Exomorpholithogenesis of the Selenga River delta at the present stage of the hydroclimatic cycle

E A Ilicheva
V B Sochava Institute of Geography, SB RAS, Irkutsk, 664033 Russia
E-mail: lenail3663@mail.ru

Abstract. The materials of complex interdisciplinary studies of the relief forming in different periods of water availability in the Selenga River delta are presented since the technogenic level rise of Lake Baikal. Four water and sediment runoff anomalies, synchronous with water level fluctuations in the Lake are identified. The current boundaries of the Selenga River mouth area (RMA), floodplain complex, flooding territories in the maximum water ability conditions are identified. The RMA covers the territory from the main channel bifurcation nod to Lake Baikal, includes subaerial and subaqueous parts of the protruding delta, the interaction zone fluvial processes and different-aged terraces deposits and adjacent lagoons Proval and Cherkalov Sor. Semi-empirical models and data on the water runoff and sediment yield are presented.

1. Introduction
The fundamental factor in the development of the Selenga River mouth area (RMA) is the geological and tectonic structure of the coastal zone, expressed by varying degrees of ruggedness of the coastline and shallow seashore. The fluvial process at the present stage is the leading one in the relief formation of the Selenga River mouth system (RMS) and, together with regional geographical conditions, form certain channel and relief forms. Water and sediment runoff, hydroclimatic conditions in the river basin, tectonic manifestations, and technogenic interference in the interaction of the river flow and the receiving water body, create the modern character of the RMA. Since the rise of the level of the receiving reservoir, there has been a change in the direction of the leading processes of relief formation. In some cases, these were catastrophic flooding in alluvial plains. Technogenic changes in the factors influencing the development of the coasts coincided with hydroclimatic anomalies, as well as geotectonic manifestations in the region during this period. Thus, a new geological and hydroclimatic stage of relief forming has emerged in the history of the structure of Lake Baikal shores, including the Selenga River delta. Directly technogenic stage is subdivided into periods of low and high water content according to runoff anomalies in the Lake Baikal basin, during which at least four deviations from the mean values of level and runoff were noted.

The Selenga RMA combines parts of a unified natural river mouth geosystem that are interconnected on the scale of geological time and according to the leading relief-forming factor, but different in age and lithology: the subaerial delta plain (active and dead parts), and a subaqueous shallow-water platform (avandelta), where the facies are gradually replaced with depth by lacustrine sedimentogenesis. The Selenga RMS is represented by a complex of subaerial and subaqueous accumulative and erosional landforms and their constituent sediments, formed by the river and
lake within the mouth during their interaction. The current conditions for the formation of the Selenga RMS are fluctuations in the level of Lake Baikal, wave activity and alongshore currents and associated sediment movements and river runoff. Also, high seismicity is the most important factor in the formation and reformation of the RMA. The combination and hierarchy of interacting factors determines the morphodynamic type of the mouth and its evolution. The geometry of the underwater slope (deep or shallow seashore) is an important development factor of the morphological type of the river mouth. The geometry is determined by the morphostructural elements of the Baikal rift and the stratum of lacustrine, lacustrine-alluvial, and other deposits which fill them.

2. Models and Methods
The morphodynamic model of the Selenga RMA is based on topographic maps published in 1956-1995, satellite images from available Internet services, and orthophotomaps obtained during field work in 2018-2021. The boundaries of the modern floodplain complex are determined using a comparative geomorphological analysis of cartographic material from different years. The method of radiocarbon dating was used to evaluate the lithological and areal boundaries of the current stage of exomorphic lithogenesis. Samples for dating were taken from buried soil horizons and interlayers or lenses of peat at the boundaries of lithological facies, from lake cores and floodplain sections in 2018-2019. Radiocarbon dating of the samples was carried out at the “Köppen Laboratory” (St. Petersburg State University). The values of the calendar age are given on the basis of the calibration program “OxCal 4.3”. All sections and columns are linked to a levelling network with absolute elevation marks.

Geomorphological work was accompanied by drone survey to obtain high-precision (up to 14 cm/pixel) orthomosaics. For the modern floodplains, a geomorphological comparative analysis between topographic maps from different years and drone surveys was carried out. These materials were used to determine the morphometry of both the mouth area and to measure the parameters of channels, channel forms, and other relief elements. The drone survey was carried out from a height of 450 and 500 m. The coverage of the resulting image is 350 m. To create orthomosaics, an overlap of about 25% was observed.

The hydrometric survey was carried out in full (flow rates, longitudinal and transverse profiling with altitude reference, measurement of suspended sediments, temperature, pH, etc.). The work was supplemented by measurements of bank erosion rates, aeolian component of suspended sediment runoff (by an aeolian traps), drilling of monitoring wells to estimate the volume of runoff inside the inter-channel spaces of the delta.

The empirical model of water and suspended sediment partitioning in the Selenga channel network is based on statistical processing of data series of observations of water and sediment flow and Lake Baikal levels [1, 2]. The model can be used in prediction under varying discharge conditions. The investigated discharges for the summer-autumn period since 2003 at the top of the delta and along 7 main channels are the basis of the model. The model includes the altitudes of Lake Baikal level, obtained from Babushkin gauging point at the moments of surveying the velocities and morphometry in the channels.

3. Results and Discussion
The Selenga RMS has a protruding delta, developing on a shallow seashore, formed in a graben which filled with Neogene-Quaternary (Baikal-type depression) easily eroded sediments. The Selenga coast itself belongs to the potamogenic (river) type which created by non-wave processes. The chain of bars bordering the delta is formed due to the wave movement of river sediments along the coast and forming a complex accumulative system (Figure 1).

The Delta is formed within the Ust-Selenga depression. The boundary of the depression is drawn along the underwater slopes of the Kukuy Bank, and a scarp in the Posolsky Sor in the Lake Baikal water area. Neogene, Pleistocene, and Holocene deposits in the Ust-Selenga depression create a shallow seashore for forming the present protruding delta. Also, smaller morphostructures
are distinguished within the Ust-Selenga depression. Negative elements are distinguished: Kaltusny, and delta deflections. The positive structures include the Kudara step and the Istok-Tvorogovo uplift, the deposits of which are involved in the modern delta forming only as an insignificant source of an aeolian material. The modern mouth area covers the territory from the main bifurcation nod (Maloe Kolesovo village) to the water area of Lake Baikal.

Geomorphologically, the subaerial delta of the Selenga River can be divided into zones. The identification of boundaries is based on the age of the relief and sediments, the altitude position of the edges of the Holocene terraces, floodplains, and the change in the channel process with distance from the top of the delta to its shoreline. The topography of the delta surface is genetically related to the periods of water content during which channel deformations and sediment accumulations occurred.

![Figure 1. Morphodynamic model of the Selenga River Delta.](image)

**Geomorphological units:**
- 1 – the Kudara Neopleistocene lacustrine-alluvial terrace;
- 2 – the Kabansk Holocene floodplain;
- 3 – the floodplains aged 1-4 thousand yr. BP;
- 4 – the floodplains aged in the last millennium;
- 5 – the floodplains aged since 1956;
- 6 – wetlands;
- 7 – avandelta and shallow coastal margins;
- 8 – modern river network;
- 9 – bars;
- 10 – drained swamps.

**Tectonic units:**
- 11 – the Kaltus deflection;
- 12 – the Istok-Tvorogovo uplift;
- 13 – the delta deflection;
- 14 – the Kudara step.

**Borders:**
- 15 – shoreline 1956;
- 16 – modern shoreline;
- 17 – modern river mouth area;
- 18 – morphodynamic sectors of the delta.
There are being created the conditions for the release of river and lake waters on floodplain surface in high-water periods. The accumulation of sediment load during this period leads to a rise in the elevation marks of the subaerial delta. The channel network cuts into the previously formed deposits and a general levelling of the surface occurs in low-water periods.

Geomorphological comparative analysis of cartographic material from different years and geomorphological profiling with a description of river bank sections and sampling for various types of research, including radiocarbon dating is conducted in occurred modern floodplains [3, 4]. Three generations of floodplain terraces formed during technogenic stage, and the territories were never affected by erosion-accumulative activity were distinguish by the analysis. The width of the modern meander belt in the main bifurcation nod of the delta reaches 1.3 km with a sediment thickness of one meter or more. The formation of modern floodplain terraces is due to the change and duration of periods of different water content.

Until now, the flooding boundary of the delta was passed up to the marks of 458-460 m (Baltic System), which corresponds to the terraces edges formed more than two thousand years ago. The dynamics of the delta area correlates with the runoff of water and sediments at a relatively stable level of Lake Baikal. An increase in sediment supply leads to an increase in the delta, due to the prograding of its individual sections. In recent years, there has been an intense flooding of the mouths of the Kolpinnaya and Sredneye Ust’e channels, which may be associated with the sinking of the tectonic block.

The development of erosion-accumulative processes, in particular, channel deformations, is influenced by fluctuations in the water level in the Lake. The water level in the Lake increased and, consequently, the hydrological regime of the delta was renewed, the river system was significantly affected by erosion-accumulative processes in the technogenic stage.

Volumes of sediment load entering the mouth system, transported along the branches, accumulating in the delta, and carried out to Baikal are calculated. In general, the area of the delta during the period under review decreased by more than 80 km² due to the flooding of a part of the territory of the Sredneye Ust’e sector. The height of the subaerial surface of the delta increased by 0.8 m as a result of the deposition of floodplain and channel alluvium on the islands and inter-arm spaces. Relatively stable sections of channels and inter-arm spaces were identified, in comparison with sections subject to active channel deformations.

The averaged data on the dynamics of the volumes of transported alluvium in the delta showed that for the period from 1956 to 1998 more than 0.75 km³ have accumulated along main channels of the delta.

| Water discharge (m³/s) | Selenga sector | Lobanova sector | Sredneye Ust’e sector |
|-----------------------|----------------|----------------|----------------------|
| 1,100                 | 40             | 40             | ~ 20                 |
| 1,700                 | < 20           | > 20           | ~ 20                 |
| 500 – 1,000           | ↑ 35 – 40      | ↓ 50 – 40      | < 20                 |
| 1,000 – 1,500         | ↑ 35 – 45      | ↓ 40 – 35      | ~ 15                 |
| 1,500 – 2,000         | ↑ 45 – 50      | ↓ 35 – 20      | ↓ 12 – 5             |
| 2,000 – 3,000         | 35             | 35             | 15                   |
| > 3,000               | 50             | 35             | 12                   |

*a Water discharge in the top of delta.
The water and sediment runoff modelling in the branched channel network of the delta, depending on the geometry of the channel makes it possible to predict the distribution of runoff in various discharge conditions. The model is based on field data and has a complex mechanism. The flow distribution along the channel network is not the same at different water content, and changing even within one year. During the observation period, a discrepancy in the flow balance from several percent to more than half of the river flow was revealed. The detected discrepancy is associated with the release of water to the floodplain and coastal regulation and high level of ground water in high-water years. In low-water periods, the discrepancy is determined by the distribution of water flow over the sectors of the Selenga delta as a whole is relatively uniform. The Selenga and Lobanova sectors on average pass 33\% of the total flow, the average flow in the middle sector is 15-20\%. The analysis of the delta flow distribution showed that the distribution in equal shares over the delta marginal sectors is observed at flow rates at the delta head of 1,100, 1,700 and 2,000-3,000 m$^3$/s. From 5 to 20\% passes through the Srednaye Ust’e sector (Table 1).

In low-water years, the leading position is occupied by the channels of the Lobanova sector - up to 50\% of the flow. The channels of the central part of the delta (Srednanye Ust’e sector) pass no more than 20\% of the runoff. With an increase in water discharge in the Selenga up to 2,000 m$^3$/s, the share of runoff in the channels of the Selenga sector increases due to a decrease in runoff through the Lobanova sector. The main role in the distribution of runoff is played by the channels of the Selenga sector, first of all, the share of runoff along the Levoberezhnaya channel increases during high water content. The runoff through the Sredneye Ust’e sector is relatively stable under various water conditions.

4. Conclusion
The increase in the level of Baikal led to a significant restructuring of the Selenga coast, and the hydrographic network of the delta. Four anomalies of water and sediment flow were identified for the technogenic stage of exomorpholithogenesis of the Selenga River delta. The anomalies led to a change in the topography of the delta, expressed by the formation of a complex of floodplain terraces reaching 1.3 km in width and a meter of deposits. The conditions for the outflow of river waters to the floodplain and the flow distribution along the main branches were determined by an empirical method in the delta. The boundaries of the modern river mouth area, as well as sections of the ancient mouth area, which currently takes an indirect part in relief formation, are determined.

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References
[1] Ilicheva E A 2017 Interdeltaic flow partitioning of the Selenga river delta 2017 Vestnik of Buryat state university. Biology. Geography 4 pp 64-7
[2] Dong Tian Y, Nittrouer Jeffrey A, McElroy Brandon, Il’icheva Elena, Pavlov Maksim, Ma Hongbo, Moodie Andrew J and Moreido Vsevolod M 2020 Predicting Water and Sediment Partitioning in a Delta Channel Network Under Varying Discharge Conditions Water Resources Research 56(11) pp 1-21
[3] Pavlov M V, Ilicheva E A, Kobylkin D V, Mcelroy B, Nittrouer J A and Dong T Y 2020 Radiocarbon dating of lake bottom sediments and river bank sections of the Selenga River Delta Proc. Int. Conf. “Environmental Transformation and Sustainable Development in the Asian Region” (Irkutsk: Institute of Geography SB RAS Press) p 118
[4] Ilicheva E A, Pavlov M V, Mcelroy B, Nittrouer J A and Dong T Y 2020 Formation of the Floodplains of the Selenga River Delta Geography and Natural Resources 41 pp 113-19