Ground Penetrating Radar Investigations of the River Ice Cover in the Integrated Monitoring of Dangerous Hydrological Phenomena

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Abstract. Ice jams are dangerous hydrological phenomena characteristic of most rivers of Russia. To reduce the risk of flooding of settlements during the spring flood, the development of technology for integrated monitoring of the river ice cover, based on the methods of GPR and the Earth remote sensing (ERS), is proposed. The advantage of the technology is the ability to obtain detailed information in vast and inaccessible areas with a bleak climate. The results of an experimental study of a site of 0.4 km² in the Khastakh arm of the Lena River are presented. The OKO-2 GPR (Logis-Geotech group of companies, Russia) determined the thickness and structure of the ice cover. Satellite images determined the tonal characteristics of the ice cover in contact with sand and water. The combination of GPR results and ERS images made it possible to obtain detailed information about the spatial change in the thickness and structure of the ice cover. The prospect of integrated information lies in the possibility of integral assessments, and their use in modeling, monitoring and forecasting ice conditions in the spring.

1. Introduction

Ice jams are dangerous hydrological phenomena characteristic of most rivers of Russia, which have a northern direction of flow [1]. A significant rise in water level during the ice-jam formation causes emergencies in the life of settlements and the activities of economic entities located on the banks and near water bodies, which means that they are potentially dangerous for a person and his life. Despite the fact that ice-jam floods are short-time, the damage they cause is estimated at many billions of rubles. To reduce the risk of settlements flooding during the period of freezing and spring flood, instrumental, visual and satellite observations of the ice situation on the rivers are carried out.

2. Research method

Currently, the solution to the problem of determining the thickness and structure of the ice cover at the end of freezing has been made possible thanks to the GPR method [2]. For the investigation, the OKO-2 GPR (Logis-Geotech group of companies, Russia) with automatic location sensing using a global positioning system (GPS / GLONASS) is used. Figure 1 shows the OKO-2 GPR with the AB400 antenna unit (center frequency is 400 MHz) mounted using the suspension on the bottom of the EuroStar SLW aircraft. The processed results of GPR measurements of the Lena River ice cover in the Yakutsk - Nizhny Bestyakh site are shown as a profile with color classification of the distribution of ice thickness on a map constructed using the QGIS geographic information system.
Observation of the ice situation on the rivers during the spring flood is carried out by the Earth remote sensing method (ERS) [3]. Today, the Russian satellite constellation includes eight spacecraft (SC) - low-resolution geostationary satellites “Electro-L” No. 1, No. 2 and six polar-orbiting satellites - medium spatial resolution “Meteor-M” No. 1, No. 2, high spatial resolution “Resource-P” No. 1, No. 2, No. 3 and “Canopus-V”. These spacecrafts have optoelectronic equipment, the operation of which depends on cloudiness and lighting conditions in the survey area.

Operational management of the ground-based complex for the reception and processing of satellite information is carried out by the State Research Center “Planeta”, which includes three regional centers - European (Moscow), Siberian (Novosibirsk) and Far Eastern (Khabarovsk). Reception areas of regional centers provide satellite information throughout Russia. There is also an engineering and technology center (ITC) of the ScanEx group of companies (Russia) using its own network of ground-based stations for receiving satellite information from radar and optical data of various spatial resolutions. The company has developed the “Cosmoplan” information system for the National Crisis Management Center (NCMC EMERCOM of Russia) in order to analyze situations on the rivers of Russia.

At the same time, it is worth emphasizing that satellite monitoring of the ice situation on the rivers of Russia during the spring flood period records ice movements, ice drift and ice cleansing. During the monitoring, temporary series of images that show the dynamics of river opening and the development of floods, including the detection of ice jams and rising water levels are studied. Obviously, satellite imagery can assess the extent of the situation, obtain an operational forecast of the flood zones, assess the damage caused, and also identify areas threatened by flooding [3].

Currently, the GPR technology for sensing the Earth's surface and methods for processing the data are actively developing. Radar survey materials have a number of features, such as all-weather, high penetration, signal intensity depending on surface properties. For ice reconnaissance of water bodies,
the radar satellite RADARSAT-2 (Canada) is actively used. The paper [4] is devoted to the development of a method based on the acquisition of images from the RADARSAT-2 radar satellite for monitoring the time domain changes in the ice cover, as well as determining the ice types during the freezing period using the Slave River in the north-western part of Canada as an example. The time domain variation of the river ice cover was analyzed using the coefficient of variation based on backscatter in the winter of 2013-2014 and 2014-2015 (Figure 2). The monitoring algorithm based on RADARSAT-2 can also be applied to other rivers to track the formation of ice cover during the freezing and ice drift in the spring.

![Figure 2. The formation of the Slave River ice cover.](image)

Also, in the paper [5] the results of integrated field studies of the ice cover on the cascade of jam sites of the Sukhon River in 2015-2016 are shown. At the beginning of the investigation, the hydrometeorological situation on the river was analyzed according to the gauging stations and satellite images “LANDSAT-8” (USA). During field surveys, complex hydrological measurements were carried out. The following characteristics were measured - deep, direction of flow and its speed, thickness and structure of ice, thickness of the sludge layer, thickness of snow cover, and height of ice ridges. In addition, the PIKOR-2M control and indicator device for measuring ice thickness was tested. Scanning results of the PIKOR-2M device showed significant interpretation difficulties. Integrated studies of a powerful ice jam formed in the winter of 2015-2016 allowed us to obtain its objective quantitative characteristics - volumes of ice, snow, sludge, hummockiness and dynamics of their values in the pre-spring period on a stretch of more than 60 km.

3. Research results

We conducted experimental integrated studies of the rivers ice cover in the spring using the GPR and ERS methods. The work was carried out in three stages. At the first stage, a site was selected in the Khaystakh arm, on which one longitudinal route P003 with marks M5-M6 and two transverse routes P001, P002 with marks M1-M2, M3-M4 were laid (Figure 3). In early April 2018, field surveys were performed with the OKO-2 GPR (Logis-Geotech group of companies, Russia) with the AB-250 antenna
unit (central frequency is 250 MHz) in foot mode. Measurements by the antenna unit were carried out in contact with the ice cover. Investigation routes were navigated using the Garmin eTrex20 GPS receiver.

Figure 4 shows a radargram of profile P002 showing a cross section of the arm, on which the ice cover, bottom topography and arm deep are traced. The left radargram scale shows the ice thickness, and the right arm deep. According to the amplitudes of the reflected signals, characteristic areas were recognized on the radargram, such as: ice cover in contact with sand, monolithic ice in contact with water, frozen sands and thawed sand [6]. These characteristics on the radargram are highlighted in color: brown - frozen sand, orange - ice in contact with sand (bottom), blue – ice cover in contact with water. The average value of the ice thickness was 1.25 m. The maximum deep in the arm was 1.4 m. The data of the transverse profile P001 show that the average value of the ice thickness is 1.46 m, the maximum deep is 2.5 m. On the longitudinal profile P003, the average of the ice thickness was 1.24 m, and the maximum deep was more than 3 m.

The second stage included the search and collection of free high-resolution satellite images of the ice cover on the arm site at the end of the freezing. In the case of the high cost of satellite observations, satellite imagery or lack of imagery, it is advisable to obtain information from an unmanned aerial vehicle, on which a high-resolution optoelectronic system should be installed.

Figure 4. Radargram P002.

Satellite images obtained after the snow cover disappeared from the ice are necessary for the qualitative recognition of the ice cover characteristics. Then the thematic processing of images, including their combination, modification of brightness and contrast was performed. Existing decryption methods make the transition from image brightness to the characteristics of the ice structure [7, 8]. An interpretation uses a number of features. Direct signs are the tone, tonal structure and texture of the object image, size and shape. Indirect signs - the interconnection of objects with the environment. An example is a fragment of a satellite image of PlanetScope (www.planet.com) with a resolution of 4 m (04.05.2018) [8] of the Khatystakh arm site, which shows the tone heterogeneity of the ice cover characteristics (Figure 5).
Visual analysis of the image showed that the ice cover in the main part of the arm is expressed from dark gray to light gray. In this area, the ice is transparent, having a monolithic structure. According to GPR data, the ice cover is in contact with water. Confidently different ice cover along the ice-free area, which is shown in Figure 5 in white. According to the GPR data, it was established that the ice cover along the ice-free area is in contact with the sand (bottom). It is worth noting that in the Figure, in a wide part of the arm, one can confidently recognize the ice cover in contact with water. Although in a narrow part of the arm, near the island, the ice cover is difficult to classify by color, and this can lead to an error in the ice classification. In this case, a combination with GPR data can improve the recognition capabilities of satellite images.

The last step was the combination of the GPR data and satellite images using the QGIS geographic information system, which made it possible to obtain a map of the distribution of ice thickness in the arm along the profiles P001, P002 and P003 (Figure 6). In Fig. 6, the white color of the ice-free area is confirmed by the data of transverse GPR profiles P001, P002, in which the ice cover is in contact with the sand (bottom). Throughout the arm, according to the P003 GPR profile, the ice cover is in contact with water, which corresponds to the tone of the satellite image.

**Figure 5.** Tonal heterogeneity of the ice cover on the Khatystakh arm section.

**Figure 6.** Map of the distribution of ice thickness in the site of the Khatystakh arm.
4. Conclusion
As a result of the investigation, it can be said that the use of satellite images with a high resolution of 3 m and the GPR data is an important step in the development of integrated monitoring of river ice cover. The images can be used to classify the ice cover in contact with water and sand, the structure of the ice cover, and also determine their boundaries. According to the GPR data, it is possible to determine the thickness and structure of the ice cover, to determine the signs of ice contact with sand and water. The prospect of integrated information lies in the possibility of integral assessments, and their use in modeling, monitoring and forecasting ice conditions in the spring. The use of detailed information will contribute to the development of optimal technological measures for the prevention of dangerous hydrological phenomena and the effective solution of problems of protecting the population from emergencies caused by spring floods on rivers.

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