Morphodynamics of the river mouth systems of the southern Baikal depression

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Abstract. The researches covered the largest river mouths, representing the main morphogenetic types of river mouth systems (RMS) of tributaries of the southern depression of Lake Baikal. On the coastal area of the southern depression there are 3 types of RMS: few-arm with channel opening or with a spit; multi-arm with phytogenous-delta coast (on the terrigenous cone); arched protruding deltas on a shallow seaside. The results of morphometric analysis in dynamics for the period from 1897 to the present time are presented. The various morphometric parameters and coefficients of development of the RMS are given. The increase in the level initially led to the flooding of the mouths and adjacent territories, and then to a new stage of development of the RMS at the «river-lake contact», both subaerial and underwater parts of them. An attempt was made to consolidate the concepts of river mouth system, river mouth area, and river mouth geosystem with the definition of the borders. The conclusions about the factors of formation of various RMS are presented: the water level regime of the receiving reservoir, hydro-climatic conditions, seismotectonic expressions, and the technogenic factor. The leading processes of relief formation at the present stage of development are revealed.

1. Introduction
The concepts and definitions of river mouth system (RMS) an driver mouth area (RMA) are considered in sufficient detail in the works of domestic researchers in the field of hydrology and geomorphology of river mouths [1–4], where subaqual and subaeral areas of land and sea, formed by the interaction of the underlying surface and the receiving reservoir with river flows are identified. They have developed a classification of types of river mouths by morphometric parameters. The authors focuses on the geological component of the river mouths, namely the thickness of the sediments involved in the modern formation of river mouth systems, where the river mouth is considered as a modern «volumetric geological body». There are contemporary areas of relief formation of the river mouth area and more ancient. The question of the contemporary relief and associated sediments is very often affected, especially in the stratigraphy of Holocene sediments [5, 6]. V N Mikhailov [1] and V N Korotaev [2] consider the river mouth area as a relief surface with a hydrographic network, having specific, azonal manifestation of the landscape: soils, vegetation, and special sediments, forming the body of the river mouth area. Thus, the authors connect geographical shells into a single system – geosystem.
By river mouth systems we mean the sections of the channel network, interacting with the receiving reservoir. River mouth area covering a larger square: channel network in bankfull, floodplain terraces and above flood-plain terraces, islands, midstream sandbanks, and interchannel spaces with an abundance of ancient superimposed forms, and the ancient river mouth area. It is advised to separate the modern river mouth area or river mouth geosystem as a section of the river mouth, located in the active interaction of geographical processes of the system "river-sea". And also to separate the main elements of the river mouth system such as the top, where the separation of a single channel on a separate branches or manifested change of the channel process, and interchannel spaces, sections of the banks, participating in modern relief development (source of sediment supply), and ground water level. Morphostructures are of particular importance for morphogenetic typification of river mouths and their evolution, creating conditions for their formation: shallow or steep-to coastal waters, bays or gulfs. Different conditions help to form protruding delta systems, estuarine-deltaic systems and a simple river mouths.

2. Objects and methods
There are more than 470 river mouths on the Baikal coast, 230 of them belong to the constant rivers with different morphogenetic types of the river mouth system (RMS), so for the morphometric analysis their typification was initially carried out and only some of them with the most striking characteristics of their type flowing into the southern basin of the lake are considered in detail (figure 1).

The morphometric analysis of cartographic materials has been carried out, complemented by the results of field observations in the performance of hydrometric and geomorphological routes with a description of coastal sections and drill cores of bottom-set beds of lakes and gulfs. We used maps and satellite images showing the geometry of objects in different periods, starting with the sailing of F K Drizhenko [7] 1897-98 years to the present. Topographic maps and images are given in a single coordinate system and scale. Also we used the materials by A N Beshentsev presented a GIS service (BINM SB RAS) [8].

The classification of morphological signs of river mouth systems was carried out according to the method proposed by V N Mikhailov [1], for which the length of the sea edge (Lshoreline), the width of the protruding area above the general coastline (B) and the length of the envelope of the sea edge curve (Lround) were measured. We considered the method of measurement of morphometric parameters as exemplified by the river mouth system (RMS) of the Selenga is (figure 2).

Then, we calculated the area of the protruding sea edge of the delta (F_delta) and the area of the semicircle (F_B), constructed in diameter B, as the width of the river mouth system, using the obtained length values. The parameters under consideration are not constant in time and depend on many factors: the basic level of the receiving reservoir and its amplitude; the flow of water and sediment, in turn, depending on climatic conditions; seismotectonic phenomena inherent in the rift zone of Lake Baikal; and the anthropogenic factor of various scales of manifestation, from changes in the lake level to hydraulic works in the channels, arrangement of ditches and berths on the coast. The coefficients of development (N) and indented (K) coastal region of the river mouth system was calculated.

3. Results
The coast of the southern basin of Lake Baikal is divided into several types of activity manifestations of exogenous processes [9]. The leading factor in their development is the fluvial one, causing sheet erosion from the slopes of the foothills and river valleys, and catastrophically manifested during periods of intense moisture. The south extremity of the lake is represented by river valleys Snezhnaya, Vydrinnaya, Khara-Murin, Solzan, Utulik, etc., having relatively small watershed areas and length of main river, high slopes, and very steep slopes of the sides of valleys, and creating favorable conditions for the occurrence of mud flows. This category also includes the rivers of the Primorskii Range, such as Goloustnaya and Bugul'deyka. The river mouth area of these rivers is occupied by deposits of deluvial-proluvial removal cones, where the modern channel network is developed. The main
difference between the river mouth area of the southern tip and the rivers of the eastern coast is created by the morphostructure of the Baikal rift and is manifested in the absence of shallow coastal waters in the south of the basin. The hydro-climatic factor provides the considered area with the greatest precipitation throughout the year, due to the most favorable exposure of mountain ranges to the main direction of moisture transfer. The southern tip is open to the northwest transport of atmospheric precipitation and the channel network in the basin is more developed (the maximum density of the river network) reaches 0.4-0.7 km/km². On the west coast, these values are significantly lower. Besides, the west coast and the underwater slope are characterized by the severity of littoral for several kilometers with small depths. A relatively quiet mode of sediment accumulation is presented in the river mouth area of the Selenga river.

**Figure 1.** Morphogenetic types of river mouth systems: 1 - few-arm with channel opening or with a spit; 2 - multi-arm with phytogenous-delta extension coast (on the terrigenous cone); 3 - arched protruding deltas on a shallow seaside; 4 - order of the river system according to Horton-Strahler.

**Figure 2.** Map of the Selenga river mouth system with morphometric parameters: 1 – B_delta – width of delta; 2 – L_shoreline – length of shoreline, 2011 yr; 3 – L_round – length of rounding line; 4 – shoreline, 1952 yr; 5 – shorelines of Proval bay and Cherkalov Sor.

The largest accumulative formation on the area is the only one on the Baikal coast, a protruding delta of the Selenga river, developing on a shallow coastal waters created by lake-alluvial delta sediments with a thickness of more than 3 km, filling the Ust-Selenginskaya depression. The river mouth area of the Selenga should be divided into the modern part between the river mouth opposing spits and terraces edge of Holocene and Pleistocene terraced levels, and the modern top in the node of branching at the village of Maloe Kolesovo, with a total area of about 600 km², and on the territory of interaction of waters of the Selenga and Baikal in the pre-Holocene era, covering an area of more than 1400 km². This area includes the surface Kabansk and Kudara terraces on the left and right banks of the Selenga, complicated by aeolian form of relief, Kaltusnyi deflection to the south, previously occupied by the main channel up to the Posolskii gulf and cape Oblom, which is the edge of the river mouth area in the north. Morphometric characteristics are given in table 1.

A distinctive feature of many Baikal river mouth systems is the presence of "pseudodelta" formed by non-alluvial deposits in the river mouth. Visually, this pseudodelta has a convex cone, developed modern hydrographic network, opposed to a phytogenous-deltaic increasing lake margin, often blocking with shingle opposing spits and bars, with deltaic water bodies: inland lakes, lagoons and limans, as exemplified by the river mouth area of the Goloustnaya river.
The river mouth system of the Goloustnaya river with the combination of morphological features is an arc-shaped extension system. The growth of the river mouth is carried out due to the extension of the phytogenous-deltaic complex and is limited to blocking opposing spits. The river network consists of three active streams, cutting through a mud-flow fan. Temporary channels have a seasonal nature of the runoff, however, quite clearly expressed in the relief (figure 3a).

Formation of removal cones of the western coast of Lake Baikal is explained by S A Makarov activation of washout of terrigenous material accumulated in river basins at the beginning of the Holocene era [9]. The river mouth system of the river cuts through the previously formed cone fan, the flow from the seasonal sleeves is carried out in the high-water phase of the water regime. During the considered period, the lake district of the Goloustnaya retreated from its bars, forming a lagoon-liman complex.

Table 1. Morphometric parameters of the river mouth systems.

| Years | B, km | L_shoreline, km | L_round, km | F_B, km^2 | F_Delta, km^2 | K | N |
|-------|-------|----------------|-------------|-----------|---------------|---|---|
|       | RMS of the Selenga River | | | | | | |
| 1908  | 34.9  | 119.5          | 60.1        | 478.1     | 483.2         | 2.0 | 1.0 |
| 1956  | 36.9  | 126.3          | 60.4        | 534.4     | 512.5         | 2.1 | 1.0 |
| 1986  | 38.2  | 132.3          | 61.1        | 572.8     | 514.8         | 2.2 | 0.9 |
| 1998  | 38.4  | 189.5          | 59.6        | 578.8     | 451.3         | 3.2 | 0.8 |
| 2007  | 38    | 159.9          | 60.5        | 566.8     | 471.5         | 2.6 | 0.8 |
| 2011  | 38.3  | 161.8          | 59.8        | 575.8     | 453.5         | 2.7 | 0.8 |
|       | RMS of the Goloustnaya River | | | | | | |
| 1982  | 5.1   | 6.4            | 6.1         | 10.2      | 4.7           | 1.0 | 0.5 |
| 2015  | 5.2   | 10.2           | 6.4         | 10.6      | 4.3           | 1.6 | 0.4 |
|       | RMS of the Bugul’deika River | | | | | | |
| 1983  | 0.9   | 2.1            | 1.2         | 0.3       | 0.2           | 1.8 | 0.6 |
| 2014  | 0.9   | 1.6            | 1.2         | 0.3       | 0.2           | 1.3 | 0.6 |

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Figure 3a. Geomorphological diagram of the Goloustnaya RMA: 1 – channels; 2 – lagoons and limans; 3 – wetlands; 4 – interchannel space; 5 – remnants of mudflow cone; 6 – loops under the mountains; 7,8 – river terraces and islands; 9 – barrier bars; 10 – technogenic dumps; 11 – Baikal.

Figure 3b. Geomorphological diagram of the Bugul’deika RMA: 1 – Baikal; 2 – wetlands; 3 – river network; 4 – lagoons, limans and oxbows; 5,9 – bars; 6,7 – erosional remnants; 8 – loops under the mountains; 10 – slopes of the mountains; 11 – technogenic dumps.
In its appearance the river mouth system of the Goloustnaya river is similar to the river mouth system having protruding delta. However, as mentioned earlier, the river mouth cone is mainly composed of non-alluvial deposits.

The river mouth area of the Bugul’deika river is represented by a simple channel with old lakes. This morphogenetic type of river mouth system is typical for the southern coast (figure 3b).

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