Polarforschung 87 (2), 81 – 88, 2017 (erschienen 2018)

Geographical Profile of the Lena Delta Area and a History of Hydrologic Investigation of the Lena River Lower Reach and Delta

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Abstract: The delta of the Lena River is one of the most amazing river deltas of the world. It is located in the mouth of the second-large river of Russia, has a huge size, complex hydrographic and morphological structure and hydrological regime. The delta plays an important ecological role in the region as a sedimentation barrier to the river sediments and pollutants coming to the sea, serves as a place of spawning, feeding and migration of numerous fishes, habitat of migratory and local birds, Arctic mammals, etc. It represents the "sea gate" of Yakutia. On the other hand, being centuries-old result of specific estuarial processes, it continues to evolve also due to climate change. It involves hydrological, economic and ecological consequences, which have been the subject of research by many scientists since 1920th. In the last 20 years the investigation of the processes in the Lena Delta is supported by numerous Russian-German research projects on the basis of the scientific station on the Samoylovsky Island.

Zusammemfassung: Das Lena Delta ist eines der erstaunlichsten Flussdeltas der Welt. Es liegt an der Mündung des zweitgrößten Flusses Russlands, hat eine riesige Größe, eine komplexe Hydrografie und morphologische Gliederung sowie hydrologisches Regime. Das Delta spielt in der Region eine wichtige ökologische Rolle als Barriere für Flusssedimente und Schadstoffe vor dem Eintrag in das Meer; es dient als Laichplatz und Futterplatz für Zahlreiche Fische, als Lebensort für zahlreiche lokale Vögel und Standort für viele Zugvögel, für arktische Säugetiere usw. Das Delta ist für Yakutien das Tor zum Meer. Zum anderen bietet es als Jahrhunderte altes Ergebnis spezifischer aestuariner Bildungsprozesse ein Beispiel für die Entwicklung unter dem Einfluss des Klimawandels. Das schließt hydrologische, ökonomische und ökologische Folgen ein, die seit den 1920er Jahren viele Wissenschaftler beschäftigen. In den letzten 20 Jahren wurde die Untersuchung der im Delta ablaufenden Prozesse von zahlreichen Russisch-Deutschen Projekten im Umfeld der wissenschaftlichen Station auf der Samoylov Insel unterstützt.

NATURAL GEOGRAPHICAL FEATURES

The Lena River is one of the largest rivers on the globe, the second in Russia after the Yenisei River by runoff, which amounts to ~543 km^3 per year, and the third by its watershed area. The Lena's length is estimated 4,400 km. The catchment area totals 2,490,000 km^2, and permafrost underlies nearly the whole area. The Lena starts in the mountains that frame Lake Baikal, 10 km from the western shore of the lake. The upper reaches of the river are situated within the boundaries of the Irkutsk Region, Zabaikalsky, Krasnoyarsky and Khabarovsky Krai, Buryat Republic. The major part of the river basin, as well as its mouth, is located within the Sakha Republic (Yakutia). At its entrance into the Laptev Sea, the Lena forms a huge delta with a network of multiple distributary channels. Before that, the Lena cuts through the Verkhoyansk Range forming the narrowing of the so-called "Lena Pipe" of 150 km in length and 2 to 2.5 km in width. Between the Khara-Ulakh mountains and the Chekanovsky ridge the river flows through the valley of only 1.5 to 4 km wide. The ridge rises 250-300 m over the delta valley.

The head of the Lena Delta is situated at the connection of the Lena Pipe's end and a funnel shaped widening of the river valley at Tit-Ary Island (Fig. 1). Here the Bulkursky branch cuts the left shore, flows northwest and discharges into Olenek channel, which frames the delta in the southwest. The head of the delta is situated 170 km from the sea and 64 km from the rocky island Stolb, the major joint where the largest delta channels take their start. The part of the Lena between the head of the delta and Stolb island is called Main channel. The pre-estuary section of the Lena River is considered the end segment of its lower reach, between the settlement of Kyusyur (Kusur) and the head of the delta. While storm surges or tides never reach the head of the delta (Mikhailov 1997) it is considered the upper boundary of the mouth region of the Lena River.

The delta of the Lena was formed as a result of filling by the river sediments the sea bays that appeared after the rise of the Arctic Ocean level in the last 5-7 thousand years. The formation of independent extended deltas by some of the channels, erosion and abrasion of the older landforms by the waters both of the sea and the river also contributed to the delta formation process (Bolshiyanov et al. 2013, Korotaev et al. 2007). At present, the Lena Delta is considered classical delta extending onto the open micro-tidal estuary seashore and of multi-arm sub-type (Mikhailov 1997). The area of the delta with its head at Tit-Ary island, as estimated earlier, amounts to 32,000 km^2 (Antonov 1967, Lopatin & Fedorov 1947-1948), and with its head at the Island of Stolb it amounts to 28,300 km^2. According to the new data (Bolshiyanov et al. 2013, Schneider et al. 2009) the area of the delta with the top at the Island of Tit-Ary amounts to 29,630 km^2. This means it is the largest river delta in Russia and the 5-6th largest in the world. However, if we consider only that part of the delta which has been formed by the accumulation of the river sediments since the end of the last transgression of the World Ocean and during the period of relative stabilization of its level, its area is close to 21,000 km^2 (Korotayev et al. 1990, Bolshiyanov et al. 2013). The delta coastline to the sea is strongly indented; its entire length is 1,930 km (Lopatin & Fedorov 1947-1948).

Keywords: Arctic, river mouths, delta channels, hydrologic exploration

doi:10.2312/polarforschung.87.2.81

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Manuscript received 19 May 2017; accepted in revised form 26 June 2018.

Fig. 1: The scheme of the Lena River delta with the positions of main gauge stations measuring discharges (black circles) and water levels (white circles) and permanent gauging cross-sections presented by: 1: "4.7 km upper Stolb Island" (the end of Main channel); 2: "Olenekskiy" (Olenekskaya channel); 3: "Tumatskiy" (Tumatskaya channel); 4: "Trofimovskiy" (Trofimovskaya channel), in the head of respective channels.

Abb. 2: Übersicht über das Lena Delta mit Lage der wichtigsten Pegel Stationen, die den Abfluss messen (schwarzer Kreis), den Wasserstand messen (weiße Kreise) und die permanenten Querschnittspegel bei 1: „4,7 km stromauf Insel Stolb"; bei 2: „Olenekskiy" (Olenekskaya Kanal); bei 3: „Tumatskiy" (Tumatskaya Kanal); bei 4: „Trofimovskiy" (Trofimovskaya Kanal) jeweils am Beginn der Kanäle.

The latitude of the most northern point of the delta is 73°48'24" N (on the island of the Danube 73°55'57" N), the most southern point (at the outlet of the river from the Lena Pipe) is 71°50'30" N. The longitudes of the western and eastern extremities of the delta are 122°04'00" E and 129°36'10" E, respectively. At the mouth's seashore, the delta is extended with underwater alluvial fans.

Natural environment of the Lena Delta is conditioned by its location in high polar latitudes, as well as on the coast of the arctic Laptev Sea, relatively close to the edge of the drifting and never melting sea ice masses. Another group of factors includes geology, geomorphology and hydrography of the delta, and the presence of permafrost.

The climate in the Lena Delta area is cold and typically continental. The average annual temperature is -14.2 °C (KOTLYAKOV 2007, HTTP://METEO.RU/DATA). Summers are cold (t_{July} = 4-8 °C), winters are harsh ($t_{January}$ = -33 °C) and not snowy; during the year, there is a long period of negative air temperatures, which is about 260 days. Total annual precipitation reaches 290-300 mm (with share of solid phase up to

50 %), annual evaporation is 130-135 mm, which characterizes the moisture condition of the delta as excessively humid (Hrawl 1996, Kotlyakov et al. 1997, Kotlyakov 2007). The severe and cold Arctic climate in the delta supports the preservation of permafrost, as well as of underground ice. The thickness of the permafrost layers reaches here 300-650 m; the depth of seasonal thawing of soils in summer is 0.5-1.5 m, the ice content of rocks reaches 20-40 % or more (up to 60-75 %), and repeated-wedge ice is widely spread (Kotlyakov et al. 1997, Kotlyakov 2007, Sakha Republic 2000). Under the Main channel, as well as under large branches and lakes, taliks (unfrozen ground layers) of various capacities are often formed.

The landscape of the Lena Delta has features both unique and typical for this region (Fig. 2). The unique ones resulted from the transformations of the huge water flow in the delta, due to the impact of certain seashore factors, differences in the genesis and the structure of morphologically diverse segments of the delta.

The Lena Delta can be divided into three large parts, morphologically homogeneous, but having different origins and age (Bolshiyanov et al. 2013, Grigoriev 1991, Korotaev et al. 2007, Morgenstern et al. 2001, Schwamborn et al. 2002; Fig. 2). The first part combines rocky eroded relics of the underlying bedrock (Stolb Island – the highest point of the delta, Amerika-Khaya Island) and, mainly, flat, also denuded, relics of the ancient Primorsky Plain landform, or Yedoma represented by the islands Hardang-Sissyo with the area of 1,136 km^2, Sardakh-Khaya, Sobo-Sissyo, Esme-Sissyo, Kurungnah and etc., enveloped by the Arynskaya and other

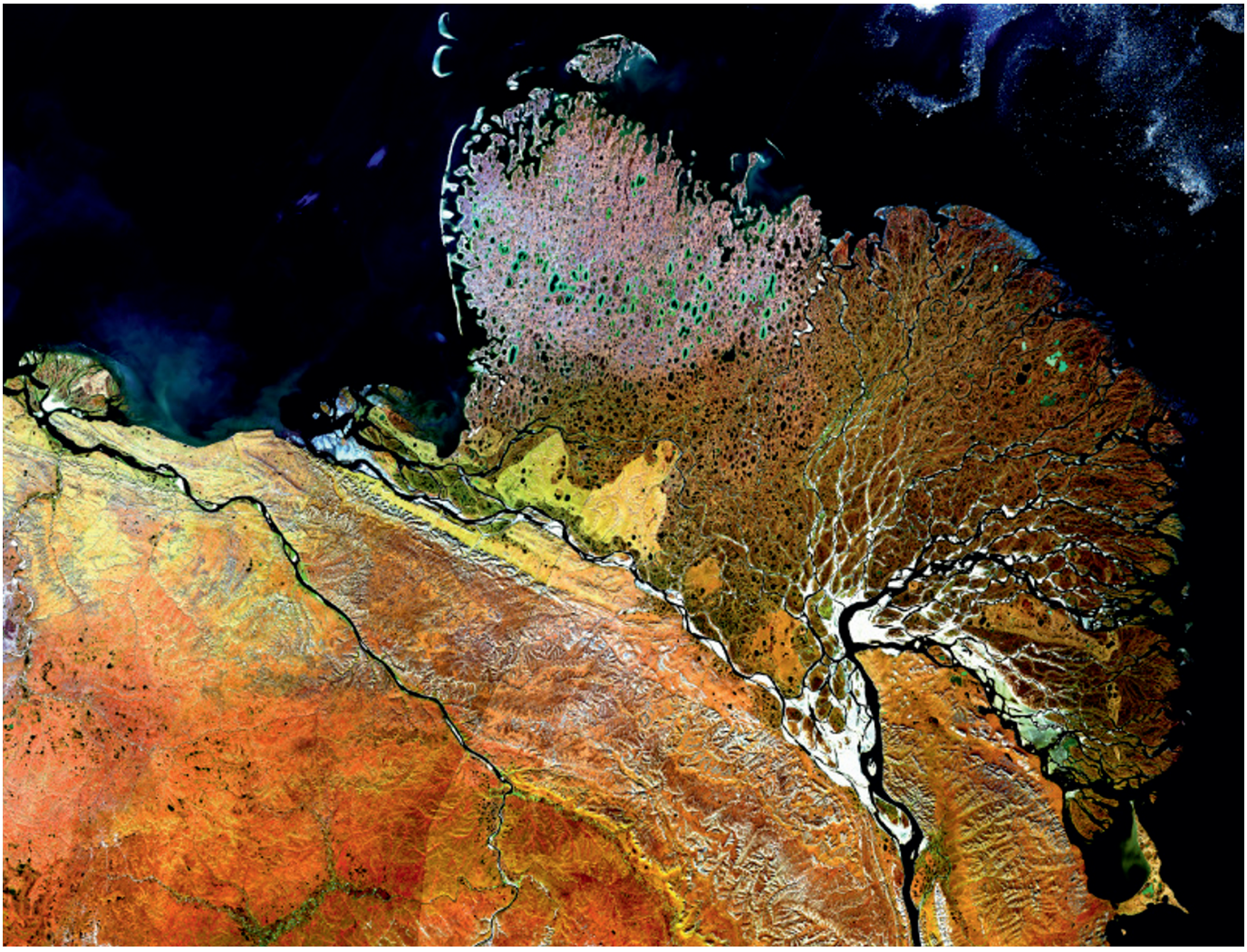


Fig. 2: Satellite image of the Lena Delta (mission Sentinel 2) showing the channel distribution, the white sandbanks and green floodplains with shrub and grasses and the three geomorphologic terraces. The "first Holocene terrace" is characterized by the darkest colour due to the large abundance of lakes and ponds and moisture. In the northwest – the "second terrace" – light pinkish colours indicate that there is not a great abundance of green vascular plant cover: the dry sandy 2nd terrace has a moss and lichen cover. The "third terrace", the Yedoma, is characterized by green-olive and light yellow-brown colours with much more green vegetation classified as shrub tundra (Kravtsova & Mitkinykh, 2013; personal communication with B. Heim).

Abb. 2: Satellitenaufnahme des Lena Deltas (Mission Sentinel 2) mit Darstellung der Kanalverteilung, den weißen Sandbänken, den grünen Überflutungsebenen mit Buschwerk und Gras und den drei geomorphologischen Terrassen. Die „Erste Holozän-Terrasse" ist charakterisiert durch dunkle Farben wegen der Häufigkeit von Seen und Tümpeln und Feuchtigkeit. Die „Zweite Terrasse" deren blassrosa Färbung auf eine weniger häufige Besiedlung durch grüne Gefäßpflanzen hindeutet: diese trockene, sandige Terrasse hat im Wesentlichen eine Moos- und Flechten-Bedeckung. Die „Dritte Terrasse", „die Yedoma" charakterisiert durch grün-olive und gelbbraune Farben wegen der kräftigeren grünen Vegetation wird als Strauchtundra klassifiziert (Kravtsova & Mitkinykh 2013 und pers. comm. B. Heim).

water channels, joining with the Olenekskaya channel down their flow. The relics of the Yedoma are located in the south and the southwest of the delta, rise up to 20-60 m, and are composed of ice-rich sediments. Their flat surface topography is modulated by deep thermokarst depressions that origin from former larger lake basins (Morgenstern et al 2011, 2013). Thermokarst valleys deeply dissect the Ice complex. The relics of the ancient Primorsky Plain are often called the "third terrace" of the Lena Delta.

The so-called "second terrace" (the second part of the delta) is also a very old and denuded area, but greater in size and less fragmented. It occupies the northwestern part of the delta (Arga-Muora-Sissyo Island of 5,320 km^2, and Jipiriyes-Sissyo Island), rising up from 11 to 30 m, dissected by shallow valleys, numerous lakes and alasses; composed of alluvial and marine sediments with low ice content, it has inclusions of ice veins. There are no delta watercourses on it.

The third, Holocene part of the delta or "first terrace", has completely different character, presenting three floodplain surfaces of various ages and a complex of modern channel forms, exposed in low water season (sand banks, braid bars, spits, shoals). It occupies the eastern, central and southern sectors of the delta. The height of the channel forms increases from 1 m at the sea and to 4 m near the delta head. The heights of the old, mature and young floodplains average 5-10 m (up to 12 m), 3-5 m and less than 3 m, respectively. The deposits of the old floodplain, which are in the stage of transition to the "first terrace" above the floodplain, already contain ice lenses. Delta channels and their water flood occupy a significant area of the Holocene part during floods and high water.

The delta areas not covered by water are mostly Arctic (25 % of the territory) and typical (75 %) wet and dry, sedge-moss, moss-grass, grass and shrub tundra (Alexeevsky 2007, Mikhaylov 1997, Kotlyakov 2007, Sakha Republic 2000, Wet lands of Russia 2000).

The number of watercourses in the delta is estimated 6,100 with their total length of 14,626 km (Ivanov et al. 1983). About 42 % of all delta watercourses belong to the Trofimovskaya channel system, 29 % to the Tumatskaya, 18 % to the Olenekskaya, 11 % to the Bykovskaya (Alexeevsky et al. 2014). Branches and shallows occupy 7,317 km^2 (Schneider et al. 2009). The number of thermokarst, oxbow lakes and lakes of other genesis is estimated about 59,000 (Ivanov et al. 1983), but going by the 1:100,000 scale map and according to (Bolshyianov et al. 2013) data there are at about 29,483 lakes. The area of the lakes is estimated from 3,196 to 6,175 km^2 (Ivanov et al. 1983, Schneider et al. 2009). Lakes, connected with riverbeds (oxbow and residual), prevail in the eastern part of the delta, while thermokarst lakes are observed in the western and, particularly, northwestern part (on the relics of old plains and sea terraces). The Lena Delta consists of about 1,600 islands of various genesis, morphology and elevation.

Water channels in the southwestern part of the delta belong to the Olenekskaya channel system (Fig. 3). This navigable arm, separates from the Main channel near the Stolb Island, flows westward to discharge into the Olenek Bay, forming a series of islands, essentially its own protruding delta, and a large river bar (Bolshiyanov et al. 2013, Ivanov et al. 1983, Korotaev et al. 1990). The channel is 210 km long, it takes from right the large Gusinaya and Arynskaya channels, and on the left Bulkurskaya channel, separating Angardamskaya channel, which flows into the same bay as an independent flow.

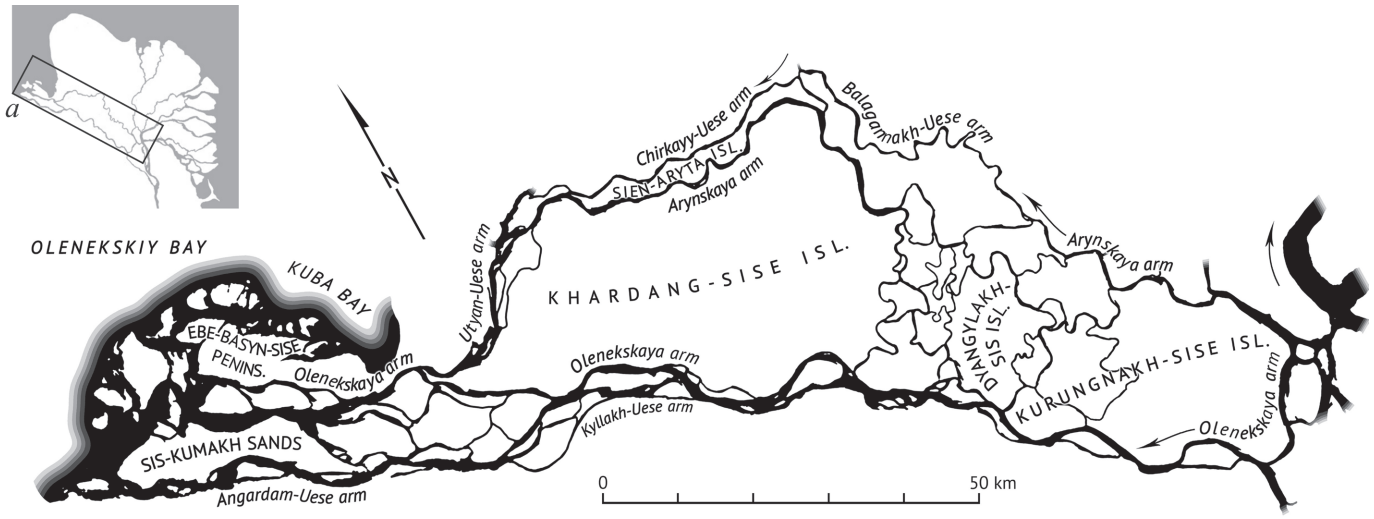
The eastern part of the delta is a complicated network of riverbeds belonging to Tumatskaya, Trofimovskaya and Bykovskaya channels, fanning out from the Stolb Island (Fig. 1). At their entrance into the sea, some of them form either widening mouths or small independent protruding deltas. Riverbed systems of the branches consist of numerous elements such as nodes of braiding and merging. Tumatskaya (or, Bol'shaya Tumatskaya) channel flows northward and is 155 km long (Fig. 4). To the west, two large Arynskaya and Malaya Tumatskaya channels and some smaller arms branch off Tumatskaya channel. Trofimovskaya channel is 142 km long; this flow is even larger and in fact continues the Lena River (Fig. 5). On the way to the sea, it divides into numerous smaller channels, flowing northeast and eastward, and several larger ones such as the Bolshaya and Malaya Trofimovskaya, Sardakhskaya (97 km), Barkhakh-Uesse and others. Bykovskaya branch (length 105 km) is the main navigable and the widest sleeve (Fig. 6). Its width at the beginning of high water is 5 km. It flows eastward into the Laptev Sea, passing to the right the residual Neyelov Bay, the Bykovskyi Peninsula (the remnant of Yedoma), and forming an elongated river bar. Kuruelyakh-Uesse and Byrdakhtakh-Uesse as well as other smaller channels flow from Bykovskaya channel to the left, and Sinitzyn channel flows to the right into Neelov Bay. Ispolatov channel continues Bykovskaya channel below the Dashka bottom bank.

Points of branching are dominating in the delta, being 1.9 times more numerous than the nodes of merging. The maximum intensity of the transverse flow distribution is characteristic of the Trofimovskaya watercourse system, where consistent decrease in the size of the Main channel due to its branching into sleeves occurs at 12 levels of bifurcation (flow dispersal). It is minimal in the direction of Olenekskaya channel, as this system has only five levels of bifurcation.

Geographic location and harsh natural environment tend to condition the specifics of the delta's socio-economic development. The Lena Delta's population is about 500 individuals, which is scarce. Main settlements are Tit-Ary, Turakh, Chai-Tumus, Bykovskiy. Major water transportation routes pass through the delta, joining the regions of Yakutia, belonging to different watersheds, as well as connecting the republic itself to the European part of Russia. River traffic and serving shipping on the Lena River are based on ports and quays in the delta and in Tiksi settlement. Regular dredging works in the river, navigable branches and in the mouth bars help to support navigation. Fishing in the delta channels and in the sea, is customary, and there are two fish processing plants in the delta.

A HISTORY OF HYDROLOGIC INVESTIGATION OF THE LENA RIVER LOWER REACH AND DELTA

The first visits to the delta by Russian explorers date back to the first half of the 17th century, namely years 1633 and 1636 (Bolshiyanov et al. 2013). Actual information about the Lena



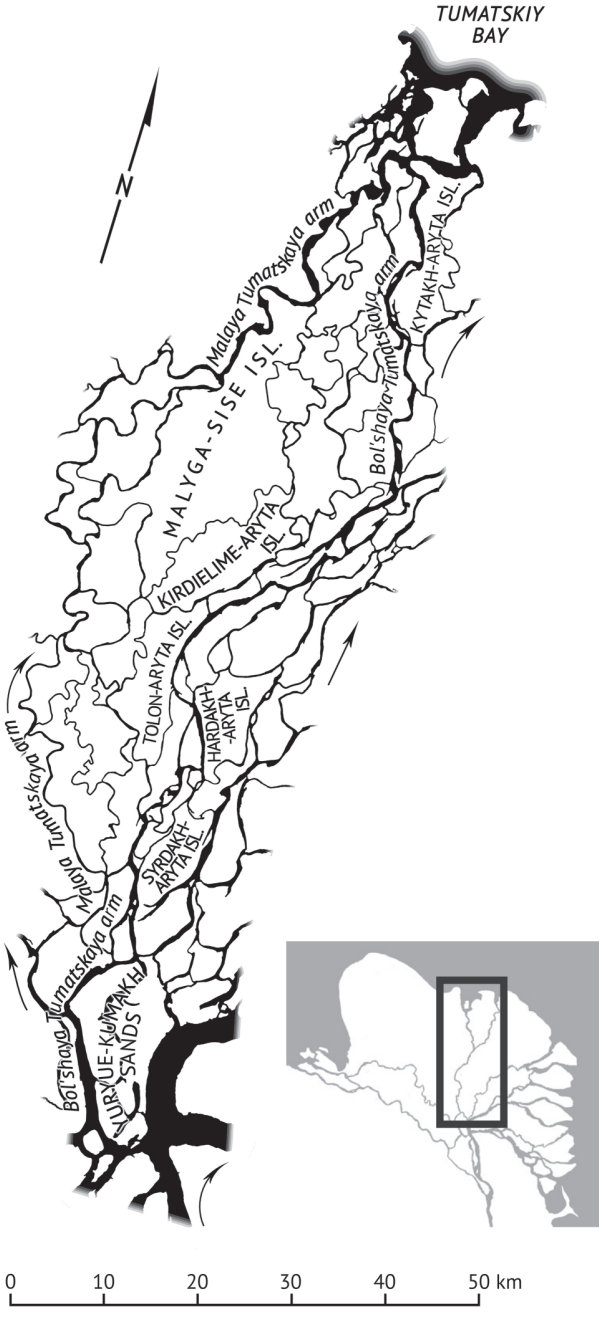


Fig. 3: Detailed scheme of channel systems of Olenekskaya deltoid branch.

Abb. 3: Detaillierte Übersicht über den Flussverlauf im Olenekskiy Kanalsystem.

Fig. 4: Detailed scheme of channel systems of Tumatskaya deltoid branch.

Abb. 4: Detaillierte Übersicht über den Flussverlauf im Tumatskiy Kanalsystem.

River mouth is reported to be filed during the Great Northern Expedition, which took place in 1733. In the 19th century, a number of complex expeditions worked here, run by P.F. Anjou (1821–1823) and N.D. Jurgens (1882–1884).

The first hydrologic measurements at pre-estuary area and in the delta, were performed in 1914–1921 due to rising requirements to navigable routes in the north of Yakutia. The first level gauge was organized in the village of Bulun (on the left bank of the Lena River, 308 km from the sea) in July 1914; it was functioning during several years. The first river discharge measurement was performed in September 1921 in a distance of 228 km from the sea (REYNBERG 1938). In 1934 regular observations started at the basin outlet station in the area of settlement Kyusyur.

In the first part of 1950s, Ust-Lensky hydrological expedition of the Arctic and Antarctic Research Institute installed permanent and temporary gauging stations within the delta area, and performed a significant number of hydrologic observations and measurements. At the source of Bykovskaya channel, the polar station Stolb (Fig. 1) was permanently installed in 1950 to monitor water levels, temperatures, flows and ice phenomena. This station was later renamed into Yu.A. Khabarova. In 1968 measurements of water turbidity and suspended sediment discharge started on the polar station Stolb (Yu.A. Khabarova). In 1948 a water stage station was installled near the head of the delta in the Tit-Ary settlement. In 1953 on Ispolatov channel, a polar station of Malyshev Island started to function.

In 1961 in the mouth of Trofimovskaya channel, a station of Sagyllakh-Ary was launched. The expedition determined the gauging stations in Bykovskaya, Trofimovskaya, Tumatskaya and Olenekskaya channels, in which measurements of water and sediment discharges were carried out in 1950–1953. The

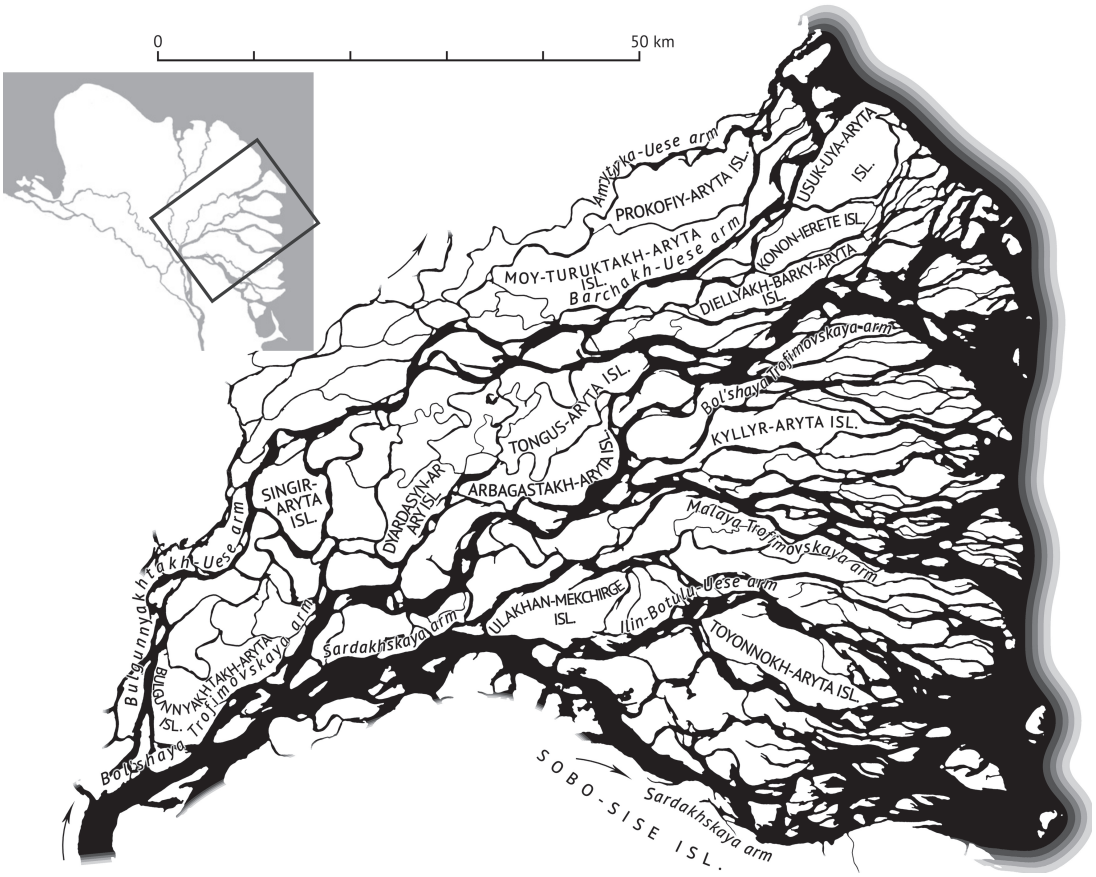


Fig. 5: Detailed scheme of channel systems of Trofimovskaya deltoid branch.

Abb. 5: Detaillierte Übersicht über den Flussverlauf im Trofimovskiy Kanalsystem.

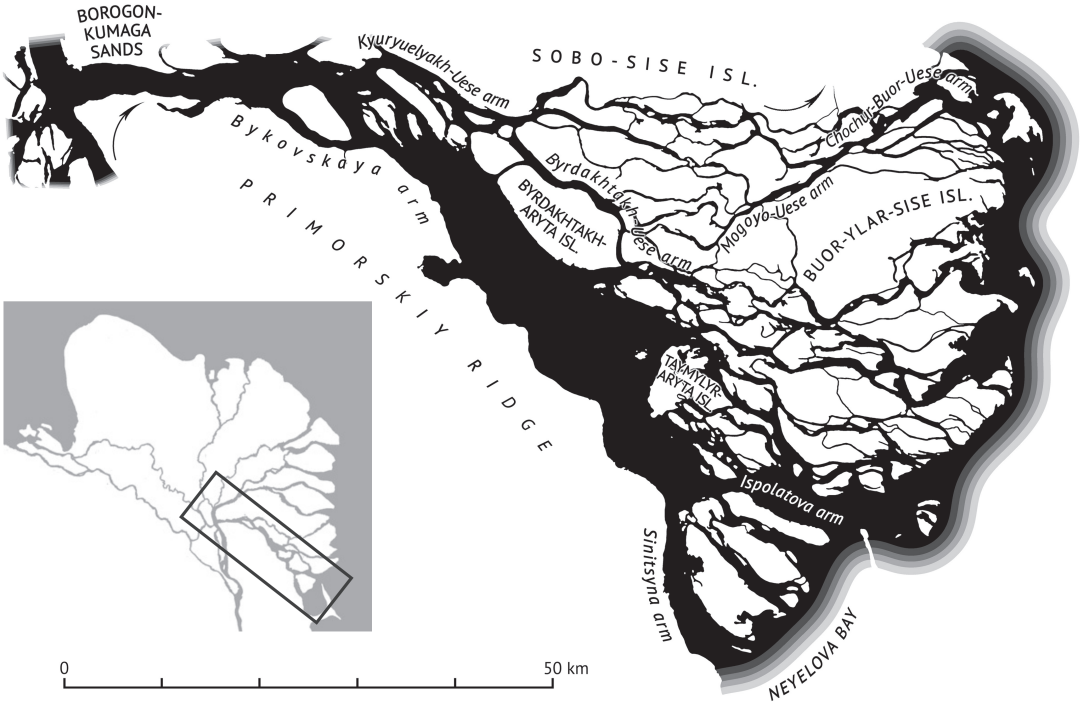


Fig. 6: Detailed scheme of channel systems of Bykovskaya deltoid branch.

Abb. 6: Detaillierte Übersicht über den Flussverlauf im Bykovskiy Kanalsystem.

expedition for the first time estimated the bed load yield and its grain-size distribution (TASAKOV 1965). The first significant conclusions and generalizations based on the data received from the above-mentioned expeditions and hydrologic network observations in the lower reach and the delta of the Lena River were accumulated in the works of researchers REINBERG (1938), LOPATIN & FEDOROV (1947–1948), ANTONOV (1960, 1967), IVANOV (1963, 1964) and TASAKOV (1965).

A new stage in the study of the hydrological regime of the delta and field hydrometric observations began in the mid-1970s. Since 1973, the Tiksinsky Center of Hydrometeorology and Environment Monitoring (CHEM) has begun to perform occasional (during 1973, 1975 and 1976), and since 1977 regular measurements of water discharge and suspended sediment load at the sources of the Trofimovskaya, Tumatskaya and Olenekskaya branches. In 1979–1981, the estuary field party of the Complex Riverbed Erosion Expedition of the geographic faculty of Moscow State University surveyed the delta. Analyses of station and expedition measurements of water discharge and suspended sediment load in the channels of the delta can be found in the publications of researchers ALEXEEVSKY (2007), GUKOV (2001), IVANOV et al. (1983), KOROTAEV et al. (1990), MAGRITSKY (2001) and others.

By 1991, the overwhelming majority of the gauging stations, measuring water levels, were closed down, and after 2002, regular systematic measurements of water discharge in the delta near head area were stopped, while the number of water discharge and suspended sediments measurements was significantly reduced at Kyusyur Station. However, since 2000 numerous measurements of water discharge and suspended sediment load, as well as other hydrologic and morphometric characteristics of the delta streams have been performed in the frame of the Russian-German Expeditions "LENA". (BOLSHIYANOV et.al. 2013, FEDOROVA et al. 2013, FEDOROVA et al. 2015).

On Samoylov Island in the central delta, a Russian-German research station was established in 1998 (Fig. 7), which has been operated jointly by the Lena Delta Reserve and the Alfred Wegener Institute (AWI), Bremerhaven and Potsdam.

It has served as a scientific and logistical base for the annual Russian-German Expeditions LENA to the Lena Delta and Laptev Sea region, which are being organized by the Arctic and Antarctic Research Institute, the Melnikov Permafrost Institute (Siberian Branch of the Russian Academy of Sciences) and the Alfred Wegener Institute (Helmholtz Center for Polar and Marine Research). The LENA Expedition has been opeing long-term measurement and experimental field sites on Samoylov Island and in its vicinity including meteorological and soil stations, trace gas flux and hydrological measurements.

Fig. 7: The new and old (small huts to the right) research stations on the Samoylov Island (photo: A. Morgenstern).

Abb. 7: Lage der alten (kleine Gebäude rechts am Wasser) und neuen Forschungsstation auf der Insel Samoylov (Foto A. Morgenstern).

Since 2013, the new modern research station "Samoylov Island" offers the possibility of year-round research, laboratories with high-end instruments, and access to field sites in the wider vicinity of the island using the station's extensive vehicle fleet (Fig. 7). The station is operated by the Trofimuk Institute for Petroleum Geology and Geophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk; its main users are the Russian-German Expeditions LENA.

ACKNOWLEDGMENTS

This research was performed within Russian Science Foundation grant #14-37-00038. We are indebted to B. Heim, A. Morgenstern and D. Fütterer for valuable comments and suggestions and to B. Juhls for providing the satellite image. Also, authors are grateful to the project "LenaDNM" supported by the German Federal Ministry of Education and Research (BMBF), grant identifier is 01DJ14007.

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