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ORIGINAL ARTICLE

Experience of GIS modeling of extreme floods on Siberian rivers

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Results of GIS-mapping of flood zones during the spring flood season due to snowmelt for settlements located on the Tom River and the Ob River within Tomsk region (Western Siberia, Russia) are presented. “Flood” application of the Tomsk region Geoportal is created, where there are more than 40 3D models of settlements, including houses, infrastructure and current water level, which is calculated daily based on data from the nearest gauging stations. Analysis showed that the flood zone for the maximum water level covers more than 50% of the area in 19 settlements. The inundation flow simulation and evaluation of the evacuation route availability for the village of Black River showed that already after 6 hours after the start of flooding, residents of more than a third of the houses will not be able to independently reach the evacuation points. The results of this research can be used for decision-making in case of flood emergency during the flood season.
Key words: GIS, flood zones, Western Siberia

Introduction

One of the most important hydrologic seasons of Siberian rivers is the snowmelt flood period (Taratunin, 2008). Maximum river water levels determine a flood situation on river banks, floodplain inundation conditions and parameters. Over 40 settlements located on the Ob River and Tom River within the Tomsk Region are subject to flooding during the spring flood season due to snowmelt. Thousands of people are within the risk zone. High hazardous floods cause intensification of fluvial processes, river banks erosion, damage for settlements, engineering constructions and people living in riparian zones. The situation is complicated by the lack of necessary information about water levels - there are only nine gauging stations here. There is a need to predict the flooded zones of populated areas at risk. This problem can be solved using high-precision digital elevation models (DEM) and hydrological data. The goal of our work is the creation of flood monitoring system (computer application) based on data from unmanned aerial vehicles (UAVs), hydrological calculations and GIS-modeling.

Materials and methods

The Ob is the third largest northward flowing river in Siberia (Figure 1). Its headwaters are located in the Altai Mountains. The river originates from the confluence of the large mountain rivers of Biya and Katun near the city of Barnaul, drains a total area of 3×106 km2 and contributes about 400 km3 of the annual flow to the Arctic Ocean. The Ob River within the 1,000 km long study area reach has polyzonal water regime integrating peculiarities of water runoff formation in all crossed landscape zones. The Tom River is one of the largest tributes of the Ob River. The length of the Tom River is 827 km. These Siberian rivers are characterized by the presence of a high and long spring to summer snowmelt flood and autumn rain floods; a winter low flow period lasts about six months. Maximum water levels in the middle course of the Ob are related to the passage of the spring–summer flood water flow peak, i.e. to maximum water discharges (Zemtsov et al., 2019).

The first flood wave in the Ob River coming from the mountainous part of the basin merges with the floods of lowland tributary rivers and in most cases produces the highest water discharges at Novosibirsk. High water flows of the Tom River at Tomsk have several peaks, the first of which is close in magnitude to the maximum of the Ob at Novosibirsk and passes almost at the same time. As a result of the superposition of these waves, the maximum flow rates of the Ob flood in the area downstream the mouth of the Tom are formed. Maximum water levels at the downstream gauge stations usually are observed during the ice drift and sometimes caused by ice jams in the river. In Nikolskoye and Molchanovo, it occurs likely due to the great water inflow from the Tom River, the flow of which is formed in the mountains of Kuznetsk Alatau and is not controlled by dams. Downstream of Kolpashevo, at Kargasok and Aleksandrovskoye gauge stations, an even smaller number of maxima are associated with ice phenomena. At those locations, the highs are often associated with the third flood wave, which can combine with the second one and takes place in the middle-to-late June (Zemtsov et al., 2019).

Our analytical review of the existing flood monitoring and forecasting systems in Russia showed that mainly methods based on remote sensing data obtained from space systems predominate (Tararin, 2007, Alabyan et al., 2015, Novakovsky et al., 2015). First of all, it is worth mentioning specialized applications for flood monitoring at the main suppliers of satellite imagery - ScanEx and Sovzond. Roscosmos also offers similar developments (as part of its Geoportal). "GIS-Hydrology" (Hydrometeorological Center) is based on the use of satellite images from the "Landsat-8" and "Resource-P" platforms (Shagaev, 2017).

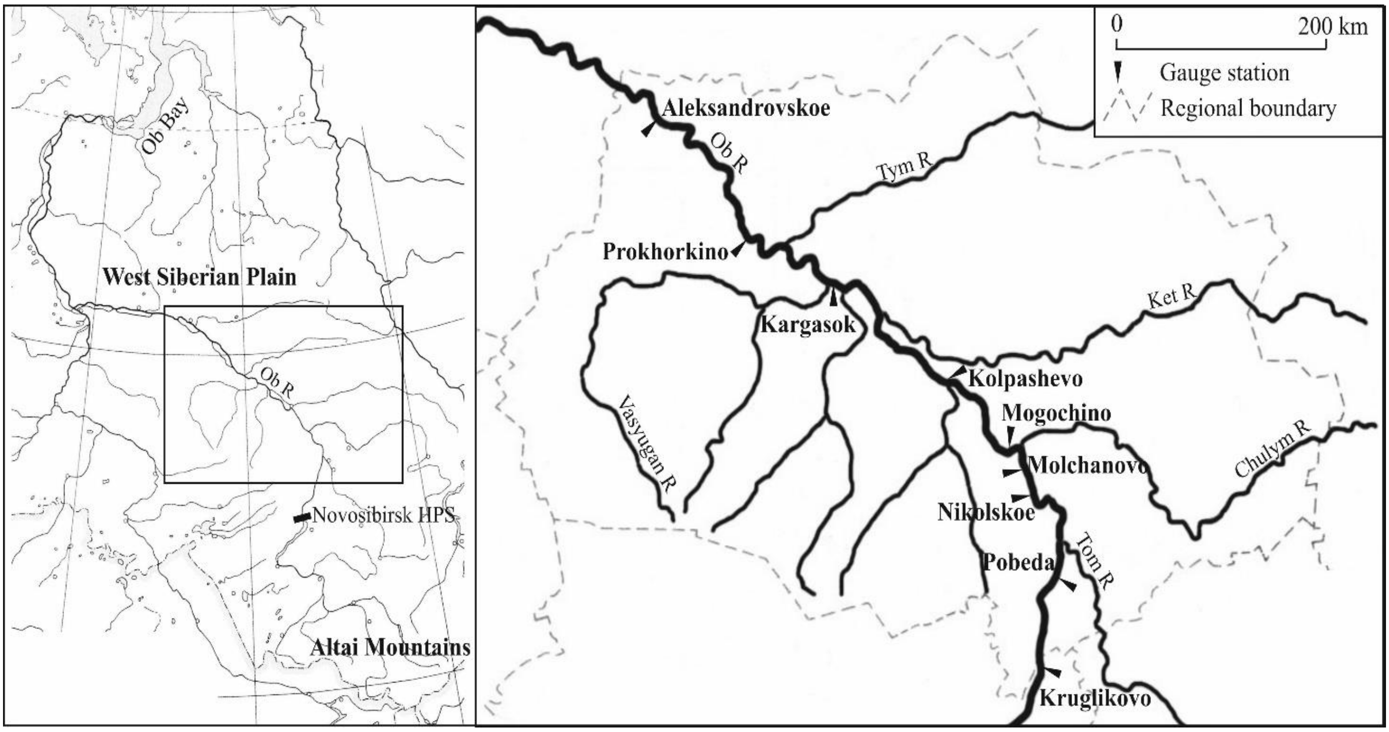

Fig. 1. Study area and gauge stations in the middle course of the Ob River

An automated complex based on space remote sensing data - "Flood Monitoring" was created in the Research Center "Planet" (Asmus, 2017). Regional flood monitoring systems are also being actively developed – for example, GIS "Amur" (Frolov et al., 2016).

Since 2015, the Tomsk State University (TSU) geographers have been developing GIS for monitoring and forecasting the state of natural resources of the Tomsk region, one of the applications of which is "Flood". The system operates on the basis of the TSU supercomputer SKIF Cyberia using a data storage system of more than 40 Tb. The software: ArcGIS Server (ESRI Inc.), Agisoft PhotoScan (GeoScan), EasyTrace (EasyTrace Group), and free software SAGA, QGIS and GeoServer. Access to the system is carried out through the Tomsk region Geoportal.

For GIS modeling of flood zones for settlements located on the Tom River, the Tom River Valley DEM was used, created by geographers of TSU earlier (Khromykh, Khromykh, 2007a) as well as digital landscape maps of the Tom River Valley (Khromykh, Khromykh, 2007b, 2013, 2015). For settlements located on the Ob River UAVs data were used to determine and map the flooded areas. The DEM, based on UAVs data, is a significant source of information in assessing the spatial coverage and potential for the development of flooding. To estimate the level of flooding, the use of absolute altitudes with the DEM is advisable only for small sections of lowland river valleys, where the slope of the river channel is insignificant. For longer sections, it is necessary to obtain a digital model of relative heights from the water edge, which, for example, is possible when working with the Vertical Distance to Channel Network module of the SAGA software (Glotov, 2013). Orthophotomaps from Geoscan 201 UAV were used for GIS-mapping. Employees of "Tomskgiprozem" and geographers of TSU made UAV-survey during autumn 2018 and summer 2019 with a spatial resolution of 0.04–0.05 m. As a result of photogrammetric processing of this data, high-precision digital terrain models (DTM) with a resolution of 0.15–0.5 m were created using Agisoft PhotoScan (Figure 2). To obtain hydrologically correct DEM from DTM, masking of houses and woodlands on orthophotomaps was carried out, and the ArcGIS tools "Con", "Raster domain", "Append" were used. Orthophotomaps of all settlements were used to vectorize hydrographic objects. In September 2018 and July 2019, field works were carried out in order to survey the state of the Ob River banks. At the same time, algorithms for calculating water levels in settlements without gauging stations have been developed in cooperation with the staff of the Hydrology Department and the Faculty of Innovative Technologies at TSU. Determination of flooded areas of each locality was based on hydrological calculations and DEM.

Another interesting task is online computer simulation of the process of settlement flooding (inundation flow) based on DEM and finding the best routes to evacuate the population (evaluation of the evacuation route availability). This simulation was performed on the example of the village of Black River near Tomsk using the techniques of Japanese colleagues from Tokyo Metropolitan University (Nakayama et al., 2008, Nemoto et al., 2011, 2013). Preliminary a geodatabase for all houses of the village based on the information received in the Ministry of Emergencies was created in ArcGIS. This geodatabase includes houses with the residents with limited mobility (disabled people, the elderly, children) (Figure 3).

ArcGIS Network Analyst and Spatial Analyst (ESRI Inc.) software was used for simulation. The simulation area is approximately 20 km^2 (5 km in WE, 4 km in NS). 2-D planar dynamic wave model was used for flood simulation with next parameters: backward inlet water from the Tom River – 100 m^3/s, manning's roughness coefficients – 0.04 (cf. floodplains - pasture, farmland – 0.035), calculation interval – 1.2 sec, calculation duration – 12 hrs. Evacuation simulation parameters were next: road data – OpenStreetMap (OSM) data, origin – each building (centroids of buildings), destination – 5 evacuation points on a mound of highway Tomsk–Novosibirsk, evacuation method – on foot, walking speed depends on the water depth – 2 km/hr (33.3 m/min) for 0 m water depth, 1 km/hr (16.7 m/min) for 0–0.5 m water depth, closed for more than 0.5 m water depth. Necessary refuge time and nearest evacuation points from each building were evaluate.

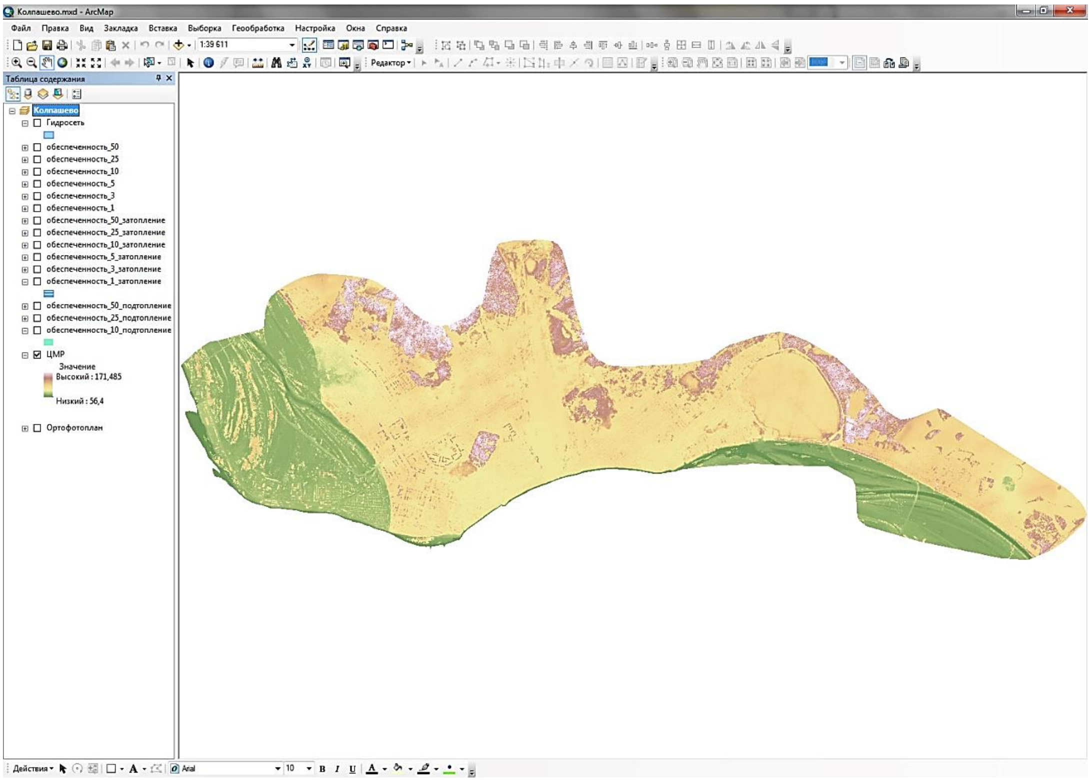

Fig. 2. DTM of Kolpashevo city resulting photogrammetric processing of UAV-images

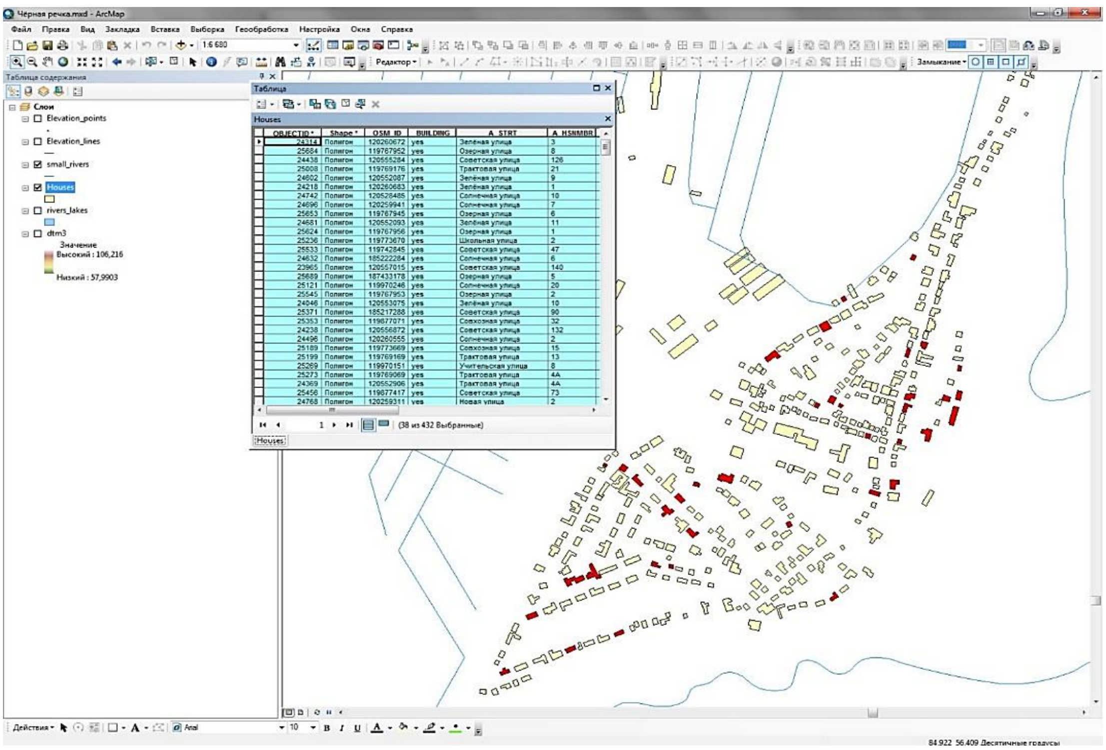

Fig. 3. Map of the village of Black River (houses with the residents with limited mobility are highlighted)

Results

Phylograms Flooded areas were designated as linear and polygonal objects using ArcGIS Spatial Analyst and 3D Analyst (ESRI Inc.) for the calculated different water levels in each settlement (Figure 4). Thus, the situation with each water level was simulated and mapped. Now the results of GIS modeling of the flood zones are used in the “Flood” application of the Tomsk region Geoportal, where you can see 3D models of more than 40 settlements, including houses, infrastructure and current water level, which is automatically calculated daily based on data from the nearest gauging stations (Figures 5, 6).

Fig. 4. Orthophotomap of Kolpashevo city with a flood zone at a water level +8 m

Fig. 5. 3D model of the Krasny Yar village (DEM draped with orthomosaic)

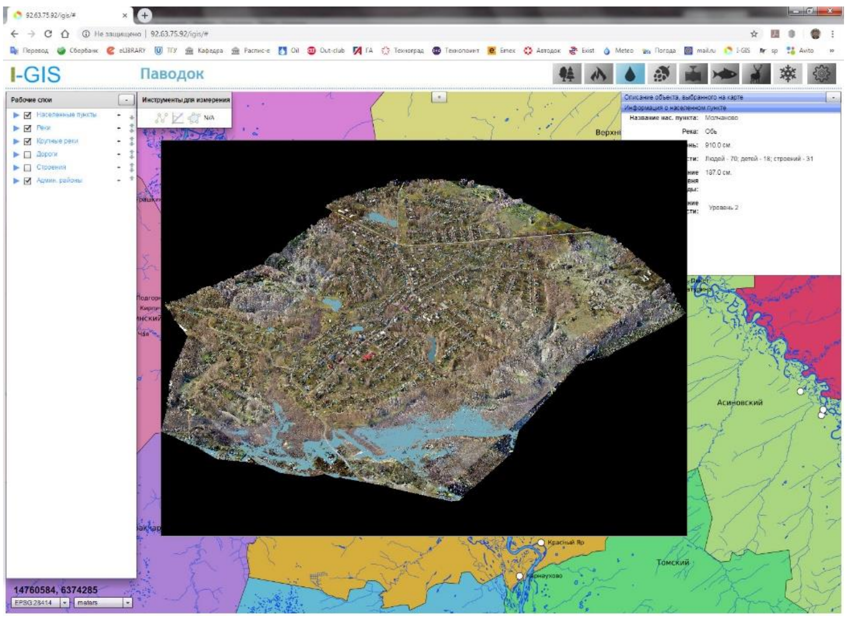

Fig. 6. Interface of the “Flood” application of the Tomsk region Geoportal

The results of inundation flow simulation and evaluation of the evacuation route availability for the village of Black River showed that after 2 hours inlet water fills small channel of the Black River riverbed. After 2.5 hours there is outflow from small channel and the nearest evacuation point of some residences are changed due to flood water effects. After 3 hours flood water reaches residence area increasing refuge time in some residences. After 3.5 hours the situation becomes serious and flood water surrounds residence area increasing refuge time in more residences. After 4 hours the situation becomes severe. A part of residence area is isolated and impossible to take refuge by flood water. A lot of residence requires more time to take refuge. After 6 hours the situation becomes critical and more part of residence area is isolated by over 0.5 m depth water and impossible to take refuge. Some evacuation points do not work. Concentration of refugees to specific evacuation points.

Conclusion

The flood zones for 42 settlements located on the Ob River and the Tom River were mapped and analyzed for different water levels (from 0 to +9 m). Our analysis showed that the flood zone for the maximum water level covers more than 50% of the area in 19 settlements.
The inundation flow simulation and evaluation of the evacuation route availability for the village of Black River showed that already after 6 hours after the start of flooding, residents of more than a third of the houses will not be able to independently reach the evacuation points.
The results of GIS-modeling of flood zones in settlements (“Flood” application), and the results of inundation flow simulation and evaluation of the evacuation route availability for the village of Black River can be used for decision-making in case of flood emergency. It will reduce the threat to people's lives and material values during the spring flood season due to snowmelt

Acknowledgments

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