Mapping of hazardous hydrological events in the Russian part of the Selenga River basin

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Abstract. The Selenga River is a major tributary of Lake Baikal. Its basin is characterized by a fairly high degree of economic activity. Floods in the Selenga River basin are hazardous natural phenomena which can cause threats to people's lives and enormous damage to the settlements and infrastructure. The flooded areas in the settlements are delineated by using various methods: hydro-morphological surveys, leveling of sections along riverbeds and floodplains (151 profiles in total), as well as results of hydrodynamic modeling of flooding processes by using a program, HEC-RAS, developed by U.S. Army Corps of Engineers. The flood zones are simulated for maximum water levels with 100, 33, and 20-years frequency. In the future, the compiled flood database is planned to be published as part of an online web map service, "Hydro-Ecological Safety in the Selenga River Basin".

1. Introduction
Cartographic display of floods, bank erosion, and other negative processes form a necessary basis in the planning, implementation, and assessment to combat hazardous hydrological events. The increase in the number of floods and their increasing destructive power against the backdrop of ongoing climate change are of serious concern [1]. The Selenga River is the main tributary of Lake Baikal which provides more than 50% of the total annual runoff into the lake [2]. The Selenga River basin is the most economically developed area of the Lake Baikal catchment area. This territory is characterized by arid climate conditions, where droughts and forest fires alternate with floods. Floods in the Selenga River basin are one of the most hazardous natural phenomena, which cause a threat to human lives and enormous damage for settlements and the infrastructure. The goal of this study is mapping of the zones of flood and bank erosion in the Russian part of the Selenga River for risk assessment.

2. Study area
Lake Baikal and its adjacent territories were included in the UNESCO World Natural Heritage List in 1996. Therefore, the problem of protection and preservation of the lake water resources has become extremely urgent. The basin of Lake Baikal is located almost in the center of the vast Asian continent and covers an area of 545 thousand km² (without the area of the lake), 45% of which is within the Russian Federation, and the rest is in Mongolia. About 73% of the river waters are formed on the territory of Russia, and 27% in Mongolia [3]. The main tributaries of Lake Baikal are the Selenga, Barguzin, Upper Angara, Turk, Tya, Snezhnaya, and Kika Rivers, which undergo various annual and
seasonal changes in some components of the flow under the influence of natural factors and anthropogenic pressures. Selenga is the main river of the Lake Baikal basin. The area of the Selenga River basin is 82% of the catchment area of Lake Baikal or 447 thousand km² (Figure 1). The total annual flow of the river is 30 km³, 15.4 of which is formed in the Russian part. Its main tributaries are Orkhon, Eg (Mongolia), Chikoi, Khilok, Uda, and Dzhida (Russia).

In terms of the water regime, the rivers of the Selenga basin are classified as rivers with high water periods and floods. The rivers in the southern part are not characterized by high floods, except for mountain tributaries of the Selenga, as well as watercourses flowing from the Khamar-Daban and Primorsky Ridges. The rivers with spring and summer high waters are located in the middle and northern parts. Rainwater floods occur in the decline of the high waters and are observed throughout the summer. The maximums of rainfall floods significantly prevail over the maximums of high water levels, both in absolute value and in their number in the selection of annual maximums. For some rivers in the northern regions, the main phase of the water regime is high waters. Analysis of averaged data shows that the main part of the runoff takes place in the warm part of the year and constitutes 85-93%. The runoff during the cold period is minimal at 7-15%. Such irregularity in the distribution of the annual runoff is mainly due to a peculiarity of the synoptic processes: cyclone migration in the
summer period and significant snow reserves in the mountains. In addition, the important predetermining natural factors are: contrast of the relief with high altitude differences and erosion dissection, widespread permafrost development, deep seasonal freezing, specific hydrogeological conditions, and a number of local factors.

3. Initial data and mapping

For the assessment of the channel process intensity and bank erosion, Landsat-5 TM spectroradiometer multispectral images were used, uploaded from the USGS geoportal using the GloVis search engine (http://glovis.usgs.gov). The spatial resolution of the images is 30 m/pixel. The absolute absence of cloud cover (0%), high quality (Qlty = 9), and sufficient image preparation (L1T level - orthotransformation, radiometric and atmospheric correction) were the obligatory conditions for imagery uploading. Using simple regression, we made a forecast of the bank caving zone for 5, 10, and 25 years. Rare high-water levels were obtained with the help of frequency curves of water levels and discharges in hydrometric stations on the considered watercourses using Q = f(H) diagrams. For the settlements considered in this project and that do not have hydrometric stations, the interpolation method was used taking into account the longitudinal profile and the drop of elevation of the river based on large scale maps.

For the creation of a digital elevation model, topographic maps were used, which were converted into images by scanning and digitized using a specialized software. The digitized horizontals were used to produce a triangulation network, which was later converted into a regular grid of points with known and/or interpolated elevation values. Thus, correct hypsometric surfaces suitable for hydrological modeling and adjusted to the relief features of the study area were created. The relief model was calculated by the method of weighted average interpolation, which provides search of the nearest objects in 16 directions, as well as additional operations to improve the quality of the formed surface.

The flood zone algorithm is based on the standard map algebra capabilities. Intersection of the water surface, which represents a field of calculated water levels at flooding of a given frequency, with the relief surface allows one to determine the required boundary of the flood water influence. The flood zone is obtained automatically and represents a polygonal shapefile, which is further used to generate maps of flood zones within settlements. As a result, 3 flood zones of 1, 3, and 5% frequency were obtained, which correspond to 100, 33, and 20 years returning period. The accuracy of the flood zone boundaries is influenced by various factors, in particular, by the accuracy of input data. The accuracy of the calculated data depends on the scale of the input information: the larger the scale of the used map, the more accurate DEM is developed. In return, both the accuracy of flooding level calculation and the accuracy of flood zone formation based on the obtained calculation level depend on the model quality.

According to the requirements of GOST R 51608-2000 [4], the altitude accuracy of cartographic materials is limited to 1/3 of the horizontal section shown on the topoplane. For map materials of M 1:25 000 the horizontal section is usually equal to 5 m (2.5 m for additional horizontals), and the accuracy of relief representation ε is limited to a value of 0.8-1.7 m.

The planimetric error in contouring when constructing flood zones depends, first of all, on the accuracy of the horizontals drawn on the maps, and is 0.5 mm scale of the original map (for maps of M 1:25 000 - 12.5 m). On maps and plans of a larger scale, the horizontals were considered as basic if they did not contradict the horizontals drawn on maps of a smaller scale. In such areas, the model was built with higher accuracy (the planned error is 1 m). Since the horizontal pitch of M 1:25 000 maps is 2.5-5.0 m, any height change within this value between the horizontals is not displayed on the map and is not taken into account in the digital elevation model. Thus, the error of displaying flood zones is within the distance between the horizontals. The results obtained during modeling were verified using materials of a reconnaissance survey of the territory and hydromorphological works.

Modeling of the flood zones within the settlements was produced with the use of the HEC-RAS, HEC-GeoRAS, and ArcGIS software packages. Setting of boundary conditions of the model
(estimated water discharge, Manning roughness coefficients for the channel and floodplain) was performed. A solution to a simplified one-dimensional shallow water equation in the HEC-RAS (Saint-Venant equation) was obtained using an implicit finite-difference scheme. The solution is valid for a continuous steady flow.

In the process of water regime modeling, the calculated flood zones within the limits of the Selenga and Chikoi River study areas were determined at water levels of 1, 3, and 5 % of coverage. The flood zones obtained at different levels, including ice jams and bank cavings, are shown on topographic maps within the settlements. Mapping of the flooded zones served as a basis for determining the list and parameters of economic objects located in areas of a possible negative impact.

4. Conclusions
In this study, we compiled a three-level GIS database of hazardous hydrological events in the Selenga River basin from the start of the observation period. The database structure is developed according to a scheme developed in [5]. The first level (phenomenon) represents a flood event reported by hydrological gauges of the Russian hydrometeorological service, and also in a settlement or other location (e.g. flooding of an infrastructure facility). The second level (flood event) is an ensemble of flood reports along a river in a limited period. The flood events are related to “triggers”; these are weather events causing flooding (e.g. heavy rainfall or intense snowmelt). The observed precipitation amount and a short description of the synoptic-scale environments will be provided for each weather event triggering flood. Rivers and flooded settlements are two basic GIS layers in the database. For 60 settlements which have high or moderate flood risk, the flood zones are estimated and uploaded as additional information sources in the database. In the future, the compiled flood database is planned to be published as part of an online web map service, "Hydro-Ecological Safety in the Selenga River Basin”.

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