Flood monitoring using GIS technologies: A case study of the Selenga River basin

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Abstract. The article contains data on catastrophic floods on the rivers of Lake Baikal basin in the past century. It describes the functional structure of the GIS of flood monitoring. The study justifies the advantage of the basin approach in flood assessment and mapping. We determine the basic regional climatic and physico-geographical factors of flood formation and characterize the main indicators of the territory danger from floods: frequency, magnitude and extent of floods. As hydrological information, we used the calculated water levels in the sections obtained from annual probability distribution curves of exceeding the maximum water levels from rainfall floods. The flood indicator is calculated as the difference of the maximum rise in the water level above the critical level of water outflow to the floodplain. Calculation data show that the maximum values of water levels in the basin's rivers are the most characteristic of the summer flood period. We have determined physico-geographical features of flood distribution on the main rivers of the study area, performed geoinformation mapping of flood parameters within the main river basins and described the technique of interactive work with GIS through geoinformation queries as well as characterized the response models of the hazard development.

1. Introduction

The procedure of mapping of hazardous natural processes is of great importance for the organization of sustainable economic activities and rational use of natural resources. It involves solving many scientific tasks: spatial and temporal recording of hazards; modeling the mechanism of their development; analysis of the vulnerability of economic infrastructure; determination of economic damage of emergencies; and assessment of environmental risk. Floods cause the most frequent and significant damage to the population, agriculture and real estate. Flood monitoring and assessment require significant amounts of cartographic, satellite and statistical geodata. The introduction of geoinformation technology automates the mechanism for using large volumes of heterogeneous and multi-format data as well as the technology of mapping and modeling hydrological hazards.

At present, ministries, departments, research organizations, public and business representatives pay considerable attention to the problem of floods. Many works are devoted to studies of their genesis, mechanisms of formation and physical-geographical peculiarities. Much attention is paid to the assessment and mapping of flood hazard [1-9], as well as the identification of risk and possible damage from floods using modern geoinformation technology [10-15]. Flood hazard zoning was carried out for the Baikal region [16, 17].

The most developed part of the Lake Baikal basin is the transboundary Russian-Mongolian basin of the Selenga River, which is the largest ecosystem with a total area of approximately 450000 km2. It is
home to strategic industrial enterprises and unique mineral deposits. The economic development of the study area is accompanied by various dangerous natural processes, primarily floods. On a Russian scale, the Selenga River basin is one of the regions with a high probability of flooding. In the past century, there were recorded six catastrophic floods above 400 cm: in 1908 – 408 cm, in 1932 – 450 cm, in 1936 – 464 cm, in 1940 – 416 cm, in 1971 – 410 cm, and in 1973 – 437 cm, as well as a series of large floods (above 300 cm): in 1927, in 1938, in 1942, in 1962, in the 1990s. The size of the damage caused to the republic is significant: in 1971, the amount of damage was approximately 1.4 billion rubles, in 1973 – 0.7 billion rubles, in 1993 – approximately 40 billion rubles. (in current prices of the flood period). Most settlements periodically prone to flooding, as well as large areas of agricultural land, are located in the river valleys of the basin. The high economic importance of this area determines the need to search for sound management decisions on prevention, mitigation and forecasting of possible losses as well as the assessment of flood risk. Thus, the creation of a reliable geoinformation system (GIS), which allows storing and processing large amounts of spatial data, analyzing it and obtaining new information on floods, responding to requests and providing information in the required form, is an urgent task.

2. Models and methods
The specifics of modern flood monitoring is that spatial and temporal assessment is carried out using cartographic tracking of its metric parameters and topological relations with objects of vital importance in the information environment. To organize permanent flood monitoring in the Selenga River basin, the Baikal Institute of Nature Management of the Siberian Branch of the Russian Academy of Sciences (BINM SB RAS) has developed and implemented a GIS flood monitoring system based on the ArcGIS package, which consists of four open subsystems.

The technical base of the measuring subsystem consists of geochemical and geophysical instruments designed both for field recording of geographical properties and office analysis of geodata. Availability of a differential global positioning station, a Phantom UAV and a Leica laser scanner provides reliable measurement of flood parameters and high accuracy of the mathematical basis for monitoring. The information subsystem is based on multi-temporal digital topographic and thematic maps, space and aerial images, statistical and literature data, as well as the system of classification and coding of multi-temporal spatial information. The technological subsystem consists of hardware and software required for computer evaluation of metric flood parameters, as well as input, compilation and low-volume edition of maps. The analytical subsystem is represented by the methodology of geoinformation mapping, a system of algorithms and mathematical models of processing and analysis of spatial data of ArcGIS program.

An important task in the geoinformation assessment of floods is the production of derivative materials from basic spatial data, reflecting the physical and geographical features of the hazard. The layout of the geoinformation assessment of floods is based on a 1:100,000 scale topography. The altitude basis for the assessment is the digital elevation model (GRID-surface). The initial data for the formation of a digital elevation model are vector-based relief isolines and marks of heights and depths of the topographic scale 1:50 000. As a result of the projection of the Landsat space images scene on the GRID surface, a digital terrain model was created, which has high metric accuracy and the necessary visibility and obviousness to make grounded territorial decisions.

3. Results and discussion
We carried out flood recording and mapping in the study area within the boundaries of the main river basins. This approach is based on the understanding of the river basin as an integral geosystem with hierarchical horizontal and vertical links, which formation and functioning are conditioned by geological, hydrological, climatic and other factors of the river network development within the unified orographic boundaries. The determining factors of flooding in the basin are the cyclonic activity of the second half of summer, which causes continuous or heavy rainfall nature, as well as a
significant amount of snowfall accumulated in the mountains of the Baikal region, mountainous terrain and anthropogenic disruption of some parts of the channels.

The main indicators of the territory flood hazard are the frequency, magnitude and extent of floods. The indicator of occurrence frequency or repeatability (cases per year) is the ratio of the number of years with floods to the number of years of the studied period (figure 1a). Thus, the highest occurrence frequency of 0.8-0.9 (water outflow to the floodplain) is typical of some hydrological stations: Dzhida-Khamney, Selenga-Ust-Kyakhta and Selenga-Novoselenginsk. The greatest floods with significant flooding of farm facilities and some settlements located in the floodplains of the rivers occur with a frequency of 0.05-0.12, and medium to small ones, flooding mainly agricultural land and some settlements – 0.15-0.34.

We have determined the probable borders and areas of flooding through the calculated indicator of flood size based on the topographic scale of 1:100,000 and multi-temporal Landsat space images (figure 1b). Mapping of flooded areas was performed in the ArcGIS software environment. We used the calculated water levels in the stations as hydrological information obtained through annual probability distribution curves of exceeding the maximum water levels from rainfall floods. For settlements that do not have hydrometric stations, we used the method of interpolation, taking into account the longitudinal profile and the fall of the river based on large-scale maps. Within the boundaries of settlements, the topographic basis of the scale was 1:25000. A quadcopter performed a detailed mapping of individual complex areas within settlements. To create orthophoto plans and DEM of the territory, we used Mavic Pro imaging equipment; the images were processed in Agisoft PhotoScan environment. The accuracy of the flooded areas corresponds to the resolution of the used space images of 15 m, as well as the accuracy of the topographic basis of 0.2 mm in the map scale.

In case of catastrophic floods, the total area of possible damage zones reaches 3123 km2, 2363 km2 of which are agricultural lands, which is 3.4% of the basin area and 9.5% of the agricultural lands area. In addition, more than 100 settlements, including the city of Ulan-Ude, are located in or adjacent to hazardous areas and are at risk of partial flooding and waterlogging, some of which are protected by dams. The conjugate analysis of the hazard indicators shows that floods do not occur uniformly in individual rivers, as well as in their sections. This is confirmed by significant, frequently recurring floods in the middle-lower reaches of the Selenga and Dzhida rivers, in the lower reaches of the Chikoy and Uda rivers, the most widespread in the Selenga River delta and the middle reaches of the Uda River, where the height of the water edge on the floodplain is only 20-50 cm.

The indicator of the flood magnitude is individual for each river and determined by the hydrological conditions and morphology of the valley (figure 1c). It is calculated as the difference of the maximum rise in the water level above the critical level of water reaching the floodplain [18]. Calculation data show that the maximum values of water levels in the rivers of the basin are the most typical for summer floods, and the excess above the critical level is between 30 and 437 cm. Exceptional rises of water on the floodplain of more than 200 cm were recorded at the following hydrological stations: Dzhida-Khamney – 437 cm, Dzhida – 295 cm, Selenga-Novoselenginsk – 419 cm, Selenga-Ust-Kyakhta – 198 cm, Selenga-Ulan-Ude – 207 cm, Chicoi-Povorot – 267 cm, and Uda-Ulan-Ude – 266 cm.

As a result of geoinformation mapping, we have created digital flood models of various repeatability in the form of a set of vector layers and attribute charts. Based on the cartographic assessment of the dynamics of flooding of settlements, agricultural lands and economic infrastructure, we have determined physical and geographical characteristics of environmental changes.

An important prerequisite for an automated system is the ability to work interactively with a multilayer working coverage and a large number of thematic layers. Such interaction is ensured through geoinformation queries to the stored data. The working coverage of GIS is created as a result of mapping individual components of the environment and the subsequent combination of thematic layers. For example, in response to the request "Assessment of agricultural damage in the Zaigrayevsky Administrative District from the flooding on the Uda River", the first step in the implementation of the request is the selection of objects (agricultural land) and spatial modeling
Figure 1. Main flood characteristics within river basins.

criteria (administrative district and flood zone). Then, topological relations between these layers are established and automated metric assessment of the formed polygons is performed. As a result of these operations, a new layer is created that records the spatial and quantitative state of the simulated phenomenon (agricultural damage). Then, the aggregation of the phenomenon attributes as well as the metric, qualitative and quantitative assessment of the possible damage from the flood are performed. As a response, cartographic, graphical and tabular models of the phenomenon are generated. The cartographic model allows for a spatial assessment of negative flood dynamics. The graphic model represents the quantitative characteristics of affected agricultural lands as a whole and for each object of land use. The table model is a relational database containing metric parameters (to the accuracy of 1 m) of all formed polygons of the phenomenon. The digital elevation model allows performing an altitude assessment of the possible occurrence of flooding.

4. Conclusion
The developed GIS of cartographic flood monitoring is a modern automated complex providing collection, processing and analysis of spatially coordinated information. It is open for geodata of any origin, technologically simple and manageable, which implies rapid creation of inventory and assessment maps of floods. The system provides the possibility of both interactive work of the user in the mode of requests and low-volume printing of maps. Technological implementation of GIS allows reliable recording of spatial and temporal parameters of floods, prediction of possible intensification of their development, quantitative assessment of material and social damage, as well as the formulation of recommendations for territorial administration authorities.

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