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Lena Delta hydrology and geochemistry

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Abstract

The Lena River forms one of the largest deltas in the Arctic; studying this delta has raised many questions regarding processes that occur there that remain open today. Comparing long-term hydrometric observational data of Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) from the Khabarova polar station, located at the head of the delta not far from where the Lena River divides into its main branches, with field observations, which have been carried out since 2002 revealed new insights into the hydrological, hydrochemical, and geochemical processes within the delta. Three periods with various water volumes and intensity of fluvial processes were chosen from the long-term record of water and sediment discharge. The role of ice event (ice blockage and ice floating) during high water in reconfiguring branch channels and influencing the volume of sediment runoff was identified. Results were obtained quantifying the increase of water and sediment discharges in the middle part of the delta main branches. This increase is to a great extent connected with an additional influx of water, as well as an increase of suspended and dissolved material released from the ice complex. A range of major ion and biogenic element contents in the delta branches in summer is introduced, and differences specified between the hydrochemical composition of thawing ice complex waters, of small Lena River branches, and of estuarine areas. The conservative character of some dissolved substances was analyzed along the length of the river branches. The contents of carbon and geochemical substances in suspended and bottom sediments are reported.

1 Introduction

1.1 The Lena River delta study area

The Lena River, which flows into the Arctic Ocean, is one of the biggest rivers in Russia. The Lena River is 4400 km long from its source near Lake Baikal to its mouth. According to data from of Russian Arctic coast and their safety of nature management (2007) the average annual water discharges Lena River rate is 16 800 $m^3 s^{-1}$, and sediment discharges, the average annual discharge of suspended supply is 680 $kg s^{-1}$, and of bottom sediments – 170 $kg s^{-1}$, the average discharge rate of major ions is, on average, 1460 $kg s^{-1}$, the average discharge of plankton is 12 $kg s^{-1}$, and the average heat discharge is 0.49×10^{12} $J s^{-1}$. The Lena can be divided into several areas, characterized by differences in gradient of water surface altitude mark, fluvial forms, hydraulics, and transporting capacity. As it passes through its estuarine area, the main Lena flow is divided into numerous arms and transverse branches, creating the most spacious delta in the Russian Arctic. The Lena delta area also comprises two large units that are hardly influenced by modern active deltaic processes, but represent late Pleistocene accumulation plains (Schwamborn et al., 2002). The total area of the Lena River delta, if Stolb Island is accepted as the delta head, constitutes $> 25\,000$ km^2 including > 1500 islands, $\approx 60\,000$ lakes, and many branches of the Lena River (Antonov, 1967). If the delta head is defined from the first (Bulkurskaya) Lena River branch to Tit-Ary Island, the delta area is considerably larger at $> 32\,000$ km^2 (Walker, 1983). The Lena River delta is a complex of more than 800 branches with a total length of 6500 km. River branches flow in different directions, some diverging, others converging. The biggest branch is the Trofimovskaya branch; from this branch the Sardakhskaya diverges after Sardakh Island (Fig. 1). The second water volume has the Bykovskaya branch, which turns sharply to the east after Sardakh Island and flows into the Buor-Khaya Gulf. The next two largest branches are Olenekskaya branch flows west into Kuba Gulf, and the Tumatskaya. Lately, a decrease of water runoff has been observed in the Olenekskaya and Tumatskaya branches (Fedorova et al., 2009a). The quantity of eroded material carried by the river plus the processes that occur where the river water and sea water come into contact have facilitated the formation of a rather long, shallow Laptev Sea marine shelf.

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1.2 Hydrology of the Lena River delta

Observations of the principal Lena River delta hydrological features have been carried out since 1951, when the Khabarova polar station (Khabarova) was established. Hydrographic parties and expeditions from the Arctic and Antarctic Research Institute (Marine transport, 1956), Moscow State University (Korotaev, 1984), Tiksi hydrological party (Seleznev, 1986; Yakutian steamship company, 1948), and others also worked in the delta at various times. A huge volume of data had been collected by the beginning of the 21stcentury describing the long-term change of river water volume and the redistribution of water and sediment discharge in the delta branches. Publications since about 2000 have dealt either with assessments carried out on the basis of already-published hydrological data (Berezovskaya, 2005; Ivanov et al., 1983, 1999; Rawlins et al., 2009; Shiklomanov, 2009), or with new data for the Lena River catchment area to the outlet gauging section with measurements on the river before delta at polar station Kyusyur (Ye et al., 2003, 2009).

We investigate water discharge changes, sediment supply, and changes in channel cross-section morphology and aerial extent of sandbanks that occur in the delta branches.

1.3 Hydromorphology of the Lena River delta.

A few researchers studied the long-term change in the supply of suspended materials, as well as of the peculiarities of the fluvial processes that are related to the Lena River delta cryolithic zone, but they have not investigated features of the hydrological processes within the delta itself. Syvitski (2003) modeled an increase of Lena River sediments due to water discharge increase and found that a variation of temperature on a river basin increases runoff more than does increased precipitation in the catchment area. However, first, the model was not validated using independent data, and second, calculations for the delta itself were not carried out. The conclusion that erosion and runoff of sediments is intensified in places where the ice cover of the catchment area is degraded is the important result of this work and presented in a discussion.

Lena River delta riparian zone erosion processes and precipitation accumulation in the delta front and inner shelf of the Laptev Sea have been rather well studied (Are, 2000; Grigoriev, 1993; Korotaev, 1984a, b, c, 2002; Stein et al., 2004; Wegner, 2012). Rachold et al. (2000) assumes that most sediment entering the Lena River delta with river runoff is carried to the sea, which is contradicted by the findings of Charkin et al. (2011). However, Rachold et al. (2000) and Are and Reimnitz (2000) that most Laptev Sea sediments are composed of material from thawing ice complex banks on the edge of the delta. “Ice complex” is a term used to describe surface permafrost that is a combination of minerals and ice (Schirrmeister et al., 2013). The sediment volume originating from ice complexes of the delta coastal zone that enters the sea is almost 2.5 times more than the volume of sediments carried by river.

Semiletov et al. (2011), Charkin et al. (2011), Heim et al. (2013), and Gordeev (2006) have analyzed the geochemical composition of the substances that are carried to the sea by the Lena River. However there is no indication in the abovementioned works of sediment runoff and composition in the Lena branches (of analysis of fluvial processes within the delta itself. Here we consider a complex of hydrological processes like water discharge distribution; sediment runoff, load geochemistry formation, and river-bed morphology changing that occur on the delta branches. We describe the changing hydromorphology of channels in the Lena Delta to provide possible explanations for the observed changes in discharge and suspended load along the delta arms.

1.4 Hydrochemistry and geochemistry of the Lena River delta

It is difficult to access the Arctic zone throughout much of the year; therefore, data describing Arctic river hydrochemistry are poorly reported in the literature. The first expeditions to collect Arctic river hydrochemical data describing the chemical composition of Arctic river waters were conducted by the Omsk and Yakutsk territorial department offices of The Federal Service for Hydrometeorology and Environmental Monitoring of

Russia (Roshydromet) and were published in Resources of surface waters (Hydrometeoizdat, 1972) and in Yearbooks o f quality of surface waters (Hydrometeoizdat, 1989–1992). Lena River hydrochemistry at the gauging section at Kyusyur and the seasonal dynamics of the main channel hydrochemistry over various time periods have been studied (Alexeevskiy, 2007a, b; Gordeev et al., 1999; Hoelemann et al., 2005; Izrael et al., 2004, 2012; Schpakova et al., 2009 and Zubakina, 1979) have studied the hydrochemistry of the Lena River estuary. Geochemistry of suspended matter was presented in Gordeev (2009), Hoelemann et al. (2005), and Savenko (2006).

We present the hydrochemistry and geochemical composition of suspended material of the delta branches during the summer (July, August).

2 Materials and methods

2.1 Long-term hydrological data

Five standard hydrometric cross sectionsare located within the Lena River delta, one on the main channel (4.7 km upriver from Khabarova Station) and the others on the Bykovskaya, Trofimovskaya, Tumatskaya, and Olenekskaya main delta branches (Fig. 1). Observations at the Bykovskaya and Trofimovskaya cross sections began in 1951; observations began in 1977 at the other three. Long-term data on discharge of water and sediments including data from the Hydrological yearbooks of Khabarova and from the Tiksi Office of Roshydromet were utilized (Hydrometeoizdat, 1956–2007). At the Khabarova water gauge located on the Bykovskaya branch water-levels (H, m) are measured according to standard Roshydromet methods and H on hydrological cross sections of other delta branches are calculated from correlation curves. Daily water discharges (Q, $m^3 s^1$) are calculated by $Q = f(H)$; sediment discharges (R, $kg\,s^{-1}$) are obtained from tables according to $R = f(Q)$. The outlet cross section at Kyusyur, which began operating in 1936, is used as the last hydrological cross section for assessing Lena River runoff before water is diverted into the delta branches near Tit-Ary Island.

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Measurements of water and sediment discharge at st. Kyusyur were carried out until 2007. From 1951 to 2005 depth and water and sediment discharge measurements were also conducted at the Khabarova cross sections. Except for water-levels, no observations were conducted at the Khabarova hydrological cross section after 2005.

To analyze the long-term data, we selected certain specific months were selected as representative of intra-annual runoff changes. The greatest water discharge occurs in June, and the minimum is in the winter months (usually in February). Graphing the increasing average monthly discharges made it possible to obtain "critical" points of hydrological (fluvial) processes in the delta, i.e. when considerable changes occurred.

For determining cycles with different water discharges value and for comparing average annual values of Lena River water discharge with average long-term runoff, differential integral curves were plotted calculated (Reshet'ko and Shvarzeva, 2010; Rozhdestvenskiy et al., 1974). A method of plotting the differential integral curve of a straight line for assessing the cyclical fluctuations of many natural phenomena was proposed by Glushkov (1934) and has found wide use in hydrology. Andreyanov (1960) was the first to conduct a comparative analysis of heterogeneous data based on the standardized differential integral curves of discharge rates. First, the discharge rate (K) for a series of observations is calculated by:

$$K = \frac{M_i}{M_\mathrm{a}}, \tag{1}$$

where M_i is the amount of a single element in the series and M_a is the average of all the observations.

Deviations from the mean ($K-1$) are determined, and the integral curve $F(t)$ (t is a period of time) is plotted via consecutive summation of these deviations according to:

$$\sum_{1}^{i}(K-1) = F(t), \tag{2}$$

Thus, a differential integral curve is an increasing sum of discharge rate deviations from the average long-term value of the series at the end of each M_i year. Positive discharge rate deviation summation values within a time interval yields a positive slope of the differential integral curve; negative summation values produce a negative slope. However, at the centennial-scale, a differential integral curve leads to inaccurate higher and lower phases of intra-century cycles or does not reproduce them at all. Therefore, to highlight cycles in which water discharge and therefore stream erosive power differed, an analysis of average monthly sediment discharges and of the total runoff was conducted over the long-term period.

The total discharge curve is shown in a graphic relation, characterizing the change of water (sediment) volumes that flow through the considered cross section of the river starting at some initial time (Shiklomanov, 1979). The discharge of the water flowing in the river at any given moment is characterized by the ratio of the tangent slope to the total runoff curve. If the discharge of water (sediments) is constant over some period of time, then the total runoff curve over this period of time will be a straight line. If runoff changes occur, whether caused by anthropogenic interference (e.g. construction of water storage facility) or by natural processes (e.g. change of river runoff or increase of precipitation on a catchment), then the ratio of the tangent slope to the total runoff curve will be changed; those inflection points are termed "critical points".

2.2 Field research

Within the framework of annual Russian-German expedition summer expeditions from 2001 to 2012, water and sediment discharges were measured and suspended and bottom sediments were sampled for geochemical and grain-size composition, in order to analyze the current hydrological regime and the peculiarities of water and sediment runoff distribution in the delta branches.

Hydrological measurements were carried out every year at the standard hydrometric cross sections; in addition, in some years other sections were added. Figure 1 illustrates all measurements cross sections, dates of measurements and coordinates of each cross section are presented in PANGEA database (Fedorova et al., 2013).

Branch length was measured over 2–3 day periods when no sizeable water level fluctuations occurred; several branch length measurements were made. The Olenekskaya branch length was measured in 2005 and 2012, and more briefly (with a fewer number of cross sections) in 2008, 2010, and 2011. The length of the Tumatskaya branch, from Samoylovsky Island to the mouth, was measured in 2006. Detailed Sardakhskaya branch measurements were carried out in 2002 and in 2005. While measuring the lengths of the Olenekskaya branch, water level at the Khabarova water gauge varied by only 20 cm during 2–3 days. Discharges recorded by the Bykovskaya branch water gauge (Khabarova) showed discharge differences of $\leq 3\,\%$, allowing values to be compared with no need to introduce additional adjustments. An exception is diurnal estuarine station measurements. Water discharges at the standard hydrometric cross sections were calculated to one water-level at the Khabarova water gauge, allowing those data to be used for long-term comparisons.

Hydrometric data collected included measurements of depth, current velocities, and water turbidity. Depth was measured twice using Garmin GPSmap 178C and GPSmap 421 s echo sounders on board a motor boat or a river port transport vessel (PTV). Sometimes position was determined using a GPSMap76CSX navigator (Garmin). Velocity verticals at characteristic points of bottom relief were conducted on each profile, ≥ 3 verticals per profile. Current velocity measurements on each vertical were carried out on standard horizons, i.e. surface, 0.2 h, 0.6 h, 0.8 h, and bottom (detailed five-point method) (where *h*, *m* is depth on the vertical). Truncated velocity measurements were frequently made, i.e. (a) 0.6 h (single-point); (b) 0.2 h and 0.8 h (standard two-point) and (c) 0.2 h, 0.6 h and 0.8 h (three-point); such measurements can be used to produce a velocity curve on the vertical at 20, 60, and 80 % of surface depth. Current velocity measurements at the selected hydrometric cross sections and surveying work at the cross sections were carried out in accordance with Instructions to Hydrometric Stations and Posts (Hydrometeoizdat, 1978).

Current velocities in the river during 2002–2010 were measured with a GR-21M pre-calibrated velocity meter, while in 2011 and in 2012 measurements were carried out with a 2D-ACM multi parametric probe (FSI). To ensure that data collected using two different devices were equivalent, measurements were first conducted using both devices simultaneously. The obtained measurement error = ±0.01 $\mathrm{m\,s^{-1}}$ allows measurements made using these devices to be combined.

Water discharge was calculated by analytical method according to the formula:

$$Q = 0,7\upsilon_1 f_0 + \left(\frac{\upsilon_1 + \upsilon_2}{2}\right) f_1 + \ldots + \left(\frac{\upsilon_{n-1} + \upsilon_n}{2}\right) f_{n-1} + 0,7\upsilon_n f_n, \quad (3)$$

where Q, $\mathrm{m^3\,s^{-1}}$ is water discharge; v_{1-n} is average current velocity ($\mathrm{m\,s^{-1}}$) on the 1st–n velocity verticals; f_0, $\mathrm{m^2}$ is water-section area between the bank and the 1stvelocity vertical; f_1 is water-section area ($\mathrm{m^2}$) between the 1st and 2nd velocity vertical, etc.; f_n is water-section area between the last vertical n and the bank.

Velocity V_m averaged over the 1–n velocity verticals was calculated according to the formulae:

for five-point method: $V_m = 0,1 \cdot (V_\mathrm{s} + 3 \cdot V_{0.2\mathrm{h}} + 3 \cdot V_{0.6\mathrm{h}} + 2 \cdot V_{0.8\mathrm{h}} + V_\mathrm{b})$ (4)

for three-point method: $V_m = 0,25 \cdot (V_{0.2\mathrm{h}} + 2 \cdot V_{0.6\mathrm{h}} + V_{0.8\mathrm{h}})$ (5)

for standard two-point method: $V_m = 0,5 \cdot (V_{0.2\mathrm{h}} + V_{0.8\mathrm{h}})$ (6)

When measuring velocity at one point, an average velocity was taken as equal to velocity on the horizon at 0.6 h.

Areas between velocity verticals were calculated according to the formulae:

$$f_0 = 2/3 h_1 b_0, \quad (7)$$

$$f_1 = \left(\frac{h_1 + h_2}{2}\right) b_1 + \left(\frac{h_2 + h_3}{2}\right) b_2 + \ldots + \left(\frac{h_{n-1} + h_n}{2}\right) b_n, \quad (8)$$

$$f_n = 2/3 h_n b_n, \quad (9)$$

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where h_{1-n} is depths of the measured verticals; $b_1, b_2, \ldots, b_{n-1}$ is distance between the measured verticals; b_0, b_n are distances between outer measured verticals and encroachment lines. Depth measurements on the profiles were most often carried out twice, and then areas were calculated using the average of these two measurements. When data were collected on board a vessel the depth was adjusted by the vessel's draft.

Calculations were carried out using on the 102 water discharge measurements for all cross sections by analytical method (Guidance document, 1989). The velocity meter measurement systematic error is $(\sigma_{\text{sys}}) = 0.02$ and the random experimental error $(\sigma_{\text{ran}}) = 1.23$. The summarized field observations error (S_Q) is also 1.23 following Eq. (10):

$$S_Q = \sqrt{\sigma_{\text{sys}}^2 + \sigma_{\text{ran}}^2}, \tag{10}$$

It should be also noted that water discharge on the branches measured during Russian-German expeditions differs from discharge calculated using the formula $Q = f(H)$, sometimes by 30–40 % (Fedorova et al., 2009a). This is due to the fact that the required adjustment of correlation coefficients between water-levels and water discharge volumes are not carried out at hydrometric stations. In recent years the water gauge altitude elevations also appear to be in doubt. Starting in 2007 water level and runoff data have been checked for errors at AARI in order to prepare them for publication in Hydrological Yearbooks.

To calculate sediment discharge, turbidity samples were selected from the same horizons where measurements of vertical current velocities had been conducted. Sometimes the number of horizons used for turbidity determination was reduced to two-point or one-point because it took a long time to collect the water in a vacuum bathometer. In this case standard selection horizons were preserved. For turbidity measurements samples were filtered through a 10 cm diameter, 0.45 mm thick paper filter matrix using a GR-60 vacuum pumper. For geochemical analyses a glass fiber filter (GF/F; Whatman) was used for total nitrogen/total carbon/total organic carbon (TN/TC/TOC) determination and a polycarbonate filter (PC; Sartorius AG) was used for major and trace element content. Filters were dried at 60 °C for paper and PC filters, and 500 °C for GF/F and weighted before filtration.

The concentration of suspended sediment discharge, R, was determined by analytical method according to equation calculated with addition adding the terms representing of the Suspended Matter concentration ($\mathrm{mg\,L^{-1}}$) (turbidity) on water level and averaged Suspended Matter concentration ($\mathrm{mg\,L^{-1}}$) (turbidity) on over the vertical water column (Eq. 11):

$$R = \sum_{i=1}^{n} s_i q_i, \tag{11}$$

where q_i is water discharge ($\mathrm{m^3\,s^{-1}}$) between verticals and s_i is mean turbidity ($\mathrm{mg\,L^{-1}}$) between verticals.

Bottom sediments were collected using either a UWITEC sampler with a 60 cm long, 6 cm diameter plastic pipe (gravity corer equipped with a 60 cm long and 6 cm wide PVC liner) or a Van-Veen grab sampler (Hydrobios) and were put into plastic bags, which were transported, frozen, to the laboratory.

2.3 Methods of laboratory sample processing

Suspended and bottom sediment samples that had been collected in the field were analyzed in the Russian-German Otto-Schmidt Laboratory for Polar and Marine Research (OSL) of the Arctic and Antarctic Research Institute (AARI, St. Petersburg, Russia) and at the Alfred Wegener Institute (AWI, Potsdam, Germany). The contents of TN, sulphur (S), TC, and TOC were determined using an Elemental Carbon and Nitrogen Analyzer (Vario EL III, Elementar) at OSL. The details of analysis methods are Sample preparation and lab analyses of the sediment samples followed the methodology described in Wetterich et al. (2009).

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Geochemical analysis of water and sediment samples (determination of major and trace element concentrations) was carried out via atomic emission spectrometry using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES; CIROS VISION). Before the suspended material could be analyzed the solid sample was dissolved. A small sample was put into a special teflon weighing bottle and filled with a mixture of concentrated acids, i.e nitric (HNO_3) – 3 mL, hydrofluoric (HF) – 4 mL, and perchloric ($HClO_4$) – 3 mL to dissolve the sample. Weighing bottles were closed with lids, firmly fixed in a special apparatus and heated. A sodium hydroxide (NaOH) solution was used to neutralize the volatile acids. As a result of evaporation, elements were concentrated in the solution.

2.4 Hydromorphological analysis

Long-term studies of changes in the morphometric parameters of lakes and delta branches requires the use of cartographic methods to display the spatial, temporal, and quantitative relationships between geomorphological, hydrological, and river-bed processes. For this purpose the matching detection of hydromorphological analysis was used, which is based on comparing aerial and satellite images from different years (Snischenko, 1988; Usachev, 1985). The method makes it possible to assess the rate of macroform deformation (Kondratyev et al., 1982). Sardakh Island was selected as an example of using this method to analyze changes in river-bed morphology. The obtained spatial change detections were compared with field measurements of Trofimovskaya branch depths on the Sardakh Island cross section (Bolshianov et al., 2003; Korotaev, 1984a; Yakutian steamship company, 1948), available data on suspended sediments.

Twenty-six aerial images of the studied Lena River delta area from 1951 were used as baseline data, including several topographic maps at 1 : 200 000 scales. In the course of the work, three Landsat satellite images from 26.07.1973, 05.08.2000, and 26.06.2009 with a resolution of 80 m in 1973 and 15 m in 2000 and 2009 were also obtained from internet used to investigate hydromorphological changes. The aerial images were transformed and mosaiked in Photomod software. The image data from various years were geocoded and matched to one another using MapInfo Professional 9.0.2 software; common landmark points and lines were used to obtain the best match in areas common to more than one image. Vector layers of river bank lines were created in MapInfo software: The MapInfo software was then used to compare changes of bank line contours between years revealing line shifting that represented bank cave-ins and areas of scouring or sedimentation. Average maximal rates of shifting were calculated (in meters per year) by dividing the obtained distance by which the bank had shifted (in meters) by the time interval between images (in years). For this study, the spatial resolution of the baseline data, the aerial images, the Landsat MSS image from 1973 and the newer Landsat images from 2000 and 2009 differ considerably. The picture elements of the Landsat 1973 image have an area of $\sim 4500\,m^2$, the picture elements of the 2000 and 2009 Landsat acquisitions of $\sim 680\,m^2$(multispectral bands) and $\sim 230\,m^2$(panchromatic band) (Usachev, 1985; Riordan et al., 2006).

To analyze the changes of volume and area in the braided bars and sands of Trofim-Kumaga near Sardakh Island, the Landsat satellite images from 2000 and 1973, as well as aerial images from 1951 were used. All these images were made between 26 July and 7 August, i.e. in one phase of the water regime; during this time the water level changed from 250 to 270 cm relative to the height mark of the nearest st. Sagyllakh-Ary water gauge. This similarity justifies using them for matching. The area of braided bars was digitized and measured calculated in MapInfo software.

The volume of deposited sediments was determined analytically by representing those sediments as a regular geometric figure, in the case of this study as a truncated pyramid. The calculation involves determining the volumes of different truncated pyramids. The area that existed during the most recent year of a period of interest, for example in 1973, was taken as the upper plane of the pyramid; the area that existed during the first year of the period of interest, for example in 1951, was taken as the lower plane. The selection of periods is limited by image availability. Areas were

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calculated using MapInfo software and volumes according to the formula Eq. (12).

$$W = \frac{1}{3}\Delta H\left(f_0 + f_1 + \sqrt{f_0 f_1}\right) \quad (12)$$

where f_0 and f_1 are areas of sand that existed on the dates when the images were captured, bounded by water surface; ΔH is the difference between water levels in the years under investigation.

For this study, the spatial resolution of the baseline data, the aerial images, the Landsat TM image from 1973 (80 m spatial pixel resolution) and the Landsat TM image from 2000 (30 m spatial pixel resolution) differ considerably. Areal changes that can be detected in the case of the Landsat MSS baseline data are $\gtrsim 6400\,\mathrm{m}^2$.

3 Results

3.1 Long-term water discharge changes determined using long-term data from the hydrometeorological network and from field measurements

3.1.1 Analysis of long-term water discharge changes using data from the hydrometeorological network

Analysis of long-term Lena River delta hydrological data from st. Kyusyur showed that from the middle of the last century a positive trend of average annual water (Fig. 2) and sediment discharge has occurred, yet the average annual water discharge remains below the average (Fig. 3). This is typical both for the outlet cross section of the Lena River at Kyusyur and for the cross Sect. 4.7 km upriver at Khabarova Station, on the main principal delta area channel. Figure 3 shows a decrease in water discharge before the beginning of the 1970s and then a slight increase. In 1983 there was a sharp drop in water discharge which continued until the end of the 1980s, when the delta area water discharge decrease fell to its lowest recorded level. From the late 1980s until today water discharge has continued to increase.

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A long period of observing the intra-annual water discharge distribution shows that the largest increase of water discharge is observed in May–June, i.e. during high water. Suspended sediments load is decreased during high water (June) and increased during winter low water (February). More than 50 % of the suspended sediment discharge from the Olenekskaya and Tumatskaya branches occurs in June (Fig. 4).

The suspended sediment discharges from the main delta branches continued to increase (Fig. 5); the month of highest river flow is June, and for August. Several “critical points” exist that are crucial for hydromophological processes of erosion and accumulation in the delta. The timing of the critical points is different for each branch. One can clearly see a critical point on the Olenekskaya branch during high water in 1983–1984. In August (middle of summer low water) this critical point on the Olenekskaya, Trofimovskaya, and, to a greater extent, on the Tumatsksya branches is typical for 1985–1986.

One can also observe a difference in angles of positive trend slopes during high water and low water. Since about 1987, the June water content and sediment runoff has increased slightly in comparison with previous years. An even greater increase has been observed since the end of the 1990s for all branches. At the same time there has been a slight decrease of water volume during the low water period.

3.1.2 Results of field hydrological observations in the Lena River delta during 2002–2012

All data describing discharge of water and suspended sediments, turbidity, and channel parameters measured during 2002–2012 in the Lena River delta are included in the PANGAEA database, and water discharge and suspended matter data are presented in Fedorova et al. (2013). Discharges at the main branches were measured at the standard hydrometric cross sections, and calculated to the one water level of 365 cm at the Bykovskaya branch water gauge at Khabarova, are specified in Table 1.

Our own field observations measurements carried out over the last between 2002 and 2012 showed that during the summer low water period (August) discharge volumes from the main delta branches are in the ratio of 1 : 1 : 7 : 21 for the Olenekskaya : Tumatskaya : Bykovskaya : Trofimovskaya channels, respectively, besides, discharge from the main Lena River channel before it branches near Stolb Island at the time of summer low water sometimes exceeded 30 000 $m^3 s^{-1}$.

From the central delta to the sea there is, in general, a two-fold decrease in branch water discharge and sediment supply volume (Fig. 6). But on some branches, the Sardakhskaya for example, water discharge can decrease from 7942 $m^3 s^{-1}$ near Gogolevky Island to 11 $m^3 s^{-1}$ at the mouth. The discharge of sediments shows a similar change over the same distance, from 183 to 0.03 $kg s^{-1}$. Because there are particular areas of channel scour and sediment accumulation within the delta itself, the discharge decrease along the length of the branches occurs unevenly, i.e. there could be a local increase of water discharge and sediment supply in one area and a decrease in another.

This heterogeneity reflects the complex hydrographic layout of the delta and peculiarities of delta geological and geomorphological structure (Bolshiyanov et al., 2013). Thus, in 2005 on the central Olenekskaya branch the measured water discharge was 2065 $m^3 s^{-1}$, at the beginning of this branch (after the influx of the Bulkurskaya branch) discharge was 1701 $m^3 s^{-1}$, and at the mouth it was only 956 $m^3 s^{-1}$. In 2012 discharges at the same cross sections were 1609 and 1439 14 $m^3 s^{-1}$ correspondingly. The same situation can be seen on the Tumatskaya and Sardakhskaya branches (Fig. 6).

It is also typical for turbidity to change along the length of a branch. In general, turbidity decreases from 50–100 $mg L^{-1}$ in the head of the delta to 3–5 $mg L^{-1}$ on the sea edge. A major part of suspended sediments brought by the Lena River from the water catchment has already been deposited before the Lena reaches Lenskaya Truba (Lena's Tube), where turbidity of more than 250 $mg L^{-1}$ was observed during low water (Fedorova et al., 2009b). One should also note a range of turbidity in different parts of the delta: in the center and at the edge rim turbidity can vary by 2 to 10 times, while in the middle, turbidity remains more or less the same. Thus, during low water, values of turbidity in the central delta vary from 20 to 45 $mg\,L^{-1}$, in the branch middle remain around 20–25 $mg\,L^{-1}$, and at the edge rim vary from 3 to 30 $mg\,L^{-1}$.

3.2 River-bed hydromorphology changes in the Trofimovskaya branch area and change of water discharge near Sardakh Island

Using data from previous studies (Antonov, 1967; Korotaev, 1984b, c) and from field observations carried out within the framework of a Russian-German Lena River delta expedition in the area of Sardakh Island and on the Trofimovskaya branch at the Sardakh-Khaya – Trofim-Kumaga cross section made it possible to analyze the velocity and direction of river-bed morphology changes. Cross section profiles of the branch channel that were obtained for various years during the low water period clearly demonstrate erosion in this profile, indicating and an accumulation of alluvium sediment on the left bank of the Trofimovskaya branch; the main watercourse shifted to the right river bank, i.e. near Sardakh Island, which is a rocky island resistant to scouring (Fig. 7). Over the period from 1948 to 1981 the width of the Trofimovskaya branch channel was decreased by more than half, while the depth increased from 10 to 22 m. Over the next 20 yr there were no fundamental channel changes, but from 2001 to 2010 alluvium sediment accumulated in the cross section and the channel width increased, i.e. lateral erosion increased.

These changes were also traceable in comparing the different image acquisitions. Figure 8 shows the state of the Trofimovskaya channel close to Sardakh Island in summer 1951 (aerial image) and in summer 2000 (Landsat satellite image).

These images show where sediment accumulated and where erosion has occurred. Sardakh Island is not susceptible to erosion because it is a rock ledge. The area of the Trofim-Kumaga sands has significantly increased over a 10 yr period.

In general, the Trofim-Kumaga sands opposite Sardakh Island are constantly changing. The braided sandbar area increased from 1951 to 2000, but by 2009 began to decrease again. Table 2 presents the results of calculations carried out using MapInfo software and according to formula Eq. (12).

During the period from 1951 to 1973 the area of Trofim-Kumaga sand increased by 4.13 km^2, while at the same time the sand volume increased by 2.45 km^3. During the period from 1973 to 2000 the area increased by just 1.5 km^2, but the volume increased by 6.09 km^3. Thus, an increase in the braided sandbar area does not always correspond to an increase in volume of accumulated alluvial material. Perhaps the area of the braided sandbar increases first, followed by a volume increase due to sedimentation of alluvium. Roshydromet long-term data of water discharge and suspended sediment supply for Trofimovskaya branch confirm an increase and presented on the Fig. 9. Measurements were carried out from 1977 to 2005, show a positive trend and mostly overlap the period during which changes in the Trofim-Kumaga sands morphometric characteristics were assessed.

3.3 Geochemical results: ion sinks and the composition of suspended sediments

3.3.1 Hydrochemical results

Studies conducted in the Lena River estuarine area (Zubakina, 1979), i.e. on the main delta branches, Tiksi Bay, Olenek Bay, the Buor-Khaya Gulf, and the Laptev Sea coast, established that the Lena River water mineralization exhibits significant changes during the year. In the area of Stolb on the principal channel it ranges from 84 to 613 $mg\,L^{-1}$, while in the Bykovskaya branch it ranges from 55 to 561 $mg\,L^{-1}$. Water mineralization in the Lena River delta varies inversely with water discharge. Major ion composition is practically unchanged throughout its depth, as well as downstream. In winter low water occurs near Stolb Island and chloride minerals (Cl^{Na}II) are prevalent with higher mineralization state. When high water recedes the mixed carbonate-chloride class predominates with various Ca^{2+} and Mg^{2+} ions of higher mineralization (up to 540 $mg\,L^{-1}$). From then until the freeze-up period, low-mineralized waters of the C^{Ca}III hydrocarbon-

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ate class prevail according to Alekin (1970) classification. Estuarine water pH fluctuates within narrow limits, i.e. from 7.27 to 7.82, reaching minimum values during spring high water.

Considerable attention in modern literature is paid to assessing the dissolved mineral and organic substances carried by the Arctic rivers to the Arctic Ocean. According to Hydroecological state of Arctic coast of Russia and safety of nature management, (Alekseevsky, 2007), the average long-term annual ion runoff at the Lena River closing cross Sect. 16 equals 48.4 to $59.8 \times 10^6\,\mathrm{t\,yr^{-1}}$, including a sulphate runoff of 37–104, a chloride runoff of 6.3–11.3, a hydrocarbonate runoff of 16.5–26.0, a calcium runoff of 7.6–24.7, magnesium runoff of 2.4–5.8, and a sodium runoff of $7.0–9.5 \times 10^6\,\mathrm{t\,yr^{-1}}$.

In the intra-annual distribution of nutrients runoff, the maximum runoff occurs in the spring, due to the larger water volume carried by Arctic rivers in the Asian part of Russia and the increased concentrations of nutrients in the water during this period. Major runoff of nutrients is occurred by silicon, iron and ammonium nitrogen (Yearbook of quality..., 1989–1992). The value of the annual ammonium nitrogen runoff is $\approx 44.6 \times 10^3\,\mathrm{t\,yr^{-1}}$, of nitrite nitrogen $2.6 \times 10^3\,\mathrm{t\,yr^{-1}}$, nitrates $32.5 \times 10^3\,\mathrm{t\,yr^{-1}}$, of phosphates $3.7 \times 10^3\,\mathrm{t\,yr^{-1}}$, and of total phosphorus $7.3 \times 10^3\,\mathrm{t\,yr^{-1}}$ (Gordeev, 1999).

The intra-annual Lena River ion runoff distribution varies considerably: up to 47 % of ion runoff is coming during the high water period and up to 34 % – on the ice-covered period. The highest discharge of ammonium, nitrates and iron occurs during the spring high water period, when from 64 to 84 % of the annual nutrients runoff occurs.

Tables below 3 and 4 present data from field measurements (Table 4) and laboratory tests analyses (Table 3) of water samples taken during hydrological measurements made during the summer.

The hydrochemical characteristics measured in the Lena delta correspond confirms the concentration ranges to publish in Zubakina (1979) and Alekseevsky (2007) and etc. from studies of the Lena and its delta. Water from the big branches (Table 3) is characterized by low mineralization in the summer ($\leq 84\,\mathrm{mg\,L^{-1}}$), low trace elements and nutrients contents, and high silicate concentration ($\leq 2.4\,\mathrm{mg\,L^{-1}}$). Element concentrations do not exhibit large ranges. The hydrochemical characteristics of the delta's small branches (Table 4) and streams indicate high mineralization ($\leq 285\,\mathrm{mg\,L^{-1}}$). Point measurements of temperature and electrical conductivity on small branches and streams allow the role of local factors like an ice complex to be considered as a factor controlling geochemical runoff formation in the delta.

Chemical elements sorbed on particles in suspensions and the major petrogenic elements and trace elements are in good compliance with published data (Gordeev, 2009; Hoelemann et al., 2005; Savenko, 2006). Mean data and their range for the main delta channels are presented in Table 5.

Analysis of dissolved and suspended chemical compounds and element concentrations from the delta apex to the coastline shows the difficult nature of the behavior of chemical elements inside the delta. Considering all observation data collected in the delta, some general features can be deduced that the Main dissolved elements are transferred along transported through the delta without significant concentration changes in the branch bifurcations. This hypothesis is supported by the small range of element concentrations observed in suspended material from different sized branches. Concentration changes have been noticed in dissolved nutrients and some trace elements after a channel bifurcation. Concentrations of nitrites and phosphates seem to be conserved (no changes of concentration due to bifurcation). Nitrates concentration on particulate matter filters rises at the delta coastline due to sedimentation of silt particles which sorb nitrates, and the transformation of this nitrogen via biochemical processes. The dissolved barium concentration exhibits opposite behavior; it decreases closer to the coastline because silt particles and nutrient compounds are incorporated into trophic chains and biogenic processes. The opposite situation occurs for mineralization. The degree of mineralization has been observed to increase before the river-seawater mass mixing zone is reached, which could be the result of more mineralized underground water flowing into the river or the dissolving of marine sediments in this zone.

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The analysis of concentration changes in dissolved and suspended forms of chemical compounds and elements from the delta apex to the sea edge showed that conservative change is typical for some of them, but non-conservative change is typical for others. In the first case, bifurcation of delta watercourse channels does not cause significant changes in concentration. In the second case, concentration is changed due to physicochemical and biochemical processes (Nikanorov, 2001).

Calculations using field measurement data showed that among components dissolved in water, main ions (Ca^{2+}, K^+, Mg^{2+}, Na^+, SO_4^{2-}, HCO_3^-, Cl^-), iron (Fe), aluminum (Al), barium (Ba), strontium (Sr), and silicon (Si); nutrients, such as nitrites (NO_2) and phosphates (PO_4); major suspended petrogenic components (Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, Na_2O, SiO_2), and suspended trace elements (lithium (Li), vanadium (V) and strontium (Sr)) have a conservative character. A non-conservative concentration change along the delta branches is observed for dissolved nitrates (NO_3) and barium (Ba) dissolved in water and Ba in suspension decrease as they move from the delta apex down along the branches. The reverse situation is typical for mineralization. Its increase is registered long before the mixing zone is reached. Sedimentation of finely-dispersed particles and inclusion of nutrient compounds into trophic chains, i.e. involvement of compounds into biochemical processes, could explain these greater changes.

3.3.2 The geochemical character of suspended material

Analyses of total carbon (TC), total organic carbon (TOC) and total nitrogen (TN) content in suspended and bottom sediments of the branches were conducted. The summarized results are shown in Fig. 10. The TOC/TC ratio varies from 0.07 to 1.12. The smallest values of TOC/TC (< 0.6) are typical for bottom sediments of the principal channel and the Bylkurskaya branch, whose bottom is covered by pebbles. Current velocities here during low water can exceed $2\,m\,s^{-1}$; this speed can certainly cause intensive transport of bottom sediments. Fine particles can resediment in areas with slow current or at turns of the channel. The values of TOC/TC are the same as those of suspended substances in all the branches, i.e. between 0.8 and1, which is typical for bottom sediments of the Trofimovskaya, Olenekskaya, and Tumatskaya branches. On the standard cross sections, the average suspended TOC/TC ratio equals 0.89. Slightly higher TOC/TC values (around 1) are typical for suspension in the backwaters at the Olenekskaya branch mouth. Practically all carbon in the Angardam branch cross section, the nearest to the sea, as well as for the Bulkurskaya branch is organic and reached 3 % while for other branches TOC is ≤ 1 %. TOC/TC = 0.46 in water flowing from the Kurungnakh Island ice complex. The TC/TN ratio exhibits large amplitude, from 0.7 to 29.3 in bottom sediments of the Bykovskaya branch and suspended sediments of the Angardam branch, respectively. The average TC/TN value in suspended and bottom sediments for all cross sections is 9.6. The biggest amplitudes are typically found in bottom sediments; for example, in the principal channel and Bykovskaya branch pebbles are moved along the bottom throughout the major part of the profile and the TC/TN value is less than 5. On the Bulkurskaya branch the TC/TN value reached 20.9, which indicates transfer and sedimentation of large amounts of organic material, especially during high water, because sometimes branch runoff is not observed during summer low water. TC/TN values for suspended sediments are close to average; TC/TN did not exceed 4.7 in the ice complex on Kurungnakh Island thawing water.

4 Discussion

4.1 Hydrology of the Lena River delta and river-bed morphology

Analysis of long-term water and sediment discharge measurements at the standard hydrometeorological network points showed a positive trend for these discharges. This has been observed before (Berezovskaya et al., 2004; Bolshiyanov et al., 2006; Fedorova et al., 2009a) reported a statistically significant (by Student's *t* test and F-ratio) discharge increase by an average of 35 $m^3 s^{-1}$ (0.22 % of the average long-term discharge). Nevertheless, such an increase is slight, and until 2000 Lena River runoff (measured at Kyusyur) was lower than the calculated average runoff (Fig. 3). From 2000 the increase of water discharge has begun to be more significant.

However, according to the obtained data, the increased water discharge occurs during high water (June). During summer low water (August), there is a slight water discharge decrease (Fig. 5). In our opinion, it is premature to draw any conclusions about winter low water and possibly more crucial discharge variations due to climate change. Model calculations (Fedorova et al., 2010) show that hydrological systems require a long period of adaptation when parameters that control discharge formation change. Also, in the 21stcentury measurements on the considered cross sections are often carried out without meeting the requirements of the hydrometeorological network; out-of-date devices and methods are often used. For example, winter measurements of water depth and flow have not been made for a period of more than 10 yr; thus, it is impossible to study these processes in detail. The possibility of measurement inaccuracies at the Roshydromet stations has been previously noted (Berezovskaya et al., 2004). Earlier measurements of water and sediment flow down the main arms of the Lena River delta (Antonov, 1967; Bolshiyanov and Tretiakov, 2002; Gordeev, 2006; Ivanov et al., 1983; Ivanov and Piskun, 1999; Korotayev et al., 1990) in connection with existence of a positive trend is not changing. Fedorova et al. (2009) found the following increases in flow: 100 % increase in the principal channel, 6.8 % increase in the Olenekskaya branch, 6.4 % increase in the Tumatskaya branch, 61.5 % increase in the Trofimovskaya branch and 25.3 % increase in the Bykovskaya branch. At the Sardakh–Trofimovskaya branch point during the open water period, 20–26 % flows into the Trofimovskaya and 23–33 % into the Sardakhskaya branches. However, one should note the growing number of hazardous hydrological phenomena (Izrael et al., 2012) which impact the formation of ice jams in the Lena River delta; ice jams may not only a cause a sharp increase of Bykovskaya branch water level, but also can block runoff entirely on the Olenekskaya and, sometimes, on the Tumatskaya branches.

Ice events in the delta play a significant role for river-bed processes, for example, an ice jam can cause greater fluvial adjustments than a change of water runoff volume.

During one flood caused by an ice jam 40 m of shoreline was washed away due to thermal erosion and banks being cut by ice (Are, 1983). In our opinion, catastrophic ice events were the primary cause of the dramatic increase of sediment runoff on the Olenekskaya branch in 1984 (Fig. 5), despite the fact that from 1983–1984 no Olenekskaya branch jams were officially registered in the yearbooks. However, this cross section is far from Khabarova, and visual observations are lacking because it is dangerous to access this area. In 1982 an ice jam was registered near st. Kyusyur from 1–6 June, and from 10–12 June a jam occurred near Tit-Ary Island, i.e. at the place where the delta begins to branch out; here the Bulkurskaya branch begins that later enters the Olenekskaya branch further upriver the hydrometric cross section. According to yearbook data, in 1983 there was no runoff of water and sediments on the Olenekskaya branch in June (during high water); this was apparently due to the branch channel being blocked by ice. At the same time ice jams were also observed near Kyusyur and Khabarova from 3–9 and 10–12 June, respectively. In 1984 there was a sharp increase of average suspended sediments on the Olenekskaya branch, i.e. from 290 $kg\,s^{-1}$ in 1982 up to 1400 $kg\,s^{-1}$ in 1984; in our opinion this increase is the result of ice phenomena.

The annual cutoff of river bank edges during high water (Figs. 11, 12 and Supplement 2) produces an unmeasured quantity of suspended and bottom sediments which are carried into the delta and, as a consequence, ejected into the delta front. Costard et al. (2003) noted the important role of slope erosion during flood periods for the middle part of the Lena River due to thermal erosion. A change detection study for Kurungnakh Island in the central Lena Delta showed mean annual river bank erosion rates of 2.9 and 1.8 $m\,yr^{-1}$ for two different cliff sections over the period 1964–2006 (Günther, 2009). Such erosion processes can in turn affect riverbed (fluvial) processes and cause additional sediment runoff to streams (Morgenstern et al., 2011) the delta channels.

According to opinions of Charkin et al. (2011), Heim et al. (2013) and Wegner et al. (2013) during the low water level in summer only a minor amount a relatively

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minor amount of sediments are contributed to the sea from the Lena river branches delta and can be traced to turbidity in the riparian part. Heim et al. (2013), and Charkin et al. (2011) found delta turbidity to be only 3–5 $mg\,L^{-1}$; this is confirmed by our field data. However the volume and, more importantly, the composition of sediments on the delta edge and the quantity of sediments ejected onto the inner shelf have not been quantified.

Questions that remain to be studied include how dissolved and solid substances enter the delta during ice complex degradation and flood plain terrace material resedimentation (Bolshiyanov et al., 2013). An increase of water and sediment discharge occurs in the middle part of the Olenekskaya branch, where separate ice complex masses are exposed to the warming action of the water and active processes of bank thermoerosion and thermodenudation develop. On Kurungnakh Island, water pulses loaded with high amounts of particulates have been observed flowing down a thermo-erosion valley and discharging into the Olenekskaya branch during summer 2008 (Supplement 1). A major role of groundwater runoff from the thawed horizon in the thermokarst areas of the Arctic is also mentioned in Woo et al. (2008). Unusual debris flows during summer season which originated from alases (unique central Yakutian grasslands) were observed in the Lena River delta. When ice dams break up, water carrying particulates those have been eroded from the bank rushes down the gully network and enter the delta branches. One such debris flow was registered in 2008 on Kurungnakh Island (Supplement 1). Unfortunately, in modern permafrost hydrology are mentioned only and additional influx of water can occur during active summer precipitations (Kane et al., 2003), but, for the time being, no calculations have been made of water and sediment influx due to catastrophic lake drainages emptying suddenly when an ice jam breaks up.

Possible mechanisms underlying the observed increase of water and sediment discharge in the central Lena delta include neotectonic (isostatic) processes (Bolshiyanov et al., 2013) that can cause an increase of the water surface altitude gradient and, as a consequence, an increase of erosive power and expose new sediment material for

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erosion. Such a hypothesis could be confirmed by specifying geodesic benchmarks inside the delta, as well as by conducting additional branch water level and sea level measurements.

Any local decrease or increase of water and sediment discharge in the estuary zone is often constrained by the sea. However, our studies carried out in 2005 (Fedorova et al., 2007) and 2012 (Fedorova et al., 2013) in the Olenekskaya branch delta showed an absence of seawater influx 60 and 15 km deep into the branch accordingly; electro-conductivity did not exceed 125 $\mu S\,cm^{-1}$. In addition, neither salt water nor a change of water current direction at the Angardam branch cross section was observed. The influx of sea water could certainly have an impact by changing the inclination of the branch water surface, but confirming this hypothesis will require high-precision geodesic work.

The situation on the Bykovskaya branch is slightly different. In recent times, according to observation by the hydrometeorological network (at st. Muostakh and st. Bykovsky), the hydrological regime of this branch has been estuarine with a prevalent sea influence. Roshydromet is currently considering the possibility of re-configuring the estuarine station with regard for the interface between river and sea, including additional measurements on Bykovsky Peninsula.

River water may also filtrate into the talik under the river bed of the Lena Delta. We have shown that water discharge from the estuarine areas of the measured branches decreases by orders of magnitude compared to the discharge of the central delta. For example, flow in the Sardakhskaya branch decreased from more than 11 000 $m^3\,s^{-1}$ near Gogolevsky Island (in the central delta) to 11 $m^3\,s^{-1}$ at the branch outlet. Certainly runoff can decrease due to flow branching or because of a rise in sea level, but the existence of such a huge difference in the water discharge amount invites not only more measurements, but also additional studies of hydrogeological conditions. A hydraulic connection between flow in the river and flow in the talik beneath it is possible and could explain an outflow to the talik in the summer and inflow to the river in the winter. The same result was found due to seasonal changes of water mineralization in the delta (Zubakina, 1979). Another reason of water discharges decreasing in the Lena delta at the side of Kyusyur station noticed in Burdyikina (1951) where infiltration of spring flood water from the Lena River through the Lena-Anabar depression to the Olenek and the Anabar Rivers basin had been recorded.

4.2 Cyclicity of hydrological processes

Hydrological and river-bed processes in the Lena River delta are cyclic. The relationship between long-term average monthly water discharge and increasing average annual sediment supply over the period of instrumental observations is shown in Fig. 13.

Inflection points in the plot of average monthly sediment discharge can indicate critical points. Water content of the river cannot be, in our opinion, the main criterion for highlighting certain periods because many delta processes may impact fluvial deformations and rearrangements of the delta shape. One can see from Fig. 13 that from 1977 to the middle of the 1980s a cycle existed that was characterized by low water volume and little fluvial deformation, as evidenced by sediment discharge. From the mid-1980s to the mid-1990s river water content increased and fluvial processes were active. Currently, with increased water content, the transport capacity of the Lena River delta has actually decreased slightly. Of course, a hydrological system does not immediately respond to changes in water volume or fluvial deformation; there is a certain lag time between change and effect.

Nevertheless, as has been mentioned above, at the beginning of the 1980s abrupt increases in Olenekskaya branch sediment runoff was observed. By the 1980s rapid increases had also occurred in the Trofimovskaya branch channel near Sardakh Island (Fig. 7). Trofim-Kumaga sands accumulated until 1973; in 1981 a process of active bottom erosion of these sands began near Sardakh Island. Over the period of the third period, another decrease of fluvial process activity was observed, manifested by the gradual silting up of the Trofimovskaya branch channel, decreasing the channel depth and increasing the channel width.

4.3 Geochemistry of the delta

An assessment (Chetverova et al., 2011) of the amount of dissolved substances upstream of the Lena River over the period from 1960 to 1987 produced averages of annual dissolved mineral substances at the outlet cross section of the Lena River (st. Kyusyur st.). Results obtained by the authors are consistent with published runoff assessments (Alekseevskiy, 2007a, b). Analysis of long-term dissolved substance runoff data has enabled conclusions to be drawn regarding the seasonal and long-term dynamics of Lena River runoff. On the basis of the ratio of water discharge to mass of transported dissolved substances, we conclude that water volume directly impacts the formation of an ion runoff (i.e. more water can transport more dissolved elements). In contrast, a similar relationship for nutrients was detected only in some years; i.e. during the formation of runoff, a water content factor and a substance concentration factor overlap.

Analysis of the intra-annual variations of dissolved substance runoff showed that levels are highest when the Lena River water volume is high, confirming the critical impact of water volume on ion runoff formation and organic substance runoff. From 1960–1987 the Lena River ion runoff decreased almost three-fold. A decreasing runoff tendency is observed for all major ions, except for magnesium. The runoff of calcium ions was decreased by 54 %, sodium and potassium by 43 %, hydrocarbons by 44 %, sulphates by 7 %, and chlorides by 30 %. A decreased runoff for nutrients was also observed, including a 2.2-fold decrease for nitrates and a 7 % decrease for phosphates, and more than a two-fold decrease for silicon; in contrast a nine-fold increase of iron was observed.

Geochemical processes in the delta are closely connected with the amount of river runoff and changes in that runoff due to division of the channel into smaller branches. This process is the basis of the postulated mechanism of a marginal filter which has been developed by Lisitzin (1988). However, a quantitative discussion of these linkages is lacking due to insufficient hydrological study of the delta watercourses. For

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river systems upstream from the delta, this question is being answered on the basis of linking runoff characteristics to river orders, as determined within the conceptual framework advanced by Horton (1945). The concept of conventional orders, proposed by Alekseevsky and Chalov (2009), affords the possibility of quantifying these relationships in the delta. As the main branch in the delta divides into smaller and smaller watercourses, all other characteristics of river runoff change, including the ability of the water to act as a runoff for chemicals (including ions, trace elements, and nutrients).

However, observations in the Lena River delta showed that there is no direct dependence of water discharge and material content on a branch order number. These observations revealed that changes in concentration of individual substances are either conservative or non-conservative. From our point of view, observations have failed to reveal dependence on river order for three main reasons: first, the mechanism of the marginal filter of biotic constituents in the Lena River delta has been understudied and this filter could have an important influence on substance sedimentation; second, field data have shown a huge influx of dissolved and suspended substances into the delta itself, especially where the ice complex has thawed, and additional studies will be required to elucidate the role of these substances in hydro- and geochemical processes; third, according to the obtained data, at present the Lena River delta has four regions with active sedimentation (resedimentation) of the material located in the central delta. This sedimentation process is not addressed in the current hypothesis of Alekseevsky and Chalov (2009) about geochemical processes in the delta.

Analysis of TOC, TC and TN in suspended and bottom sediments of the delta branches showed a rather wide range of values. Bottom sediments are usually lower in TOC than in suspended sediments. However, on the bottom of the Bulkurskaya branch, where often water flows only during the high water period, the value of TOC exceeds 2 %, indicating significantly greater organic matter content in the sediments during the high water period.

Suspended TOC in the Angardam branch at the mouth of the Olenekskaya branch equaled 3.02 %. This result is consistent with the hypothesis of Lisitzin (1988) about the marginal filter on the edge of the delta. Here carbon is present in much higher concentration than is nitrogen (TC/TN = 29.3). Unfortunately sediment samples for determining carbon and nitrogen content in of other branches were not obtained.

5 Conclusions

Long-term Lena River delta field observations combined with Roshydromet data and geoinformation technology have made it possible to obtain a number of new insights into the hydrological and geochemical peculiarities of the delta. The velocities of the fluvial processes that occur in the central part of the delta were also documented. In summary:

1. Water discharge and sediment supply in the delta over a long-term period was reviewed. According to data of Roshydromet a positive trend until 2007 was confirmed, as and a decrease of dissolved substance runoff from 1960 to 1987.

2. Three periods were selected that are characterized by similarity of water volume and erosive power in the delta. From 1977 (from the beginning of instrumental measurements in all the delta branches) to the mid-1980s a cycle with low water volume and minor hydromorphological changes occurred in the delta. From the mid-1980s to the mid-1990s an increase of water volume and active fluvial processes were observed; at this time (after mid-1990s), concomitant with increased water content, transport capacity of the Lena River delta decreased slightly. The data confirm considerable hydromophological changes at the cross section of the Trofimovskaya branch near Sardakh Island.

3. New data were obtained from detailed field observations in the delta; the most valuable of these were branch length measurements, which yielded new data about the formation of water discharge and sediments.

4. In the central delta an increase of water discharge and sediment supply occurs. We hypothesize that it is caused by the destruction of the ice complex, of river terraces and river bank abrasion.

5. A lateral change of suspended sediment load through the course through the Lena delta occurs during the low water period, as documented by field observations, exhibiting the following characteristics: turbidity in the delta head is 20–40 $mg\,L^{-1}$, but on the edge it decreases to 3–5 $mg\,L^{-1}$, similar to water turbidity on the inner shelf of the Laptev Sea.

6. A decrease of water and sediment discharge from the main branches on the delta edge is connected to channel branching; additional field measurements are required in this understudied part of the delta, as there may be a type of hydraulic connection between the network of channels and a talik.

7. Suggestions that changes in sea level are influencing the observed runoff increase also remain to be confirmed by data. According to Ivanov (1963) the sea level impact extends

   40–60 km inland from the branch mouths, but these measurements were taken on the Bykovskaya branch that is currently developing into an estuary. Observations carried out in 2005 and 2012 at two daily stations with measurements each hour at the Olenekskaya branch mouth (approximately 60 and 15 km from the sea) also showed that salty sea water did not penetrate deep into this branch.

8. Suspended sediments in the estuarine areas of the branches and in smaller branches that function mainly during high water are characterized by high organic particulate matter TOC contribution (2–3 % TOC). This phenomenon is explained by the additional sedimentation of material that occurs when current velocities are sharply reduced due to seawater backing up into the branch outlet or in small branches during summer low water levels.

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9. New data were obtained on the geochemistry of main branch suspended sediments in the central parts of the delta that are confirm the ranges of previously published data on the Lena River and estuarine coastal waters.

10. The range of dissolved matter content changes for the main delta branches is small; the content is comparable to the long-term values. Such local factors as ice complex runoff water that is more mineralized impact the hydrochemical characteristics of smaller branches.

The collection of long-term observational data described here has not only enabled absolutely new results to be obtained, but has also highlighted the necessity to carry out more detailed observations of the hydrological, geochemical, and channel processes inside the

Lena River delta as well as study of the estuarine branch areas and developing an assessment of the sea's impact on the delta edge remains.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/10/20179/2013/bgd-10-20179-2013-supplement.zip.

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References

Alekin, O. A.: Basis of hydrochemistry, Hydrometeoizdat, Leningrad, 413 pp., 1970 (in Russian).

Alekseevsky, N. I. (Ed.): Geoecological state of Russian Arctic coast and their safety of nature management, GEOS Publ., Moscow, Russia, 586 pp., 2007a (in Russian).

Alekseevsky, N. I. (Ed.): Hydroecological state of Arctic coast of Russia and safety of nature management, GEOS Publ., Moscow, Russia, 556 pp., 2007b (in Russian).

Alekseevsky, N. I. and Chalov, S. R.: Hydrological impacts of braided channels, Publication of MSU, Moscow, Russia, 240 pp., 2009 (in Russian).

Andreyanov, V. G.: Inter annual runoff distribution (main particularities and their using in hydrological and water service estimation), Sokolov, D. L. (Ed.), Hydeometeoizdat, Leningrad, USSR, 327 pp., 1960 (in Russian).

Antonov, V. S.: The Lena river delta, Hydrometeoizdat, Leningrad, USSR, 108 pp., 1967.

Are, F. E.: Thermal abrasion of coasts, in: Proceedings of the Fourth International Conference on Permafrost, Alaska USR, 18–22 July 1983, 24–28, 1983 (in Russian).

Are, F. and Reimnitz, E.: An overview of the Lena River Delta settings: geology, tectonics, geomorphology, and hydrology, J. Coast. Res., 16, 1083–1093, 2000.

Atlas of the Sardakhskaya channel, sailing direction, Yakutian steamship company (Ed.), Russia, 1948 (in Russian).

Berezovskaya, S., Yang, D., and Kane, D. L.: Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds, J. Geophys. Res., 31, L21502, doi:10.1029/2004GL021277, 2004

Berezovskaya, S., Yang, D., and Hinzman, L.: Long-term annual water balance analysis of the Lena River, Global Planet. Change, 48, 1–3, 84–95, 2005.

Bolshiyanov, D.Yu., and Tretiakov, M. V.: Investigation of run-off in the Sardakh-Trofimovsky bifurcation point of the Lena River Delta, Reports on Polar and Marine Research, Alfred Wegener Institute for Polar and Maine Research, Germany, 426, 57–62, 2002.

Bolshianov, D.Yu. Fedorova, I. V., and Tretiakov, M.V: Hydrological investigation in the Lena River Delta, Reports on Polar Research, Alfred Wegener Institute for Polar and Marine Research, Germany, 466, 82–91, 2003.

Bolshiyanov, D.Yu., Tret'yakov, M. V., and Fedorova, I. V.: River-bed deformation in the Lena River delta channels, in: Proceeding of the VIth All-Union hydrological congress, Sect. 6: Problem of river-bed processes, erosion and sediments, St. Petersburg, Russia 28 September–1 October, 257–260, 2004 (in Russian).

Bolshiyanov, D.Yu., Makarov, A. S., Schneider, V., and Stof, G.: Evolution and development of the Lena River delta, Publ. of AARI, St. Petersburg, Russia, 268 pp., 2013 (in Russian).

Burdyikina, A. P.: To a question of rivers freezing of the Lena-Anabar depression, Library holdings of the Arctic and Antarctic Research Institute, 2, 86–92, 1951 (in Russian).

Charkin, A. N., Dudarev, O. V., Semiletov, I. P., Kruhmalev, A. V., Vonk, J. E., Sánchez-García, L., Karlsson, E., and Gustafsson, Ö.: Seasonal and interannual variability of sedimentation and organic matter distribution in the Buor-Khaya Gulf: the primary recipient of input from Lena River and coastal erosion in the southeast Laptev Sea, Biogeosciences, 8, 2581–2594, doi:10.5194/bg-8-2581-2011, 2011.

Chetverova, A. A., Potapova, T. M., and Fedorova, I. V.: Geochemical runoff of Arctic rivers by the example of West Siberia Rivers and The Lena River, in: Proceeding of the IVth regional school-conference for young scientists/Aqueous medium and nature-territorial complex: study, using, protection, Petrozavodsk, Karelian scientific center of RAS, 26–28 August 2011, 83–90, 2011 (in Russian).

Costard, F., Dupeyrat, L., Gautier, E., and Carey-Gailhardis, E.: Fluvial thermal erosion investigations along the rapidly eroding riverbank, application to Lena River (Central Siberia), Earth Surf. Proc. Land., 28, 1349–1359, 2003.

Fedorova, I., Fedorov, G., and Makarov, A.: Hydrological investigation in the Lena River Delta, Reports on Polar and Marine Research, Alfred Wegener Institute for Polar and Marine Research, Germany, 539, 48–57, 2006.

Fedorova, I., Bolshiyanov, D., Nikels, D., and Makarov, A.: Report on hydrological work in the Lena River Delta in August 2005, Reports on Polar and Marine Research, Alfred Wegener Institute for Polar and Maine Research, Germany, 550, 233–241, 2007.

Fedorova, I. V., Bolshiyanov, D.Yu., Makarov, A. S., Tret'yakov, M. V., and Chetverova, A. A.: Current hydrological state of the Lena delta, in: System of the Laptev Sea and adjacent seas of Arctic: current state and evolution, edited by: Kassens, H., Lisitzin, A. P., Tiede, J.,

Polyakova, E. I., and Timokhov, L. A., MSU publishers, Moscow, Russia, 278–292, 2009a (in Russian).
Fedorova, I. V., Charkin, A. N., and Chetverova, A. A.: Changes of content and composition of suspended material in middle and lower course of the Lena River, in: Proceeding of the 25th plenary session on erosion, river-bed processes and estuary areas problems, Barnaul, Russia, 5–9 October 2009, 200–201, 2009b (in Russian).
Fedorova, I, Bolshiyanov, D. Yu, Chetverova, A., Makarov, A., and Tretiyakov, M.: Database of Alfred Wegener Institute of Polar and Maine Research, Germany, available at: doi:10.1594/PANGAEA.808854, 2013.
Glushkov, V. G.: Perspectives and ways of Hydrology development in USR, Izvestiya of Russian State Hydrological Institute, 65, 23–30, 1934 (in Russian).
Gordeev, V. V.: Fluvial sediment flux to the Arctic Ocean, Geomorphology, 80, 1–2, 94–104, 2006.
Gordeev, V. V.: Microelements in water, suspended material and sediments of Ob' bay, Enisey gulf and the Lena River delta and surrounded areas of the Kara and Laptev Seas, in System of the Laptev Sea and adjacent seas of Arctic: current state and evolution, edited by: Kassens, H., Lisitzin, A. P., Tiede, J., Polyakova, E. I., and Timokhov, L. A., MSU publishers, Moscow, Russia, 202–225, 2009 (in Russian).
Gordeev, V. V. Zektser, I. S., Djamalov, R. G., Zhulidov, A. V., and Bryzgalo, V. A.: Score removal of nutrients of river runoff to the marginal seas of the Russian Arctic, Water Resour., 26, 2, 206–211, 1999.
Grigoriev, M. N.: Cryomorphogenesis of the Lena River mouth area, Siberian Branch of Russian Academy of Sciences, Yakutsk, USSR, 176 pp., 1993 (in Russian).
Guidance document: Addition to instruction for hydrometeorlogical stations and posts, 6, part 1: Hydrological measurements and works on big and average rivers, RD 52.08.163-88, Hydrometeoizdat, Leningrad, USSR, 90 pp., 1989 (in Russian).
Günther, F.: Investigation of thermokarst evolution in the southern Lena Delta using multitemporal remote sensing and field data, unpublished diploma thesis, Technical University of Dresden, Dresden, Germany, 96 pp. 2009.
Heim, B., Abramova, E., Doerffer, R., Günther, F., Hölemann, J., Kraberg, A., Lantuit, H., Loginova, A., Martynov, F., Overduin, P. P., and Wegner, C.: Ocean Colour remote sensing in the Southern Laptev Sea: evaluation and applications, Biogeosciences Discuss., 10, 3849–3889, doi:10.5194/bgd-10-3849-2013, 2013.

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10, 20179–20237, 2013
Lena Delta hydrology and geochemistry
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Hoelemann, J. A., Schirmaher, M., and Prange, A.: Seasonal variability of trace metals in the Lena River and the south-eastern Laptev Sea: impact of the spring freshet, Global Planet. Change, 48, 112–125, 2005.

Horton, R. E.: Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology, Bull. Geol. Soc. Am., 56, 156 pp., 1945.

Hydrological yearbooks, basin of Kara Sea, Hydrometeoizdat, Leningrad, Russia, 6, 4–9, 1956–1973 (in Russian).

Hydrological yearbooks, basin of Laptev, East and Siberia and Chukchi Seas, Hydrometeoizdat, Leningrad, Russia, 8, 0–7, 1960–1974 (in Russian).

Hydrology of the Soviet Arctic Rivers, Proceeding of Arctic and Antarctic Research Institute, Marine transport, Leningrad, Russia, 1, 95 pp., 1956 (in Russian).

Instruction for Hydrometeorological stations and posts, Part I: Hydrological measurements and work on big and middle rivers, 6, Hydrometeoizdat, Leningrad, Russia, 384 pp., 1978 (in Russian).

Ivanov, V. V.: Runoff and velocities of the main Lena River delta branches, in: Proceeding of Arctic and Antarctic Research Institute/Hydrology of rivers of the Soviet Arctic, 234, 5, Marine transport, Leningrad, USSR, 76–86, 1963 (in Russian).

Ivanov, V. V. (Ed.), Piskun, A. A., and Korabel, R. A.: Runoff distribution between main branches of the Lena River delta, in: Proceeding of Arctic and Antarctic Research Institute: Calculations and predictions of hydrological regime of estuary area of Arctic Rivers, Hydrometeoizdat Leningrad, USSR, 378, 59–71, 1983.

Ivanov, V. V. and Piskun, A. A.: Distribution of the river water and suspended sediment loads in the deltas of rivers in the basin of the Laptev and East-Siberian Seas, in: Land-Ocean Systems in the Siberian Arctic: Dynamics and History, edited by: Kassens, H., Bauch, H. A., Dmittrenko, I. A.„ Eicken, H., Hubberten, H.-W., Mellis, M., Thiede, J., and Timokhov, L. A., Springer-Verlag Berlin, 239–250, 1999.

Izrael, Y. A., Chernogayev, G.M, Egorov, V. I., Peshkov, Y. V., and Kotlyakova, M. G.: Review of contamination in the Russian Federation in 2003: Coast of the Arctic seas: the Lena River basin, Roshydromet, Moscow, Russia, 142–144, 2004 (in Russian).

Izrael, Y. A., Chernogayev, G. M., Egorov, V. I., Peshkov, Y. V., and Kotlyakova, M. G.: Review of state and pollution of Russian Federation environment in 2011, Roshydromet, Moscow, Russia, 105–106, 2012 (in Russian).

Kane, D. L., McNamara, J. P., Yang, D., Olsson, P. Q., and Gieck, R. E.: An extreme rainfall/runoff event in Arctic Alaska, J. Hydrometeorol., 4, 1220–1228, 2003.
Kondratyev, N. E., Popov, I.V., and Snischenko, B. F.: Fundamentals of hydro-morphological theory of channel process, Hydrometeoizdat, Leningrad, USSR, 272 pp., 1982 (in Russian).
Korotaev, V. N.: Formation of the hydrographic net of the Lena delta in Holocene, Vestnik of MSU: Geography, 6, 39–44, 1984a (in Russian).
Korotaev, V. N.: Study of river-bed and hydrological regime of the Lena River estuary and feasibility of measure of deep-water route support in the navigate branches in the mouth area (results of study 1979–1981), in: Report of MSU, Moscow, USSR, 68 pp., 1984b (in Russian).
Korotaev, V. N. (Ed.): Investigation of river-bed and hydrological regime of the Lena estuary area and support of a deep route arrangement on navigation channel of the delta and coastline (results of work 1979–1981), Report of MSU, Moscow, USSR, 68 pp., 1984c (in Russian).
Korotaev, V. N. and Chistykov, A. A.: Sedimentation processes in the estuaries areas of rivers, Vestnik of MSU: Geography, 5, 3–7, 2002 (in Russian).
Lisitzin, A. P.: Avalanche sedimentation and sedimentation disconformities in seas and oceans, Nauka, Moscow, USSR, 308 pp., 1988 (in Russian).
Morgenstern, A., Grosse, G., Günther, F., Fedorova, I., and Schirrmeister, L.: Spatial analyses of thermokarst lakes and basins in Yedoma landscapes of the Lena Delta, The Cryosphere, 5, 849–867, doi:10.5194/tc-5-849-2011, 2011.
Nikanorov, A. M.: Hydrochemistry: manual, Hydrometeoizdat, St. Petersburg, Russia, 444 pp., 2001 (in Russian).
Rachold, V., Grigoriev, M., Are, F., Solomon, S., Reimnitz, E., Kassens, H., and Antonov, M.: Coastal erosion in riverine sediments discharge in the Arctic Shelf seas, Int. J. Earth Science, 89, 450–460, doi:10.1007/s005310000113, 2000.
Rawlins, M. A., Ye, H., Yang, D., Shiklomanov, A., and McDonald, K. C.: Divergence in seasonal hydrology across northern Eurasia: Emerging trends and water cycle linkages, J. Geophys. Res., 114, D18119, doi:10.1029/2009JD011747, 2009.
Reshet'ko, N. V. and Shvarzeva, N. M.: Basis of climatology and hydrology: methodic instruction for laboratory work realization for a course of lectures "Basis of climatology and hydrology" for student of 3d course, studying by specialization 280400 "Nature provision of the necessary facilities", Publisher by the Tomsk Polytechnic University, Tomsk, Russia, 39 pp., 2010 (in Russian).

Resource of surface water of USSR: Leno-Indigirskiy region, Hydrometeoizdat, Leningrad, USSR, 17, 649 pp., 1972 (in Russian).
Riordan, B., Verbyla, D., and McGuire, A. D.: Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images, J. Geophys. Res., 111, G04002, doi:10.1029/2005JG000150, 2006.
Rozhdestvenskiy, A. V. and Chebotarev, A.: Statistical methods in hydrology. Hydrometeoizdat, Leningrad, USSR, 424 pp., 1974 (in Russian).
Savenko, V. S.: Chemical composition of world River's suspended matter, GEOS, Moscow, Russia, 174 pp., 2006 (in Russian).
Schirrmeister, L., Froese, D., Tumskoy, V., Grosse, G., and Wetterich, S.: Yedoma: Late Pleistocene Ice-Rich Syngenetic Permafrost of Beringia, in: The Encyclopedia of Quaternary Science, edited by: Elias, S. A., Elsevier, 3, 542–552, 2013.
Schpakova, R. N.: Formation of water quality in the Lena River nowadays, in: Abstracts of Ph.D. Thesis of Geographical science, Moscow, Russia, 175 pp., 1999 (in Russian).
Schwamborn, G., Rachold, V., and Grigoriev, M. N.: Late Quaternary sedimentation history of the Lena Delta, Quaternary Int., 89, 1, 119–134, 2002.
Seleznev, P. V. (Ed.): Report of hydrological work in the Lena River delta in 1985, TTUGMiKPS, Hydrographic party, Tiksi, USSR, 88 pp., 1986.
Semiletov, I. P., Pipko, I. I., Shakhova, N. E., Dudarev, O. V., Pugach, S. P., Charkin, A. N., McRoy, C. P., Kosmach, D., and Gustafsson, Ö.: Carbon transport by the Lena River from its headwaters to the Arctic Ocean, with emphasis on fluvial input of terrestrial particulate organic carbon vs. carbon transport by coastal erosion, Biogeosciences, 8, 2407–2426, doi:10.5194/bg-8-2407-2011, 2011.
Shiklomanov, I. A.: Anthropogenic changes of water content of rivers, Hydrometeoizdat, Leningrad, USSR, 345 pp., 1979 (in Russian).
Shiklomanov, A. I. and Lammers, R. B.: Record Russian river discharge in 2007 and the limits of analysis, Environ. Res. Lett., doi:10.1088/1748-9326/4/4/045015, 2009.
Snischenko, D. V.: Using of aero cosmic information using in river-bed processes estimation. Proceeding of the Vth All-Union hydrological congress/River-bed processes and sediments, Hydrometeoizdat, Leningrad, USSR, 10, 55–59, 1988 (in Russian).
State water cadaster, Hydrometeoizdat, Leningrad, USSR,1, 10–11, 1989–1994 (in Russian).

BGD
10, 20179–20237, 2013
Lena Delta hydrology and geochemistry
I. Fedorova et al.

Stein, R. and Fahl, K.: The Laptev Sea: Distribution, sources, variability and burial of organic carbon, in: The Organic Carbon Cycle in the Arctic Ocean, edited by: Stein, R. and Macdonald, R. W., Springer, 213–237, 2004.

Syvitski, J. P. M.: Supply and flux of sediment along hydrological pathways: research for the 21st century, Glob. Planet. Change, 39, 1–11, 2003.

Usachyov, V. F. (Ed.): Recommendations about aero cosmic information using in river-bed processes investigation. Hydrometeoizdat, Leningrad, USSR, 50 pp., 1985 (in Russian).

Wagner, D., Overduin, P., Grigoriev, M. N., Knoblauch, C., and Bolshiyanov, D. Yu. (Eds.): Russian-German Cooperation SYSTEM LAPTEV SEA: The Expedition LENA 2008, Reports on Polar and Marine Research, Alfred Wegener Institute for Polar and Marine Research, Germany, hdl:10013/epic.38929.d001, 2012.

Walker, H. J.: Arctic deltas, J. Coast. Res., 14, 718–738, 1983.

Wegner, C., Bauch, D., Hölemann, J. A., Janout, M. A., Heim, B., Novikhin, A., Kassens, H., and Timokhov, L.: Interannual variability of surface and bottom sediment transport on the Laptev Sea shelf during summer, Biogeosciences, 10, 1117–1129, doi:10.5194/bg-10-1117-2013, 2013.

Wetterich, S., Schirrmeister, L., Andreev, A., Pudenz, M., Plessen, B., Meyer, H., and Kunitsky, V. V.: Eemian and Late Glacial/Holocene palaeoenvironmental records from permafrost sequences at the Dmitry Laptev Strait (NE Siberia, Russia), Palaeogeogr. Palaeocl., 279, 73–95, doi:10.1016/j.palaeo.2009.05.002, 2009.

Woo, M.-K., Kane, D. L., Carey, S. K., and Yang, D.: Progress in permafrost hydrology in the new millennium, Permafrost Periglac. Process., 19, 237–254, 2008.

Ye, B., Yang, D., and Kane, D. L.: Changes in Lena River streamflow hydrology: human impacts versus natural variations, Water Resour. Res., 39, 1200, doi:10.1029/2003WR001991, 2003.

Ye, B., Yang, D., Zhang, Z., and Kane, D. L.: Variation of hydrological regime with permafrost coverage over Lena Basin in Siberia, J. Geophys. Res.-Atmos., 114, D07102, doi:10.1029/2008JD010537, 2009.

Yearbook of quality of surface water in the territory of the Omsk Department for Hydrometeorology and Environmental Monitoring, Hydrometeoizdat, Leningrad, USSR, 6, 4–9, 1989–2012 (in Russian).

Zubakina, A. N.: Particularities of hydrochemical regime of the Lena estuary area, Proceeding of GOIN, 143, 69–76, 1979 (in Russian).

Table 1. Measured discharges Q ($m^3 s^{-1}$) for the main branches. All discharges have been calculated normalized to one water level equal to 365 cm at the Bykovskaya branch water gauge at Khabarova.

The Lena delta main branches	2002	2004	2005	2006	2007	2008	2010	2011	2012
Main Lena Channel	18 854		29 897		26 171		23 776* (01.08.2010)	31 998* (20.08.2011)	25 380* (29.08.2012)
Olenekskaya branch	2023	2021	1693	2335	1700	1778	1406* (02.08.2010)	1180	1696
Bykovskaya branch	4007		5641		6140			4353	
Trofimovskaya branch	12 824		15 038		14 800		20 800		15 299
Tumatskaya branch	2023	1746	1462	1730	1690	1037	2800	1225	643

* Measured water discharges without normalization

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Table 2. The measured areas and volumes of Trofim-Kumaga sands over various time periods.

Period	Changes of area for each period, km^2	Changes of volume for each period, km^3	Mean changes of volume, $km^3\,yr^{-1}$
1951–1973	4.13	2.45	0.11
1973–2000	1.50	6.09	0.23
1951–2000	5.63	7.73	0.16

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Table 3. The range of dissolved element content concentrations of (main ions and trace elements) in Lena River delta water from 2010 to 2011 laboratory tests.

Type of elements	Element	Range of concentration, $mg\,L^{-1}$	Mean value, $mg\,L^{-1}$
Main ions	Ca	15.2–18.9	16.8
	K	0.5–1.1	0.6
	Mg	3.6–4.5	4.0
	Na	4.1–8.8	5.5
	Cl	4.7–13.5	7.1
	SO_4	8.8–18.1	10.6
	HCO_3	12.0–50.8	27.8
Mineralization		63.8–83.9	71.8
Microelements	Al	0.009–0.07	0.017
	Fe	0.012–0.042	0.023
	Si	1.6–2.1	1.8
	Li	0.010	
	Ba	0.007–0.016	0.013
	Sr	0.124–0.148	0.13
Trace elements	Ni	0.020	
	Pb	0.050	
Nutrients	Silicates SiO_2	1.4–2.4	1.8
	Phosphates PO_4	0.003–0.026	0.005
	Nitrites NO_2	0.003–0.011	0.006
	Nitrates NO_3	0.003–0.035	0.02

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Table 4. Mineralization and temperature in the Lena River delta small branches and streams according to the field measurement data.

Stream/channel	Temperature, °C	Mineralization, $mg\,L^{-1}$
Ysy–Khaya–Tyobyulege branch	10.6	80
Stream 1 from Kurungnakh Isl.	6	285
Stream 2 from Kurungnakh Isl.	6	227
Sistyakh–Aryi–Uesya branch	11.2	53
Krestyakhskaya branch	10.2*	56
Stream 3 from Arga–Bilir–Aryita Isl.	–	162

* Measurement conducted on 22.08.2012; other data gathered collected on 08.08.2012

Table 5. Chemical elements found in suspended material from the Lena River delta according to 2002–2012 laboratory tests with comparison of data from Savenko (2006), Hoelemann et al. (2005), and Gordeev (2009). SPM: suspended particulate matter.

Component	Range of concentration	Mean value	Element concentration in SPM		
			Hoelemann et al. (2005)	Savenko (2006)	Gordeev (2009)
Al_2O_3, mg G^{-1}	11.9–15.9	14.2		13.91	
CaO, mg G^{-1}	0.8–1.5	1.2		5.43	
Fe_2O_3, mg G^{-1}	4.9–6.4	5.7		2.25	
K_2O, mg G^{-1}	2.2–3.0	2.6		1.57	
MgO, mg G^{-1}	1.5–2.1	1.8		2.15	
Na_2O, mg G^{-1}	1.4–1.9	1.7		2.82	
SiO_2, mg G^{-1}	66–88	70		71.87	
Li, µg G^{-1}	49–61	53		42	
Ba, µg G^{-1}	535–944	618		734	
Pb, µg G^{-1}	57–347	157	38	102	28
Sr, µg G^{-1}	147–221	182	–	195	194
Ni, µg G^{-1}	43–64	53	28	52	47
V, µg G^{-1}	970 127	113	–	84	97

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Table 6. Nomenclature.

H, m	water-levels.
Q, $m^3\,s^{-1}$	daily water discharges.
R, $kg\,s^{-1}$	sediment discharges.
K	the discharge rate for a series of observations.
M_i	the value of a single element in the series.
M_a	the average of all the observations.
$(K-1)$	deviations from the mean.
Cv	coefficient of variation.
$F(t)$	the integral curve.
t	a period of time.
h, m	depth on the vertical.
v_{1-n}, $m\,s^{-1}$	average current velocity on the 1st–n velocity verticals.
f_0, m^2	water-section area between the bank and the 1st velocity vertical.
f_1, m^2	water-section area between the 1st and 2nd velocity vertical, etc.
f_n, m^2	water-section area between the last vertical n and the bank.
V_m	averaged velocity over the 1–n velocity verticals.
V_s	velocity on the surface of a vertical.
$V_{02\,h}$	velocity on the horizont 0.2 h.
$V_{06\,h}$	velocity on the horizont 0.6 h.
$V_{08\,h}$	velocity on the horizont 0.8 h.
V_b	bottom velocity.
h_{1-n}	depths of the measured verticals.
$b_1, b_2, \ldots, b_{n-1}$	distance between the measured verticals.
b_0, b_n	distances between outer measured verticals and encroachment lines.
q_i, $m^3\,s^{-1}$	water discharge between verticals.
s_i, $mg\,L^{-1}$	mean turbidity between verticals.
σ_{sys}	the systematic error of water discharge measurements.
σ_{ran}	the random experimental error of water discharge measurements.
S_Q	the summarized field observations error.

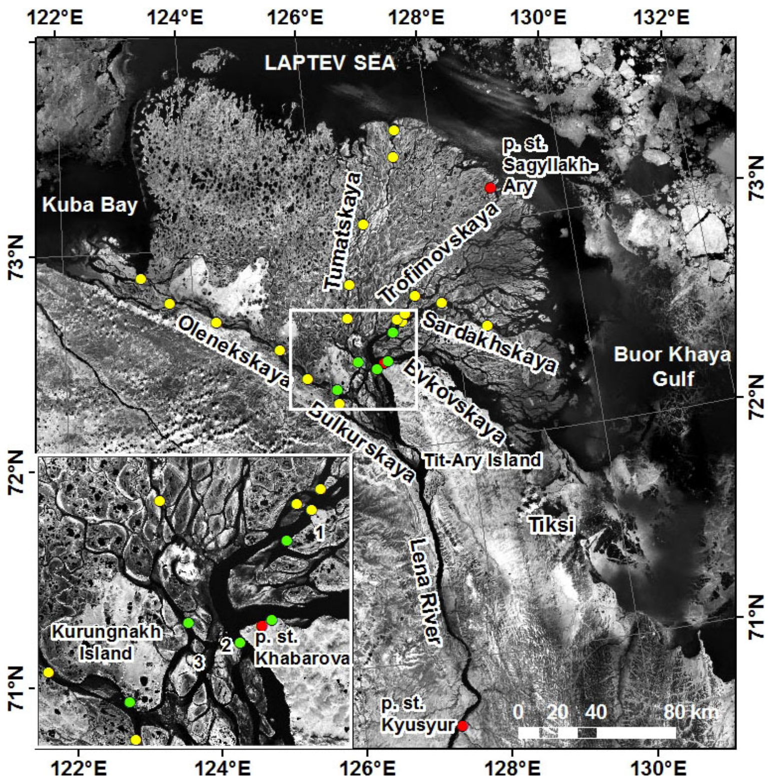

Fig. 1. Measurement profiles in the Lena River delta during expeditions from 2002–2012: red circles: polar stations of Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) (Hydrometeoizdat, 2002–2012); green circles: standard hydrometeorological cross sections of Roshydromet; yellow circle s: additional cross sections along the branches.

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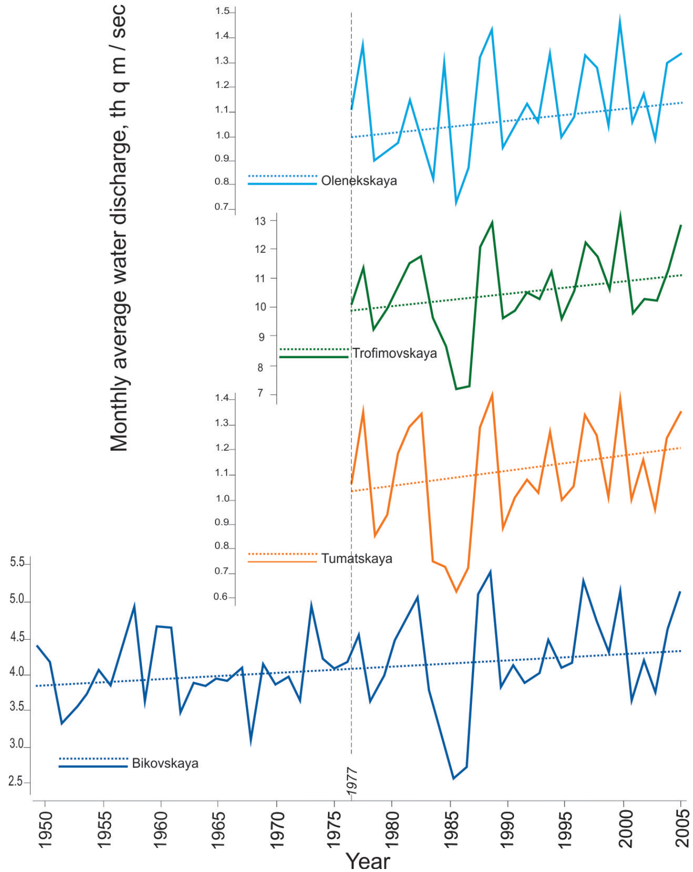

Fig. 2. Average annual water discharge from 1950–2005 on branches of the Lena River delta according to data from the Roshydromet (Hydrometeoizdat, 2002–2005).

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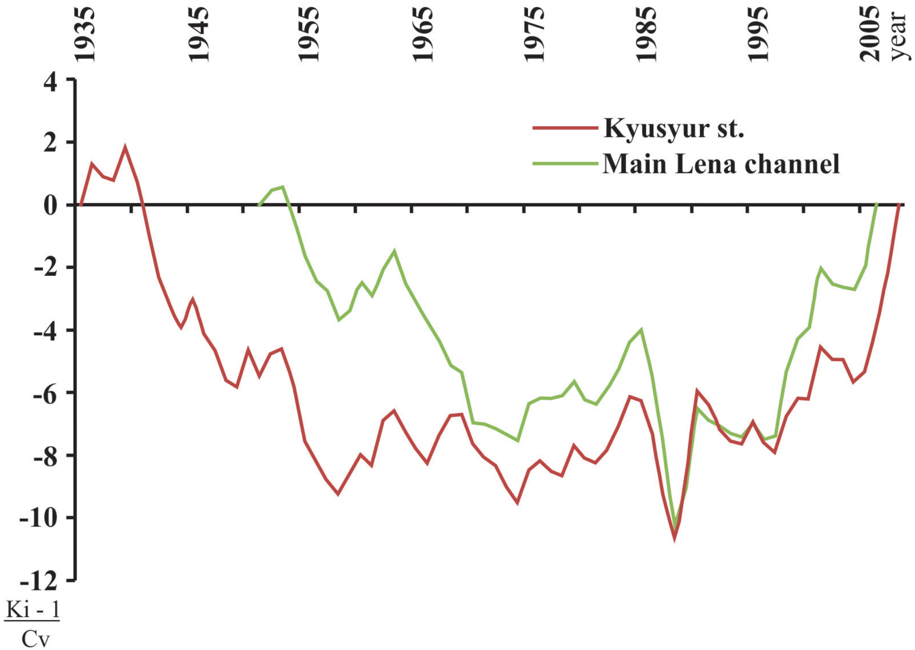

Fig. 3. Differential integral curve of average annual water discharge from 1935–2007 in the Lena River at Kyusyur, and from 1951–2005 in the Lena River main channel, at a cross Sect. 4.7 km upriver from Khabarova.

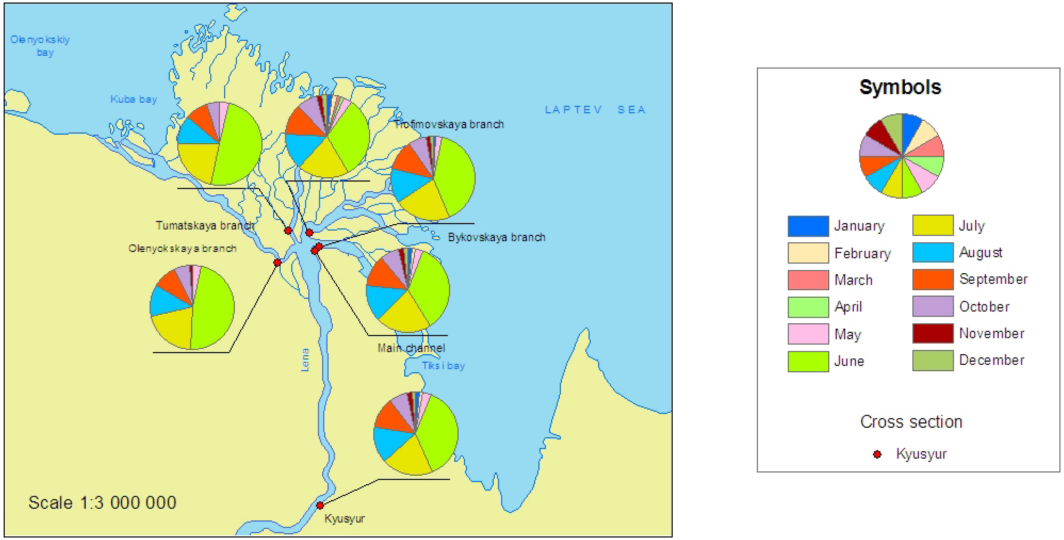

Fig. 4. Intra-annual distribution of average annual suspended sediment supply in the Lena River delta.

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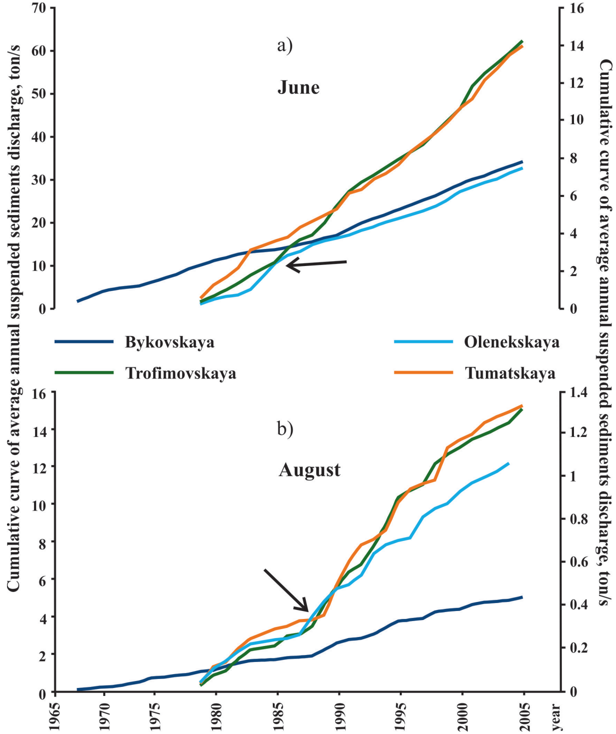

Fig. 5. Growing amounts cumulative average monthly suspended sediment supply from the main delta branches according to data from the Russian hydrometeorological network for June **(a)** and August **(b)**. Right axis is for Olenekskaya and Tumatskaya branches, left axis is for Bykovskaya and Trofimovskaya branches. The arrows represent point of suspended sediment discharge change to increase.

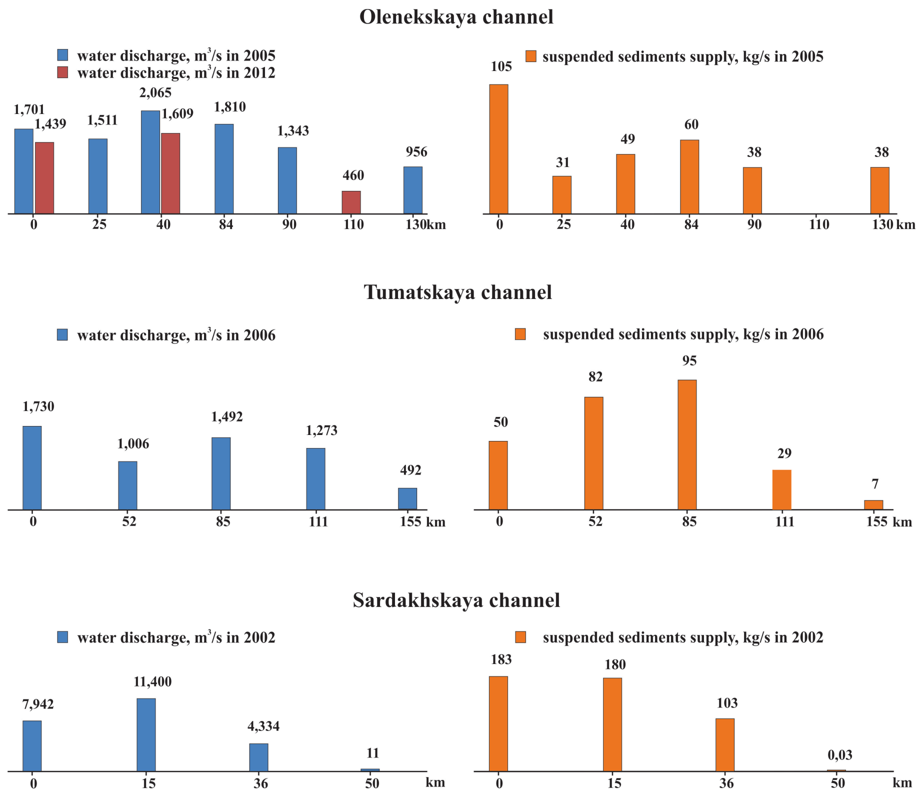

Fig. 6. Discharge of water and sediments along the branches: on the Olenekskaya branch during 2005 and 2012, on the Tumatskaya branch during 2006, and on the Sardakhskaya branch during 2002. The distance of the presented cross section from the standard hydrometeorological cross sections of Roshydromet is shown on the abscissa axis. The position of the standard hydrometeorological cross sections of Roshydromet on the branch (cross section near Gogolevsky Island for the Sardakhskaya branch) is taken as zero.

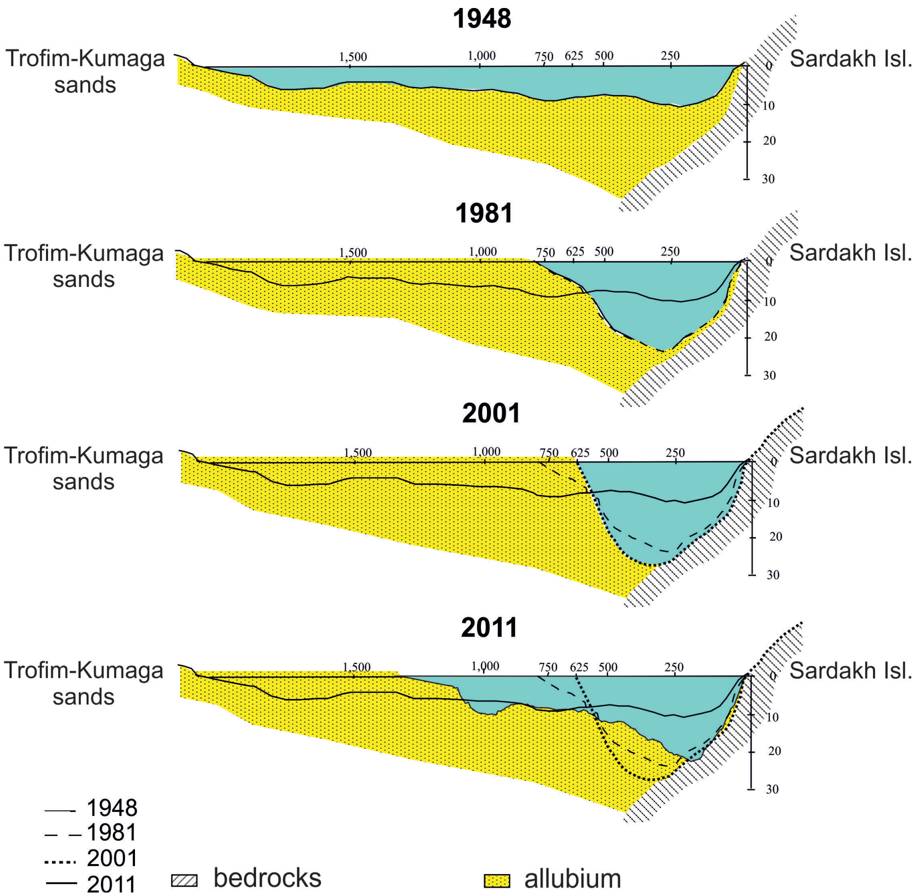

Fig. 7. River-bed deformations changes of the Trofimovskaya branch in a Sardakh-Khaya – Trofim-Kumaga cross section near Sardakh Island. The abscissa axis is a distance (m) from Sardakh Island, the ordinate axis is a depth (m) of the Trofimovskaya branch.

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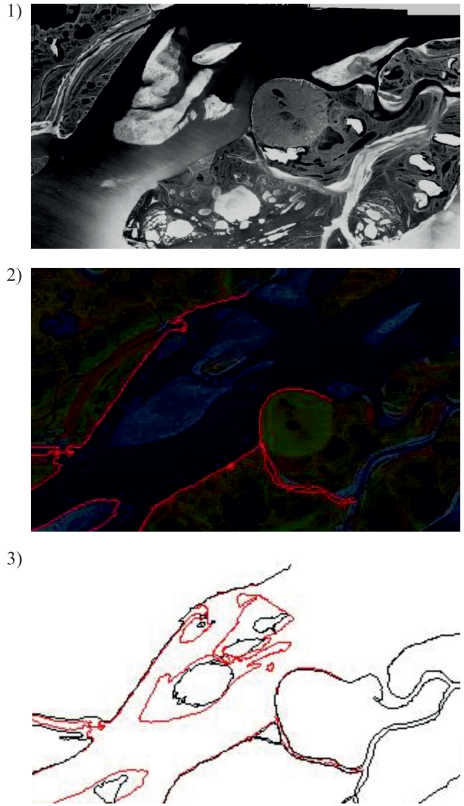

Fig. 8. Bank contours in the Sardakh Island area (1) on 10.07.1951 (aerial image), (2) on 05.08.2000 (Landsat TM satellite image), (3) digitized contours islands, watercourses and water basins (red contour line for 1951, black for 2009).

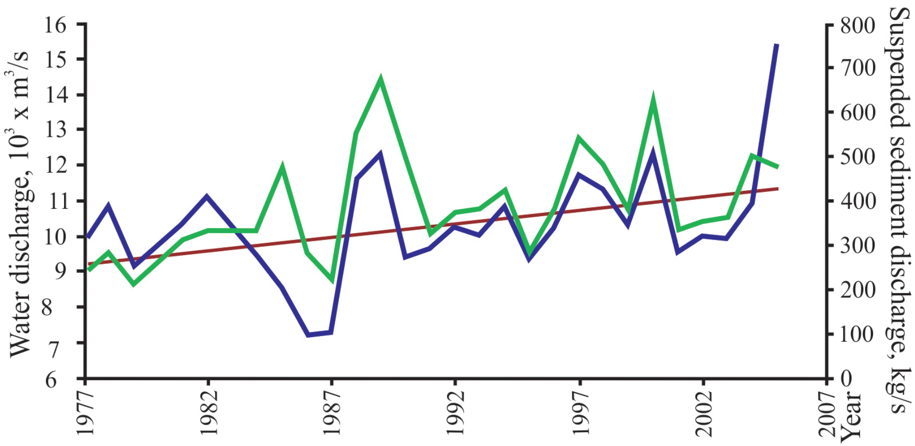

Fig. 9. Average annual of water discharge and suspended sediment supply on the Trofimovskaya branch over the period of instrumental observations according to data from the Roshydromet (Hydrometeoizdat, 2002–2012).

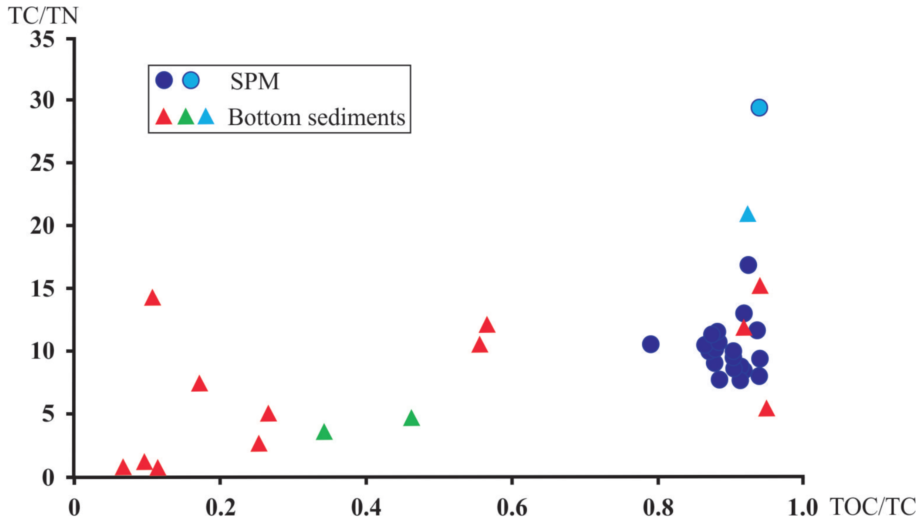

Fig. 10. Carbon and nitrogen content in suspended particulate material (SPM) and bottom sediments of the branches (abscissa axis: TOC/TC, ordinate axis: TC/TN); light blue circle: Angardam branch SPM; light blue triangle: Bulkurskaya bottom sediments; red triangles: bottom sediments of the other Lena channels; green triangles: streams from an ice complex; dark blue circles SPM of the Lena channels.

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Fig. 11. Ice on the sands of Sistyakh-Ariyta Island after a flood.

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Fig. 12. River ice during a flood on the Olenekskaya branch (photo by M. Grigoriev).

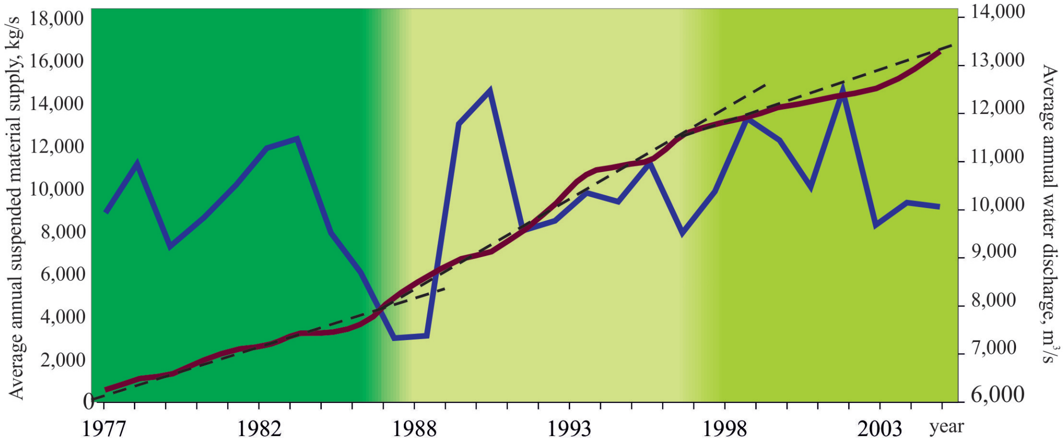

Fig. 13. Long-term average annual water (blue line) and the growing amount of average suspended sediments (red line) discharges over the period of instrumental observation. Dotted lines are trends of suspended sediments discharges for three periods with different annual water volume (green tints).

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