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GEOINFORMATION MODELING OF THE ESIL RIVER FLOOD ZONE BASED ON REMOTE SENSING DATA

The article presents the technique for geoinformation modeling of a site of a river valley with an insufficient amount of hydrological data. The technique will make it possible to carry out a forecast of hydrological phenomena in order to prevent the flooding of adjacent territories by flood waters. The study is based on the use of Earth remote sensing (RS) data and the use of geoinformation technologies (GIS). The sequence of the work is briefly described. The study was carried out on the example of a site of the valley of the Yesil (Ishim) river, located near Petropavlovsk (North Kazakhstan region, Republic of Kazakhstan). On the basis of remote sensing data and GIS technologies, a digital relief model of the studied section of the river valley was developed. The initial data were SRTM (Shuttle Radar Topography Mission) images. The modeling of the scenario of possible flooding of adjacent territories by flood waters has been carried out. Modeling and mapping of flooding carried out for the flood peak. Modeling and construction of a flood map were carried out for the flood peak. An approach is proposed that makes it possible to perform a more accurate assessment of the boundaries of flooding without the procedure for calculating the hydrological characteristics of the river during the flood period and the absence of hydrometric observation data. Recommendations are given for the prevention of flood events, measures to protect adjacent lands from possible flooding. The obtained cartographic materials can be useful for planning and carrying out measures to prevent emergency situations related to floods on the river, reduce the risk of flooding of adjacent areas, and territorial design.

Key words: mapping, modeling, GIS, remote sensing data, digital terrain model, river valley, flooding.

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Қашықтықтан зондтау деректері негізінде Есіл өзенінің су басу аймағын геоақпараттық модельдеу

Мақалада гидрологиялық мәліметтер жеткіліксіз болған кезде өзен аңғары учаскесін геоақпараттық үлгілеу әдістемесі келтірілген. Әдістеме іргелес аумақтарды тасқын сулармен су басудың алдын алу мақсатында гидрологиялық құбылыстардың болжамын жүзеге асыруға мүмкіндік береді. Зерттеу Жерді қашықтықтан зондтау (ЖҚЗ) деректерін қолдануға және Геоақпараттық технологияларды (ГАЖ) пайдалануға негізделген. Жасалған жұмыстың реттілігі қысқаша баяндалған. Зерттеу Петропавл қаласы маңындағы (Солтүстік Қазақстан облысы, Қазақстан Республикасы) Есіл өзені аңғары учаскесінің мысалында жүргізілді. ЖҚЗ материалдары мен ГАЖ-технологиялар негізінде өзен аңғарының зерттелетін учаскесінің жер бедерінің сандық үлгісі әзірленді. Бастапқы деректер ретінде SRTM (Shuttle Radar Topography Mission) суреттері алынды. Іргелес аумақтарды тасқын сулармен су басу мүмкіндігінің сценарийін үлгілеу орындалды. Жоғары деңгей кезіндегі су тасқыны картасын үлгілеу және құрастыру жүргізілді. Су тасқыны кезеңіндегі өзеннің гидрологиялық сипаттамаларын есептеу процедурасын жасамастан және гидрометриялық бақылаулар деректерінің болмауына қарамастан су басу шекараларын дәлірек бағалауға мүмкіндік беретін тәсіл ұсынылды. Су тасқыны құбылыстарының алдын алу бойынша ұсыныстар, іргелес аймақтарды ықтимал су тасқынынан қорғау шаралары ұсынылды.

Алынған картографиялық материалдар өзендегі су тасқыны құбылыстарымен байланысты төтенше жағдайлардың алдын алу, іргелес аймақтардың су басу қаупін азайту, аумақтық жобалау бойынша іс-шараларды жоспарлау және жүргізу үшін пайдалы болуы мүмкін.

Түйін сөздер: картаға түсіру, үлгілеу, ГАЖ, қашықтықтан зондтау деректері, жер бедері сандық үлгісі, өзен аңғары, су тасқыны.

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Геоинформационное моделирование зоны затопления реки Есиль на основе данных дистанционного зондирования

В статье приведена методика геоинформационного моделирования участка речной долины при недостаточном количестве гидрологических данных. Методика позволит осуществить прогноз гидрологических явлений с целью предупреждения затопления прилегающих территорий паводковыми водами. Исследование базируется на применении данных дистанционного зондирования Земли (ДЗЗ) и использовании геоинформационных технологий (ГИС). Кратко изложена последовательность проведенной работы. Исследование осуществлялось на примере участка долины р. Есиль (Ишим), расположенного вблизи г. Петропавловска (Северо-Казахстанская область, Республика Казахстан). На основе материалов ДЗЗ и ГИС-технологий разработана цифровая модель рельефа исследуемого участка долины реки. Исходными данными послужили снимки SRTM (Shuttle Radar Topography Mission). Выполнено моделирование сценария возможного затопления прилегающих территорий паводковыми водами. Моделирование и построение карты затопления проведены для пика паводка. Предложен подход, позволяющий выполнить более точную оценку границ затопления без процедуры расчетов гидрологических характеристик реки в паводковый период и отсутствии данных гидрометрических наблюдений. Даны рекомендации по предупреждению паводковых явлений, меры защиты прилегающих земель от возможного подтопления. Полученные картографические материалы могут быть полезны для планирования и проведения мероприятий по предупреждению чрезвычайных ситуаций, связанных с паводковыми явлениями на реке, снижению риска затопления прилегающих участков, территориального проектирования.

Ключевые слова: картографирование, моделирование, ГИС, данные дистанционного зондирования, цифровая модель рельефа, долина реки, затопление.

Introduction

The Yesil (Ishim) River is the main water artery of the North Kazakhstan Region and a basic source of water resources for household needs, industrial production, agriculture, tourism and recreation. Its source is located in the Niyaz mountains, in the upper part the river flows through a narrow valley in the northwestern and western direction, below the city of Nur-Sultan, the valley expands to the southwest, further to the north (in front of town Derzhavinsk) and northeast (Petropavlovsk). The Yesil River is fed by snow. Its freezing begins in the beginner of November, opening of the river is in April and May. The maximum level of water rise during the spring flood occurs in May and June. During this period the river overflows up to 15 km in its low part. Average consumption near Petropavlovsk in 1975-2019 is 60.0 m^3/s, the largest one is 2420 m^3/s in 2017. The main tributaries are Koluton, Zhabay, Akkanburluk (right). About 80% of its annual runoff is formed in the spring due to snowmelt. The Vyacheslavskoye and Sergeevskoye reservoirs are located on the river. (Geografija Severo-Kazahstanskoj oblasti, 2016:35-38; URL1:2022)

Intensive melting of the snow cover in spring often causes floods on the river, flooding the territories adjacent to the valley. Flooding processes in the form of floods cause significant social and economic damage. During such emergencies, damage and destruction of residential and industrial buildings and constructions, infrastructure facilities, flooding of agricultural land, leading to the death of crops take place. So, there is a threat to domestic animals, and most importantly, the health and life of the population living near the river.

According to the Department of Emergency Situations for North Kazakhstan Region (URL 3:2022), the area subject to flood events in the region is 43,991.95 ha (2020). To prevent emergencies there is a system of gauging stations designed to monitor the hydrological, hydrochemical characteristics and parameters of the river. Due to the specifics of the device and the nature of the relief in the flat areas, the density of observations of the parameters of rivers is much less than in mountainous areas. In total, within the North Kazakhstan region on the river Yesil operates 19 gauging stations, 5 of which were opened in 2020 to improve the quality of forecasting.

However, for a more detailed study, assessment and accurate forecasting of flood events, their number is insufficient. The available materials do not allow to accurately and quickly determining the areas of possible flooding. This makes it difficult to timely carry out the relevant work to prevent floods, and reduces their effectiveness.

The relevance of the study is connected with a significant economic development and population of the river Yesil valley and adjacent territories. There are many settlements here, including regional center – town Petropavlovsk, agricultural land, important engineering and construction facilities, elements of road transport infrastructure.

Nowadays, the development of GIS technologies, the use of digital elevation models (DEMs) has made it possible to significantly simplify and automate the process of determining zones of flooding by flood waters, modeling and forecasting flood phenomena on rivers. DEMs are very important for solving a wide range of geographic and cartographic problems. One of the most urgent among them is the problem of determining the zones of possible flooding of territories during flood events on rivers. The advantages of creating DEM based on remote sensing data are the efficiency of obtaining up-to-date data, automation of their processing, and a fairly high accuracy of the resulting models.

In the process of modeling flood zones based on RS data, no procedure for special calculations of the hydrological characteristics of the river during the flood period is required. The special significance of the use of RS for modeling and forecasting zones of inundation by flood waters is noted for territories with a rare network of gauging stations, in the absence of operational data from hydrometric observations.

The purpose of the research was to determine the areas of flooding by waters of the river. Yesil through modeling based on RS data in a GIS environment.

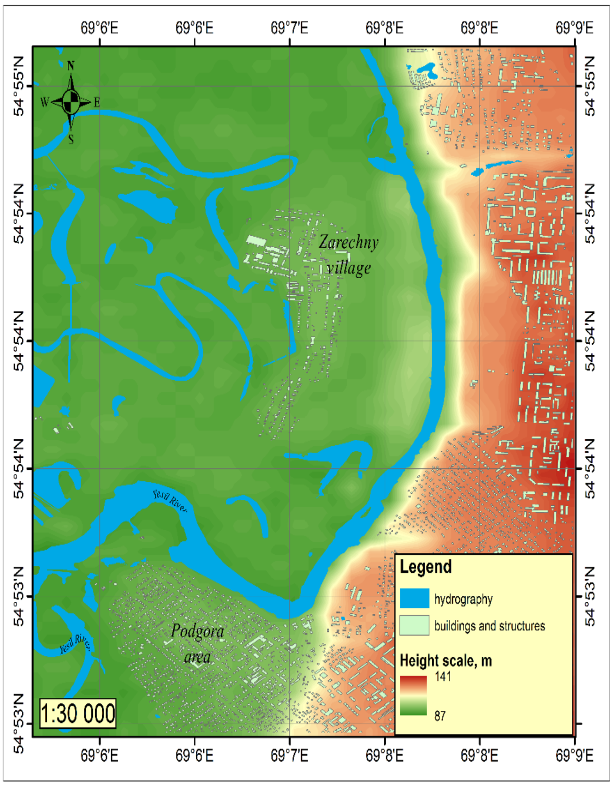

Figure 1 – Floodplain of the Yesil river (Petropavlovsk)

The purpose of the study was to test the methodology for modeling areas flooded by flood waters based on remote sensing data in a GIS environment. The study was carried out on the example of the site of the valley of the Yesil river near the city of Petropavlovsk, subject to periodic seasonal flooding by flood waters. The study area is located within the coordinates 54°52´-54°55´ N.L. and 69°6´-69°8´ E (fig.1).

Materials and methods

The methodological base of research is founded on the publications of a theoretical and practical nature on geoinformation mapping. Particular attention is paid to the study of the experience and results of research on mapping and geoinformation modeling of the relief and its parameters for solving practical problems. Among them there are works of the authors of the CIS on the basics of cartography (Berlyant, 2002; Salishchev, 1976), geoinformation systems and methods of spatial analysis (Pyankov, 2017), modeling of flood zones (Mushtaykin, 2021:1-11), methods for calculating the highest water levels of rivers (Orlyankin, 2017:98-101), geoinformation modeling of floods (Novakovsky, 2013:35-39). The experience of foreign authors in GIS and automated mapping (Dueker K., 1987:384-390), the basics of hydrological modeling (Spence C., Dalton A., Kite G., 1995: 62-66), the experience of preventing flooding of the Seine (Paris) (URL4:2018), etc.

During the research literary authors used stock and archival data, materials of hydrological observations of the Branch of RS Kazhydromet in the North Kazakhstan region, topographic maps (URL 4: 2022), schemes of territorial (agricultural) land management, materials obtained in the process of field and cameral work performed in the period 2019-2020, surveys zones of periodic flooding on the ground, a sociological survey of residents of settlements located in the valley of the river Yesil, in its lower flow.

When modeling flood events (or floods) and the high water caused by them, not only hydrological characteristics, information about the levels of water rise, but also accurate data on the terrain are required. Publicly available data from Earth remote sensing (ERS) – SRTM (Shuttle Radar Topography Mission, 2000), which are available in the public domain, were used as initial data for a detailed study and mapping of the relief of the study territory. The SRTM data are radar topographic surveys with a resolution of about 90 meters (3 arcseconds) (URL 5: 2022). To carry out cartographic work, section N50 was selected, covering the floodplain of the river Yesil.

It should also be noted that A.K. Korveul's, I. Ewiak's (Karwel A.K., Ewiak I., 2008: 169-172) studies revealed that SRTM is suitable for creating contour lines on topographic maps at a scale of 1:50,000 and smaller, as it has an error of 2.9 m for flat terrain and 5.4 m for hilly. This limits the scope of the study and determines the need for mapping and modeling in the specified interval in order to avoid errors and distortions. The solution to this problem can be the testing and improvement of remote methods and materials (radar, satellite observations). The use of images for different dates makes it possible to more accurately assess and determine the area of potential flooding. More detailed data can be obtained on the basis of aerial photography from unmanned aerial vehicles (UAVs).

The methods used in the study: comparative geographic, cartographic, modeling, observation, field methods, GIS technologies.

Terrain mapping and modeling was performed using ArcGIS 10.1 software (ESRI Inc.). This software product is characterized by a wide range of tools and modules, the functionality of which allows you to perform various operations, not only for mapping, developing various maps, spatial analysis, but also modeling processes and phenomena, and performing forecasting (URL 6: 2022).

A detailed study was carried out on the example of two key areas located in the lower flow of the river Yesil. These areas belong to the zone of periodic flooding. The key section 1 is the suburban settlement of Zarechny, the key section 2 is Podgora, one of the districts of the town of Petropavlovsk. The area of key plots was 105 ha and 52 ha, respectively. The study area is characterized by a slight difference in the heights of the surface of the territory and the water's edge. The floodplain section in this part of the valley has homogeneous morphometric conditions. According to topographic maps (URL 4:2022), the surface height in key areas is 100 m. The height of the water's edge (average level) near Petropavlovsk is 333 m.). For comparison, the lowest water level of the river Yesil is 304 m, recorded in November. The rate of water level rise per day at the Petropavlovsk Reservoir in recent years has been 5 cm, the rise of water since the beginning of the flood is 25 cm (as of 06/05/2020).

The study included a number of stages, solving the following tasks: collection and generalization of analytical data on the hydrological regime, spring floods, flood events on the river Yesil, creation of a digital elevation model based on SRTM data, creation of a predictive model of flooding near the city of Petropavlovsk.

At the initial stage, in order to compile the initial characteristics of the territory, a conjugated analysis of the natural components of the valley of the river Yesil was carried out and special attention is paid to hydrological characteristics. Flood phenomena on the river Yesil with a significant rise in the water level are recorded annually. However, the coordinated actions of all structural divisions contribute to the timely prevention of especially dangerous (emergency) situations.

The main stage of the work consisted in bringing the materials of RS data into the required cartographic projection, and their interpretation. The interpretation of the images was carried out manually using the structural geomorphological method (SGM). Based on the SRTM materials, an orthophotomap, terrain elevation matrices were obtained. On their basis, a digital elevation model (DEM), a relief map and a 3D model of the study area were developed. The reliability of the obtained DEM was improved by adjusting and enhancing it with the “Fill” tool. The initial data on the relief of the floodplain are plotted by isohypses in vector form, the horizontal spacing is 5 m (Fig. 2).

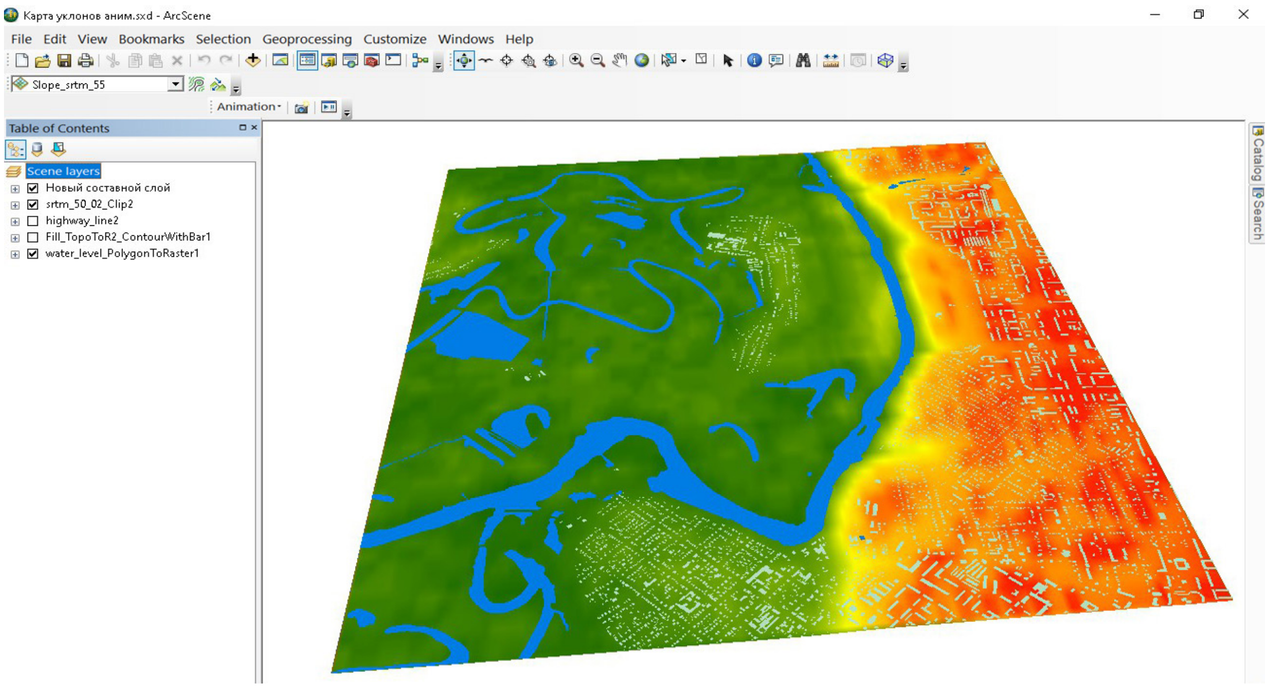

Figure 2 – Digital model of the relief of the river Yesil floodplain near Petropavlovsk

One of the areas of application of modern means of GIS technologies, materials of RS, which are of great practical importance, is their use in the construction and processing of DEM and geoinformation modeling of flood zones during flood events. The main way to determine flood zones during floods and high water in GIS is the construction of inclined surfaces. These surfaces allow to determine the most closely the water mirror or the degree of a possible rise in the water level. Next, the lines of intersection of these surfaces with a digital terrain model are determined, which make it possible to identify and outline the flood zones (Agnes Cabal, Marc Erlich, 1992: 395-406; Xiaoliu Y., Michel C., 2000; Kulp S. A., Strauss B. H., 2018: 231-239; Shakeel Mahmood, Atta-ur Rahman, Rajib Shaw, 2019: 573; Shokoufeh Khojeh, Behzad Ataie-Ashtiani, Seiyed Mossa Hosseini, 2022: 2673-2693). To solve this problem, we used the approach proposed in the following works Identification of the contours of the flood zones was carried out using the tools of the ArcScene software shell by overlaying a water layer on the relief map.

Using the GIS functionality in ArcScene, based on the slope map, a three-dimensional model of flooding of key areas was obtained, which was visualized and presented in the form of animation (Fig. 3). Modeling and construction of a flood map were carried out for the flood peak, when the greatest negative impact of flood waters on adjacent territories is manifested.

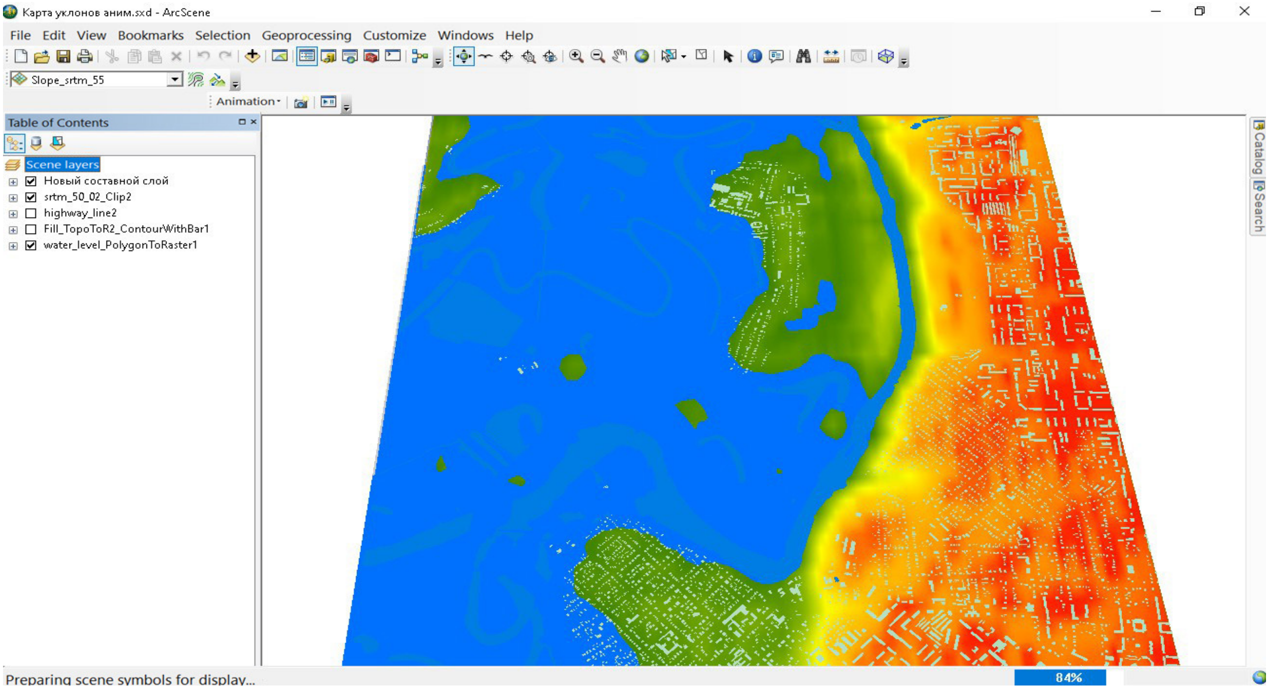

Figure 3 – Scenario of possible flooding in ArcScene

During the approbation of the modeling methodology, scenarios making it possible to determine the flood zones at the maximum level of water rise in the river Yesil were considered. According to the Department of Emergency Situations of the North Kazakhstan region, the maximum rise in the water level in the river Yesil at a gauging station near the city of Petropavlovsk in 2019 was 94.0 m (URL 2: 2022). The boundary of the zone obtained during the construction of the model allows to determine partially or completely flooded areas, settlements, roads, bridges and other infrastructure. By modeling the scenario of the consequences of flooding, it is possible to assess the possible extent of flooding, determine and take timely measures to prevent an emergency before they occur.

The degree of compliance of the flood zone modeling results obtained using GIS and RS was checked by comparing the flood boundary recorded on the date of the flood in 2019. In addition, a comparison was made with the flood boundary obtained by interpolating heights based on the values of water lines increased by the height of its rise during the flood. By comparing the territories that were flooded by flood waters in 2019, an error in modeling the flood zone in the eastern part of the settlement Zarechny was revealed. On the height map built on the basis of SRTM, this section is above 100 m, however, according to the Department of Emergency Situations of the North Kazakhstan region, it is subject to almost annual flooding by flood waters.

The development of the final map of the study area included the creation of layers of physical and geographical objects (the Yesil River, its tributaries, oxbow lakes, natural vegetation), layers of economic development of buildings (residential and industrial buildings, roads, fields, hayfields and pastures). The latest in mapping was the creation of a database, which included a list of characteristics of objects and phenomena.

Results and discussion

As a result of the research, the digital relief model and the three-dimensional model of the flooding of the valley of the Yesil river on the example of key areas were compiled. According to the compiled relief models, it can be seen that, under the condition of a maximum rise in the water level in the Yesil river, a significant area of the territory is subject to flooding. A significant part of the settlements Zarechny and the Podgora became completely flooded. More than 140 residential and industrial facilities, infrastructures, roads turned out to be under water. Omsk highway, road number P-49, 4 km long). Agricultural land, garden (country cottage) plots can be seriously affected. The area of potential flooding was more than 620 ha (Fig. 4). Extensive areas of flooding are noted in the south and west of the considered territory. The floodplain zone, the left bank of the river is subject to the greatest flooding by the Yesil river.

Figure 4 shows a map of the model of the flood zone of the site of the valley of the Yesil river, adjacent to the city of Petropavlovsk, during the period of maximum increase in water level. According to the official website of the Department of Emergency Situations of the North Kazakhstan region, in 2019 the peak of the water level in the river was on May 8 and amounted to 94.0 m relative to the zero of the gauging station. The left bank of the river Yesil to the south of the settlement Zarechny and Podgora area was flooded.

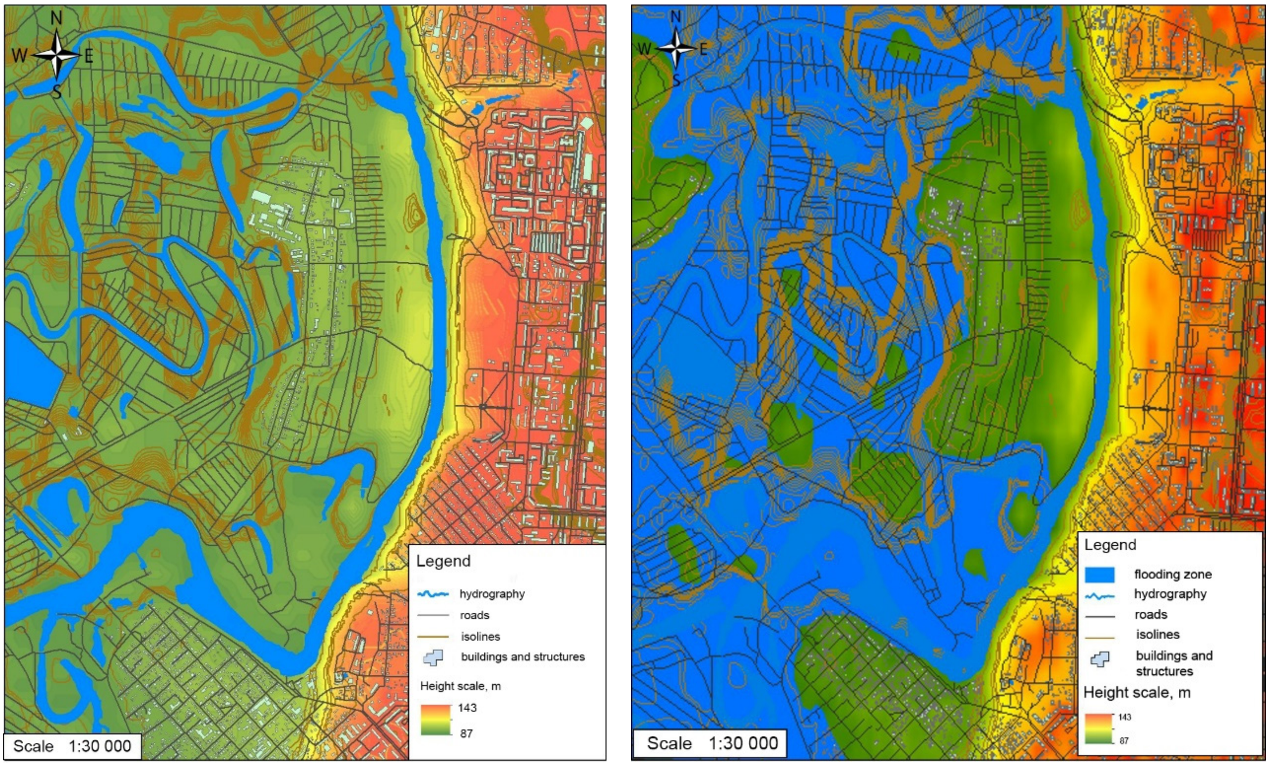

Figure 4 – Map of the relief and flood zone of the valley of the river Yesil

Thus, on the obtained model of flooding, it can be seen that the probable damage from the flooding of adjacent territories by the spring flood waters of the Yesil River is very significant, which will determine the need for operational monitoring and forecasting of hazardous hydrological phenomena.

The GIS package also gives the possibility to simulate the consequences of the emergency situation caused by a possible dam or dike break, to calculate the area of catastrophic flooding of the surrounding area. In addition, the statistical characteristics (minimum, average, maximum depth, water volume) of the flood zone can be calculated. Using the GIS-based forecasting function, it is possible to make short-term and long-term forecasting of flood events in the floodplain and channel system in space and time. However, calculations of this level of complexity require a series of additional field studies with special equipment, as well as observation over a specific period of time. The obtained data will then allow to correctly compose a GIS flood model. In this article, a GIS modeling method was proposed with insufficient hydrological data.

In areas of possible flooding, the obtained cartographic materials can be useful in assessing the potential risk of emergency, developing the most rational hydraulic engineering methods for protecting this territory and adjacent areas, and will allow timely measures to be taken to help reduce material and social damage from flooding.

Along with this, the developed cartographic materials can serve as a basis for compiling maps of the manifestation of water erosion processes, waterlogging on agricultural land located in the valley, modeling and forecasting possible damage. This will make it possible to solve the strategic tasks of the economic development of the valley of the river Yesil and adjacent territories, to choose the best methods of agricultural production in terms of erosion resistance, to optimize the land management scheme. Such maps and models have a great practical importance for the implementation of design and construction work. The created models, in turn, can serve as the necessary basis for constructing more complex maps, in particular, for the development of synthetic integrated maps for the protection of the study area from hazardous processes, schemes for optimizing nature management and reducing environmental tension. On their basis, priorities and optimal options for economic activity and environmental protection measures can be determined.

The use of RS materials, in particular SRTM, in determining flood zones on rivers, certainly has advantages over existing traditional forecasting methods (water balance, physical and statistical methods, statistical, mathematical models that describe the formation of runoff processes using differential, integral, and other equations and etc.). However, some disadvantages should be noted when modeling a surface based on height matrix SRTM (URL 7: 2022, Kim D. E., Liong S. Y., Gourbesville P., Andres L., Liu J., 2020: 1-14). First of all, it is connected with the nature and features of the relief of the study territory. The region has a flat relief, with insignificant amplitudes of heights, and a weak dissection of the surface. In the conditions of a flat relief, the construction of its detailed model is difficult, because the height amplitude is insignificant. The presence of woody vegetation and forest areas reduces the accuracy of surface modeling. To eliminate possible errors in the construction of height matrix and models, a necessary condition is to conduct a detailed analysis of large-scale (topographic) maps, data on the morphometric structure of the floodplain, field studies with clarification of the morphometric features of the relief on the ground. In this work, modeling of flood zones using GIS was performed without determining and modeling the movement of a flood wave. Carrying out the flood wave modelling contributes to obtaining more accurate results. Also, it is necessary to take into account the difference in the water level along the study area compared to the amount of water rise during the flooding of adjacent territories. Such work should be based on a detailed study and mapping of the river valley in cooperation with the hydrological service.

As recommendations for the prevention of flood events and the adverse consequences associated with them, the following measures can be considered for implementation.

Improving the accuracy of observations of the flow and level of water on the river and the operational provision of hydrometeorological information. Particular attention should be paid to determining the height and amount of water reserves in the snow cover, because flood events are directly reflected in the intensity of spring snowmelt. No less important is the study of the water absorption capacity of the basin, monitoring the state of the soil, the composition of the underlying rocks. Improving the technical equipment of gauging stations, the observation network (for example, the installation of remote instruments for assessing water reserves in the snow cover).

Conclusion

Based on the study, it can be concluded that GIS technologies are important and effective tool for solving the problems of determining the quantitative indicators of the territory relief, which must be taken into account when developing potential flood zones.

Earth remote sensing materials serve as a valuable source of data for creating accurate digital elevation models (DEMs). However, in the conditions of a flat plain relief, their use for the construction of DEMs and models should be based on taking into account possible systematic and random errors. The elimination of the errors can be carried out by introducing appropriate corrections based on the alignment of DEMs with contour lines and elevations of geodetic network control points according to topographic maps obtained in the course of field research, ground topographic and geodetic measurements.

In general, SRTM data are suitable for topography analysis and use in modeling flood zones, taking into account possible systematic and random errors. Modeling on the basis of SRTM data of flood zones can be considered as one of the approaches to model representation and forecasting of flood zones to prevent negative and emergency situations caused by floods, a sharp rise in water levels. Positive effect from the application of this approach can be achieved through the use of remote sensing data in conjunction with other methods and approaches.

In the course of the study, on the example of a section of the valley of the Yesil river, a technique for creating models of flood zones using GIS technologies based on remote sensing data was tested under the conditions of a lack or absence of hydrological and hydrometric observations.

The obtained materials can be useful to the governing bodies, the Ministry of Emergency Situations of the North Kazakhstan region for solving practical problems, and also involved in the development of an integrated GIS of the basin of the Yesil river.

For the study area, in the future, it is important to conduct studies aimed at a more detailed study of the washout and erosion hazard indicators of soils and underlying soils.

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