of delta			Main delta branch point			
Main channel, 4.7 km upstream Stolb Island		Bulkurskaya mouth	Bykovskaya source	Trofimovskaya source	Tumatskaya source	Olenekskaya downstream confluence with Bulkurskaya
Q, m^3/s	Q_s, kg/s	Q_s, kg/s	Q_s, kg/s	Q_s, kg/s	Q_s, kg/s	Q_s, kg/s
10,000	*60*	*~0*	*20*	*50*	*5*	*5*
20,000	300	*~0*	65	200	10	20
30,000	800	*0,5*	155	630	60	55
40,000	1450	*2,5*	290	1100	140	95
50,000	2250	*12,5*	500	1650	250	145
60,000	3150	*60*	755	2150	400	205
80,000	4900	–	1290	3150	800	345
100,000	*6900*	–	*1950*	*4200*	*1380*	*510*

Tab. 4: Current distribution of suspended sediment discharges in the upper part of the delta of the Lena River according to the gauge measurements in the open-channel period and the expeditionary measurements of the State Research Center «Arctic and Antarctic Research Institute» and St. Petersburg State University (BOLSHIYANOV et al. 2006, FEDOROVA et al. 2009) in the Bulkurskaya branch during the summer seasons of 2004-2006.

Tab. 4: Verteilung der suspendierten Sedimentfracht der Lena im oberen Deltabereich entsprechend den Pegelmessungen während der Periode offenen Wassers und die Messungen auf den Expeditionen des State Research Center „Arctic and Antarctic Research Institute" und der St. Petersburg State University (BOLSHIYANOV et al. 2006, 2013, FEDOROVA et al. 2009) im Bulkurskaya Flussarm während der Sommerperioden 2004–2006.

Gauge	Stream	Length from Zhigansk (km)	Average monthly water temperature			
			VI	*VII*	*VIII*	*IX*
Zhigansk	Lena	0	10.2	17.0	14.6	7.2
Dzhardzhan (1)	Lena	242	7.7	14.6	12.2	4.5
Siiktekh	Lena	386	7.1	15.6	13.7	6.3
Kyusyur (2)	Lena	543	4.7	13.7	12.7	6.0
Tit-Ary	Main channel	702	5.2	13.5	12.5	5.5
Khabarov (Stolb Is.)	Bykovskaya branch	754	5.6	14.7	14.0	7.7
Malyshev	Ispolatova branch	838	4.5	13.8	12.9	6.9
Sagyalah-Ary	Antipinskaya branch	887	2.6	10.5	8.4	3.2
Ebitiem	Ebitiem	–	3.7	9.6	8.4	2.8
Eremeyka	Eremeyka	–	4.3	9.7	7.2	1.8
Meteostation	**Water body**	**Coordinates**	**Average monthly air temperature**			
			VI	*VII*	*VIII*	*IX*
Zhigansk	Lena	66°46’ N 123°24’ E	11.7	16.0	12.1	3.5
Dzhardzhan	Lena	68°73’ N 124°00’ E	10.3	14.8	11.0	2.8
Kyusyur	Lena	70°41’ N 127°24’ E	7.6	12.4	9.4	1.8
Tiksi	Tiksi bay	71°35’ N 128°55’ E	2.8	7.3	6.9	1.4

Tab 5: Changes of water temperatures along the lower reaches and in the Lena River delta (over the period from 1962 to 1991), at the tributaries of the Lena River near Kyusyur gauge and the average monthly air temperatures at the meteorological stations of different latitudinal location. Note (1): Thermal regime of the hydrometric cross-section is distorted under the influence of colder waters of the Dzhardzhan River; Note (2): Thermal regime of the hydrometric cross-section is distorted under the influence of colder waters of the Ebitiem and other small rivers.

Tab. 5: Veränderung der Wassertemperatur entlang des Unterlaufs der Lena und im Lena Delta (über den Zeitraum 1962–1991) an den Zuflüssen der Lena nahe dem Pegel Kyusyur und die durchschnittliche Lufttemperatur an den meteorologischen Stationen unterschiedlicher geografischer Breite. Beachte (1): Das thermische Regime auf den hydrometrischen Schnitten wird verzerrt durch den Einfluss kälteren Wassers des Dzhardzhan Flusses; (2): Das thermische Regime auf dem hydrometrischen Schnitt wird durch den Einfluss kälteren Wassers des Ebitiem und anderer kleiner Zuflüsse verzerrt.

from Kyusyur to Yu.A. Khabarova gauge station. The monthly θ measured at Yu.A. Khabarova gauge over the all years of observations in the period from July to September appears to be higher than that measured at Kyusyur gauge, located 200 km to the south (Tab. 5; Fig. 11). The difference between the average June temperatures, taken at Yu.A. Khabarova and Kyusyur gauges, is generally close to zero, with upward or downward deviations, but more often, it also happens to be positive. The average summer (June–September) water temperature over the years of observations measured at Yu.A. Khabarova is 10.8 °C, and 9.7 °C is for the one measured at Kyusyur. If we analyze the daytime data averaged for 10 years, then we can spot a tendency of an increase in the positive gap between the temperatures at different stations from June to September (note, this tendency preserves nearly every year). At the same time, the air temperature is steadily lower than the water temperatures from July throughout the whole river section, and decreases from the south to the north (Fig. 11). The analysis of thermal balance of water surface and atmosphere from July to September for different years shows that the insignificant warming up of water body at the specified section (~0.25 °C per 100 km) is possible only in the end of June–July due to a large portion of short-wave radiation. Also, we should state that the ice conditions could considerably control the heat balance of the river until the end of June. The analysis of the section temperature measurements of the 1930s, 1940s and 1980s performed from July to the middle of September, shows that the water temperatures taken at Yu.A. Khabarova gauge are representative for the whole cross-section (the difference of the temperatures taken at the bank and at the waterway does not exceed 0.2 °C in the absolute value). The uniformity of the temperature profile in the place of vertical observations (except for the thin boundary layer) has been observed for the both stations. At the same time, cross-sectional measurements at Kyusyur gauge recorded a considerable increase in water temperature from the right bank to the midstream. The difference between the temperatures measured at the right bank and at the midstream in July–August was from -0.5 °C to -3.5 °C in different years. The cooling influence of the bank in the place of observations is limited during summer and cannot exceed the measurement error. However, there are some small tributaries (Eremeyka, Ebitiem, Abadakhan, Bordugas and Tikyan) upstream at a distance from 1.5 to 25 km from Kyusyur gauge that also fall from the right bank. Note, that the water in these tributaries is much colder than in the Lena River, which accumulates heat in more southern latitudes (Tab. 5, Fig. 11). The series of numerical experiments and analytical calculations (Zhilyaev & Fofonova 2016, Fofonova et al. 2018) has revealed a possibility of formation of a cold right-bank current caused by these

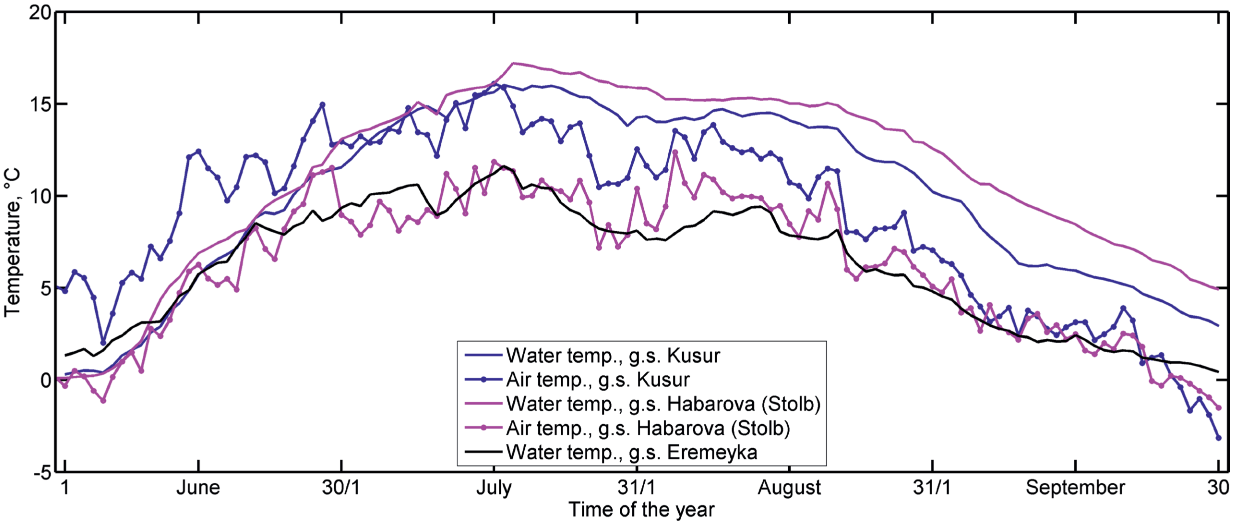

Fig: 11: Intra-annual fluctuations of the water and air temperatures measured at Kyusyur (Lena River main stream), Yu.A. Khabarova (Bykovskaya branch of the Lena River) and Eremeyka (Eremeyka River) gauges averaged over the period from 2002 till 2011.

Abb. 11: Innerjährliche Veränderungen der Wasser- und Lufttemperaturen am Pegel Kyusyur (Lena Hauptstrom), am Yu.A. Khabarova Pegel (am Bykovskaya Flussarm des Lena Delta) und am Eremeyka Pegel (Eremeyka Fluss) gemittelt über die Zeit 2002 bis 2011.

tributaries. This current explains the considerable increase in water temperature from the right bank to the waterway at Kyusyur gauge recorded by the observations and large difference between the water temperatures reassumed the Yu. A. Khabarova and Kyusyur gauges. In the numerical experiments, the width of influence area at Kyusyur (from the right bank to the waterway) averaged 170 m for the period from July to September without taking note of wind stress; the horizontal distribution of temperature in this area turned out to be close to the logarithmic one; the vertical profile in the performed simulations for the whole area was close to the uniform one (the difference between the surface and bottom temperature does not exceed 0.2 °C). The deviation of the temperature, average for the summer period (July–September), at the waterway was 0.8 °C from the measured, but this deviation considerably varied in the numerical experiments and reached 5.5 °C under some conditions during the summer season. The relation of the Lena River discharge to the total discharge of the considered small tributaries and the difference of temperatures in the Lena River and the tributaries are the major factors that determine the non-representativeness of measurements at the right bank at Kyusyur. The absolute difference of temperatures of the Lena River at the right bank and at the mid-stream is most often at a maximum in August and September. In June, the non-representativeness can be practically absent due to the huge discharges of the Lena River and a low gradient of temperatures. Thus, the real heat flux (W_θ) around Kyusyur gauge, with high probability and according to the estimates by the authors, is higher approximately by $1000 \cdot 10^{15}$ kJ/year in comparison with the value from Table 1 that is only calculated on the basis of stationary measurements of θ. Note that the total proportion of the Lena River water throughout the whole area of cold tributaries influence is 90 %, 88 % and 85% in July, August and September respectively, according to the calculation results. Thus, the estimates of long-term trends relying on the measurements at the station Kyusyur keep their relevance.

The θ changes, in general, slightly in the delta branches of the systems of the Bykovskaya and Olenekskaya branches, i.e. that of the latitudinal direction. On the opposite, θ continues to decrease in the watercourses of the systems of the Tumatskaya and Trofimovskaya branches flowing to the north and the northeast (Fig. 1). The intensity of decrease is higher (1.4 °C per 100 km in June and 1.5-2.5 °C per 100 km in other months) than in the lower reaches of the river. These estimates based on observations are confirmed by expeditionary measurements (Bolshiyanov et al. 2013). The reason for the relatively rapid decrease in θ is the distribution of water runoff over numerous branches, the reduction of stream depths and speeds (by 2 to 4 times), and the increase in water surface area. As a result, these waters are cooled more due to lower air temperature and reduced solar radiation, considerable energy expenses towards heating of the frozen soils and melting of considerable volumes of remaining river ice in the delta (in the shallows and on the floodplain) every year.

The value of heat flux at the site between Kyusyur and the head of the delta has two divisive tendencies: an increase due to the lateral inflow (~$0.12 \cdot 10^{15}$ kJ/year) and a decrease due to the reduction of water temperature. As the thermal regime at the section of Kyusyur gauge is disrupted, the influence of the second factor has not been revealed in detail. However, based on θ measurements at Yu.A. Khabarova gauge, W_θ of the Lena River at the head of the delta can be estimated as 15.6 to $16 \cdot 10^{15}$ kJ/year. At the marine margin of the delta, taking into account the regularities of distribution of the water runoff mentioned above over the systems of delta branches, its inter-annual distribution and longitudinal change of θ, the value of W_θ can be estimated as ~$11.75 \cdot 10^{15}$ kJ/year. Thus, 25 % of the value of W_θ at the delta head "are lost" through the delta. It is close to the estimation $10 \cdot 10^{15}$ kJ/year from (Antonov, 1967). In June 21.4 % of the total annual W_θ go to the marine margin of the delta in the Laptev Sea, 43.9 % in July, 25.2 % in August and 9.3 % in September. The residual goes in May and October.

CONCLUSION

1. According to the new estimates, the water runoff of the Lena River at the basin outlet station (Kyusyur gauge), at the head of the delta, and at the marine margin of the delta equals respectively to 543 km^3/yr, 547 km^3/yr and 553 km^3/yr over the period of 1927–2014; the SSL at the same sections is roughly $22.5 \cdot 10^6$ t/yr, $22.5 \cdot 10^6$ t/yr, and $7.9\text{-}13.5 \cdot 10^6$ t/yr. The heat flux is estimated respectively as $16.6 \cdot 10^{15}$, 15.6 to $16 \cdot 10^{15}$ and $\sim 11.75 \cdot 10^{15}$ kJ/year. Thus, about 40-65 % of the initial (at the delta head) SSL and ~25 % of heat flux, remain in the huge and braided Arctic delta of the Lena River. The water runoff increases, but by a negligent amount.

2. The estimates of heat flux and suspended load are influenced considerably by the accuracy and representativeness of SSC and water temperature measurements. The non-representativeness of water temperature measurements at Kyusyur accounts for the differences in the heat flux value approximately by 10^{15} kJ/yr less.

3. The regime of the river runoff and its values in the lower reaches of the Lena River, have undergone considerable changes in the last 30–40 years, reacting to climatic factors. The water runoff has increased for all hydrological seasons in general by 41.7 km^3 per year (for 1980–2014 in comparison with its values for 1935–1979), the SSL by 5,850,000 tons per year since 1988, the heat flux by $0.8 \cdot 10^{15}$ kJ/year since the end of the 1980s.

4. The water use and creation of two Vilyuy reservoirs had almost no impact on the water resources of the river ($\Delta W_{he} \approx -0.35$ km^3/year during 2001–2013), but have violated the natural conditions of winter low-water. The influence of water management activity on other components of the river runoff has not been established.

5. The runoff distribution of the Lena River in the delta head and main bifurcation node near the Stolb Island has a rather stable character. The ratios of relative runoff values in the sources of the main branches and in the head of branch nodes obtained according to the stationary monitoring have not been respected in most cases. At the Stolb Island, i.e. in the main delta branch node, the percentage of water runoff of the Bykovskaya branch was about 25.5 % in 1990–2007 (of the sums of runoff volumes in the sources of the main channels), the Trofimovskaya branch ~60.9 %, the Tumatskaya branch ~6.7 %, the Olenekskaya branch ~6.9 %. Within a year, these ratios change. With an increase in Q_K from 10,000 to 140,000 m^3/s, the percentage of runoff at the Trofimovskaya branch decreases from 72.3% to less than 50 %, whereas the water runoff of the Bykovskaya, Tumatskaya and Olenekskaya branches increases respectively from 21.3 %, 2.1 % and 4.3 % to 27.8 %, 10.7 % and 11.6 %. With high Q, huge ice jams and high-water levels part of runoff passes across the floodplain and its channels, i.e. bypasses the main hydrometric sections. The SSL is distributed in the following proportions: the Bykovskaya branch 17.2 %, the Trofimovskaya branch 70 %, the Tumatskaya branch 6.7 %, the Oleneskaya branch 6.1 %. With the change of Q in the river, this ratio also changes during the year.

6. The flux from Stolb Island to the marine margin of the Lena River delta is distributed between ~6,000 streams and is rather unstable due to the fluviomorphological processes. Standard methods of measurements are inapplicable in these conditions. Methods of indicative hydrology and remote Earth sensing can serve as one potential solution to the problem of monitoring runoff spatial transformation in the delta.

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