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HYDROLOGICAL PROCESSES MODELING USING GIS ARCGIS AND MODULE HEC-RAS

Aim of this research is to determine the area of land flooding according to a reasonably chosen hydrological model for a complex section of the Dniester River at the place of transition from the foothill to the plain with complex meandering and significant shifts of the river. **Methods.** The method of investigation of flooded areas as a result of water rise to a certain level has been processed. It includes: survey of the area with UAVs; the implementation of geodetic and hydrological activities in the field of research; creation of DEM based on survey results and analysis of its accuracy; hydrological modeling using the HEC-RAS software package; and determination of flood areas. In order to obtain the digital elevation model, which is the basis for hydrological modeling, a Trimble UX5 UAV with a Sony NEX-5R camera was used. To accurately determine DEM coordinates, a standard error for horizontal coordinates of 6 cm was established; elevation coordinates depending on the basis of images and the underlying surface equals 0,21m. The DEM was created using the specialized software Pix4D. GPS data was given as input to the hydrological modeling. **Results.** The DEM was created according to the results obtained from the UAV to the average quadratic error of 0.2 m. The technique of hydrological modeling implemented on the part of the Dniester River with a complex configuration of the channel was processed. Areas have been designated including the area of flooding at different water levels of. **Scientific novelty** is the development of a methodology for determining flooded areas based on the hydrological modeling using the HEC-RAS module for the Dniester River section, which is characterized by significant erosion of coastal soils, complicated meandering and transition from foothill to plain topography. Such conditions require precise determination of modeling parameters. In order to obtain input data for flood modeling, the UAV survey was carried out with a preliminary justification of the accuracy characteristics. **The practical significance.** Hydrological modeling is performed in order to predict the consequences of material losses due to flood events occurring in the Pre-Carpathian region. The timely receipt of information about these processes; and the monitoring of hydrological posts on the water level, which fills the beds and floodplains, allow through appropriate administrative structures to notify the population and take measures to reduce the losses resulting from these devastating phenomena. The proposed study is aimed at obtaining information on flood areas due to different levels of water uplift in the Dniester River.

Key words: hydrological modeling; HEC-RAS; flooding; hydrology; unmanned aerial vehicles; digital elevation model.

Introduction

Natural floods are among the most frequent and threatening natural disasters occurring in the world. It results in significant material and scial losses. In recent decades, the world has developed a methodology for modeling flood zones and anticipating the threat of destruction in order to minimize losses, prevent the tragic consequences of these phenomena, and promptly inform the population. Such modeling requires the study of morphometric features of river channels and is based on the use of remote sensing data and the application of special hydrological modules.

The largest floods on the Dniester River, the plot of which is the subject of this study, occurred in 1927, 1941 and 1955. The last flood was caused by prolonged rains and covered more than 70 thousand km^2.

The June 1969 flood was an unprecedented flood, called historical by hydrologists. At that time on the night of 7-8 June, downpours started and during one 40-hour rainfall more than 300 mm of precipitation fell, i.e. more than the two-month rainfall norm, and in some places the amount of precipitation even exceeded the monthly norm by three times. Water in the tributaries of the Dniester and Prut Rivers rose at a rate of 30 to 90 cm/hour. Water measuring devices failed, and the width of water flooding in some valleys reached 8 km. Rapid flows flowed down from the mountains, increasing the destructive effect of the rivers. According to hydrologists, this was the most dangerous flood in the region. This flood was attributed to those that occur only every 100 years.

The 2008 flood occurred in the summer as a result of thunderstorms. It peaked on 23–27 July. Then the territories of the Carpathian Mountains, Prykarpathian Mountains and Transcarpathia were damaged. Another noticeable flood was the flood of 14–16 May 2014, when the level of the Dniester River near the city of Stary Sambor rose by 4 m, and in places where the river channel is narrow – even up to 5 m, then the water area was flooded [Kovalchuk, & Mykhnovych, 2008].

In today's realities, significant changes in natural conditions, such as deforestation, climate change, and floodings, create almost annual environmental disasters, which are accompanied by significant economic losses and destructive processes. The essence of the danger is to raise the water level in the channels to the floodplain level and to inundate houses, lands, utilities and other economic entities, which are often brought together in the floodplain. At the same time, economic activity in the Dniester basin in recent decades has increased the influence of factors that lead to the frequent occurrence and development of floods, which cause widespread destruction.

Such natural disasters cannot be completely eliminated, but their impact can be mitigated, localized and material losses minimized through timely warning. This can be achieved through operational monitoring and flood forecasting. In today's reality, hydrological modeling by DEM is an effective method, based on channel type and floodplain data, and water level hydrometry with flood detection, calculated using the selected hydrological model and its implementation by means of special software.

In the Dniester basin, floods are dangerous for the Dniester valley within the Carpathian region, as well as for the mountainous valleys of its tributaries when they reach the valley. The mountainous part of the region is characterized by the highest rainfall intensity, which causes floods.

The author of the study [Karpets, 2014] considered the prospects of using computer technologies of water distribution to assess the situation of surface water bodies and catchment areas, to identify the possibility of emergency situations in order to promptly eliminate their consequences. In addition, the possibilities of flood protection are described, which are based on the creation of a modern automatic system of hydrometeorological observations in hydrometeorological services, collection and receipt of data by the forecasting center in real time with the necessary frequency. This allows for fast and efficient data management, storage of these data, fast and convenient access to them, and the creation of high quality maps for different purposes.

A methodological approach to distributed hydrological modelling using GIS tools is presented in the publication [Melnyk, 2012]. General features of hydrological modeling in geoinformation software environment are discussed. Two types of distributed models are considered, which are used to reproduce the hydrological component of the watershed environment. In general terms, the prospects of creating a hydrological information system are defined.

The article [Alabian, et al., 2015] describes the basics of the construction and practical implementation of systems of operational forecasting of river floods, based on the integrated use of modern developments regarding information technology and integrated preventive modeling.

Studies conducted by scientists at the University of Tennessee [Sharkey, 2014] show that the use of the HEC-RAS software for modeling river sections with reservoirs on the example of the city of Tennessee, gives positive results of modeling when using and creating a hydraulic model of a water body. The author focuses on the issues of inaccuracy of the model and instability of the problem solution during minimum water discharge through hydraulic structures, which, in turn, is able to increase the instability of direct calculation, but has a positive effect on the calculation of water volumes. The purpose of the author's work is to predict and assess dangerous hydrological situations related to high and low water discharge in the river network and directly for the operation of hydrosystems, along with the issues of sustainability of solutions in these hydrological scenarios and situations.

The author of the article [Levashova, 1993] considered the characteristics of hydraulic parameters – roughness coefficients – on the basis of generalized data of a significant number of rivers (small, medium, large) flowing in different physical and geographical areas, taking into account such factors as hydraulic parameters as: the depth of the flow, the relative width, the amplitude of the water level fluctuation, the type of channel process, the nature of soils and the form of sediment transport, the contamination of the channel by vegetation, deformation of the channel.

The paper [Starodub, 2015] considers the need to use the HEC-GeoRAS and HEC-RAS software in the project to improve safety in areas that may be flooded. The methodological basis and algorithm of the software are given, and the obtained flood data are compared with the predicted data obtained on the basis of previous years' floods.

In [Gharbi, et al., 2016], the authors simulated Medjerda River in Tunisia floods using 1D and 2D hydraulic models. It was found that 1D-modeling is quite easy and quick to perform, but the accuracy of modeling within the floodplain is lower than in 2D models. The simulation results were calibrated from the 2003 flood data.

In [Khaleghi et al., 2015], hydrological modelling was carried out in the Lighvan Chai River basin using the HEC-RAS software. Increased losses caused by floods due to land use changes in the floodplain were identified. The GIS system and remote sensing data were used for this purpose.

In a significant part of the studies related to the determination of flooded areas, modelling is performed using a one-dimensional model using HEC-RAS software [Sandhyarekha & Shivapur, 2017, Silva, et al., 2014].

Aim

Aim of work is to determine the area of land flooding according to a reasonably chosen hydrological model for a complex section of the Dniester river at the place of transition from the foothill to the plain with complex meandering and significant shifts in the course of the river, as shown by our previous studies [Burshtynska, et al., 2016, 2018].

Methods

The method of investigation of flooded areas as a result of water rise to a certain level has been processed. It includes: survey of the area with UAVs; the implementation of geodetic and hydrological activities in the field of research; creation of DEM based on survey results and analysis of its accuracy; hydrological modeling using the HEC-RAS software package; determination of flood areas. In order to obtain a digital elevation model, which is the basis for hydrological modeling, a Trimble UX5 UAV with a Sony NEX-5R camera was used to film the area. To accurately determine DEM coordinates, a standard error for horizontal coordinates of 6 cm was established; elevation coordinates depending on the basis of images and the underlying surface equals 0,21m. The DEM was created using the specialized software Pix4D. GPS data was given as input to the hydrological modeling. The primary objective of the hydrological modeling was a) to determine the geodetic coordinates of the terrain points for the construction of the DEM in a specified coordinate system, b) estimate the accuracy of the DEM and measure the depths of the channel in the modulated part of the river, which in turn were used to describe the bottom relief. Information about the water flow rate were obtained on hydrographs. The hydrological information of water flow can be obtained using a) graphs or tables with the data dependencies of the water flow from the absolute elevation, b) the coefficients of the underlying surface roughness, and c) the coefficient of the level of slope of the bed.

General workflow of research

The research was carried out in several stages, including field research, DEM creation and editing, and flood modelling. The detailed workflow of researches is presented in Fig.1.

Model selection

Depending on the details of the input data and the type of terrain, one-dimensional and two-dimensional models based on different types of equations are used for hydrological modeling. In a one-dimensional model, the morphometric characteristics of the flow are averaged across width and depth and are considered along the x-axis. In the two-dimensional model, the flow is considered along the x-axis (in width and depth with increasing number of points). Taking into account the insignificant width of the river (15–20 m), a one-dimensional model of stable flow movement according to the Manning equation is applied, which is solved by the numerical method in the HEC-RAS module.

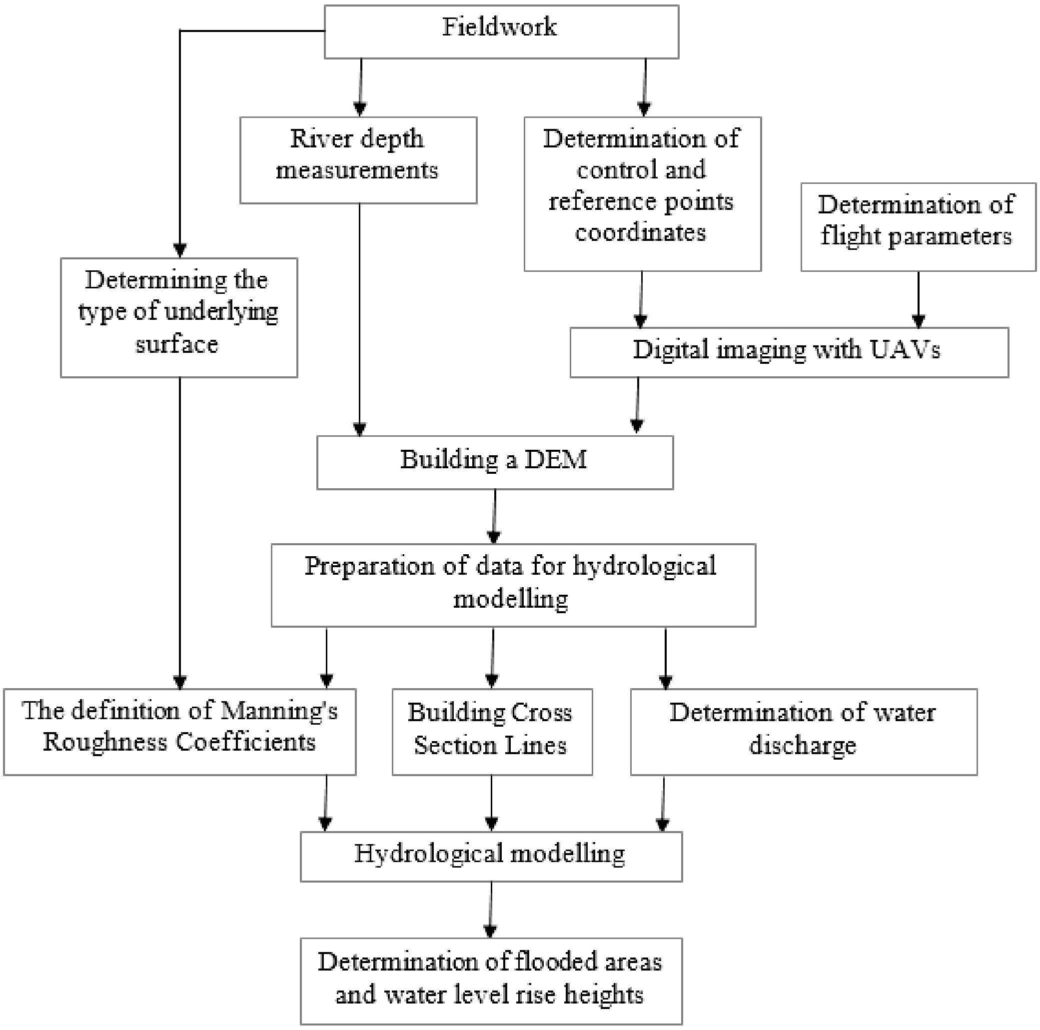

Fig. 1. General workflow of research

One-dimensional models make it possible to perform calculations for long stretches of land based on valley morphometry data presented as separate cross-section profiles. The results of the calculations are changes in water surface levels and water discharge within the study area.

The application of two-dimensional models requires more detailed information on river valley morphometry in the form of a point cloud. As a result, they provide a planned picture of the distribution of vertically averaged flow rates, water surface levels and water depths within the study area.

In order to adapt the hydrodynamic models at specific river sections, it is necessary to determine the sensitivity of the model to the composition and quality of the initial data, as well as to the details of the main calibration parameter of the model – the roughness coefficient.

The Manning equation is an empirical dependence of the natural flow rate in the open channel depending on the shape and size of the cross-section and roughness of the channel walls

$$V = (1/C) \cdot R_h^{2/3} \cdot I^{1/2} \qquad (1)$$

where V is the average speed (m/s); C – resistance coefficient; R_h – hydraulic radius (m); I – hydraulic slope (m/m).

Hydraulic radius depends on the cross-sectional area wetted perimeter $R=\omega/\chi$, where ω – cross-sectional area, χ – wetted perimeter.

The resistance coefficient is determined by the Manning formula [Chow, 1959]

$$C = (1/n) \cdot R^{1/6} \qquad (2)$$

or the more general Pavlovsky formula

$$C = (1/n) \cdot R^{y} \qquad (3)$$

where $y = 2.5 \cdot n^{1/2} - 0.13 - 0.75 \cdot R^{1/2} \cdot (n^{1/2} - 0.1)$, n – roughness coefficient.

The *y*-degree depends on the roughness coefficient and hydraulic radius, a nd the depth of the river for a wide one

Characteristics of the object of research

The object of the research was a section of the Dniester River, which is located near the village of Khatki and the city of Sambor, Lviv region. The study area is characterized by a complex winding riverbed and significant horizontal displacements, which over the past 70 years have reached values of up to 370–420 m. The location of the study area is shown in Fig. 2.

The riverbeds digitized from various cartographic sources are shown on the topographic map of 1937. The left bank of the river is high and is made up from the water mirror up to 7 m, the right bank is flatter, with the banks of the height of 1–4 m (Fig. 3). Horizontal displacements of river channel are determined by space images from Landsat 5 (1992) and Landsat 7, 8 (2003 and 2014) satellites and topographic maps (1937, 1989).

Maximum channel shifts were noted in sections 1 and 2. In section 1, channel migration towards the railway is observed, in section 2 – channel in 1989, it changed its character significantly (blue color), even in comparison with 1937. In general, the river is meandering in the surveyed areas.

Particularly dangerous to the environment is the significant bending of the river near the railway track (section 1). As this section is characterised by a precipitous landslide, it is not a potentially flood-prone area, but the main hazard is related to landslides that may be caused by shoreline scou ring.

Digital imaging with the UAV and DEM accuracy calculation

Since one-dimensional models are sensitive to the accuracy of input data (DEM), an unmanned survey was used to build DEM of the investigated area. Digital imaging with a Trimble UX5 UAV was performed by an optical-electronic camera Sony NEX-5R with aperture 5.6 and a shutter speed of 1/1250 at a height of 200 m. Processing of images was performed in the Pix4D program. Fig. 4 shows the image projection centers and the scheme of reference points arrangement.

The accuracy of the Trimble R7 GNSS receiver, which was used to determine the coordinates of the reference points is not more than 4 cm in plan and 10 cm in height. The accuracy of GPS receiver installed on the UAV is 10–20 cm.

For accuracy of determination of horizontal and altitude coordinates of points of terrain with use of optoelectronic cameras the expression [Kurczynski, Z., 2013] is offered

$$m_{x,y} = (H/f\,) \cdot P_m \quad (4)$$

$$m_h = (H/B) \cdot P_m \quad (5)$$

where H is the height of flight, f is the focal length of the camera, P_m is the size of the pixel in the field, B is the basis of images depending on the choice of overlapping images.

Fig. 2. Digitized channels of the Dniester River section for the period of 1937–2014

Fig. 3. General view of the Dniester banks: a – left bank, b – right bank

Accuracy of horizontal coordinates determination is calculated according to the formula 4.

Given the instability of the UAV in flight, 80 % overlaps of the image are selected. Then the basis on the image is:

$$b = 23.4 \cdot (100–80)/100 = 4.68 \text{ mm}$$

The error in the determination of elevation marks for the selected baseline is:

$$m_h = 200/4.68 \cdot 0.005 = 0.21 \text{ m.}$$

Building a DEM

To create a DEM in Pix4D, a point cloud was generated, which, due to the presence of vegetation, was modified in the TerraScan software module, where additional points classification was performed. In addition, the model included the points obtained by GNSS observations to refine elevation marks in complex areas of significant distortion of the model.

The created TIN-model was supplemented with information about the relief of the riverbed. Depth data were obtained as a result of field measurements. At the river section with the length of about 9 km, 258 channel depth measurements were made – two measurements (closer to the left and right banks) in increments of about 50 m. A fragment of the created DEM based on the survey results supplemented with depth measurement points is shown in Fig. 5.

Fig. 4. Projection centers and reference points

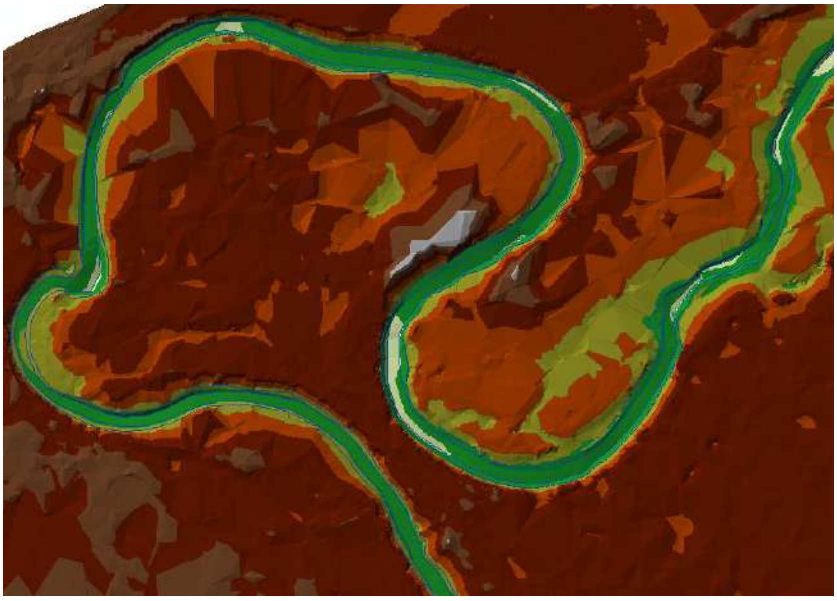

Fig. 5. A fragment of the created DEM

72 control points were used to assess accuracy. The results of a posteriori accuracy of the DEM (Table 1) indicate significant deviations of heights in places overgrown with high vegetation. Therefore, the DEM was refined in the TerraScan software module, where the points were graded. In addition, the model included points obtained by GNSS observations to refine the heights of points in areas of significant distortion of the model. After such refinement, the accuracy of determining the heights of points in places overgrown with vegetation was 0.31 m.

Table 1

A posteriori evaluation of the accuracy of determining the markings of the DMR points of the study area

Type of surface	Number of points	Root mean square error, m_h (m)
Sand, grass	28	0.19
Grass, bushes, shrubs	44	0.64

Preparation of input data for hydrological modeling

DEM serves as a basis for obtaining information on the elevation marker within the modeled area. To calculate the flooded areas in HEC-RAS it is necessary to create layers of additional information, which will include: river bank lines, floodplain boundaries, cross section lines, and riverbed and coastal area roughness factors. These layers are created using the HECGeo-RAS module, which allows the use of ArcGIS tools.

Among the layers listed above, the correctness of the river cross-sections is of fundamental importance, as they are used to model flooded areas. There are a number of requirements for the methodology of cross profiling. It is essential that the cross profiles cover the entire width of the floodplain, always run perpendicular to the river channel and are applied from left to right (looking downstream). The distance between adjacent profiles should be selected according to the changes in terrain, and the number of profiles should be greater at the turns of the channel. Cross-section spacing is a function of flow length, slope and uniformity of cross-section shape. In the studies carried out, the average distance between the profiles was 50 m. Larger, homogeneous rivers with smaller slopes usually require the smallest number of cross sections per kilometre. The study area is characterized by a complex channel shape where the direction of flow changes by 180°. The profiles in this section need to be sufficiently dense as the floodplain boundary is far from the right bank. The fragment of the created profiles on the complex section of the riverbed is presented in Fig. 6.

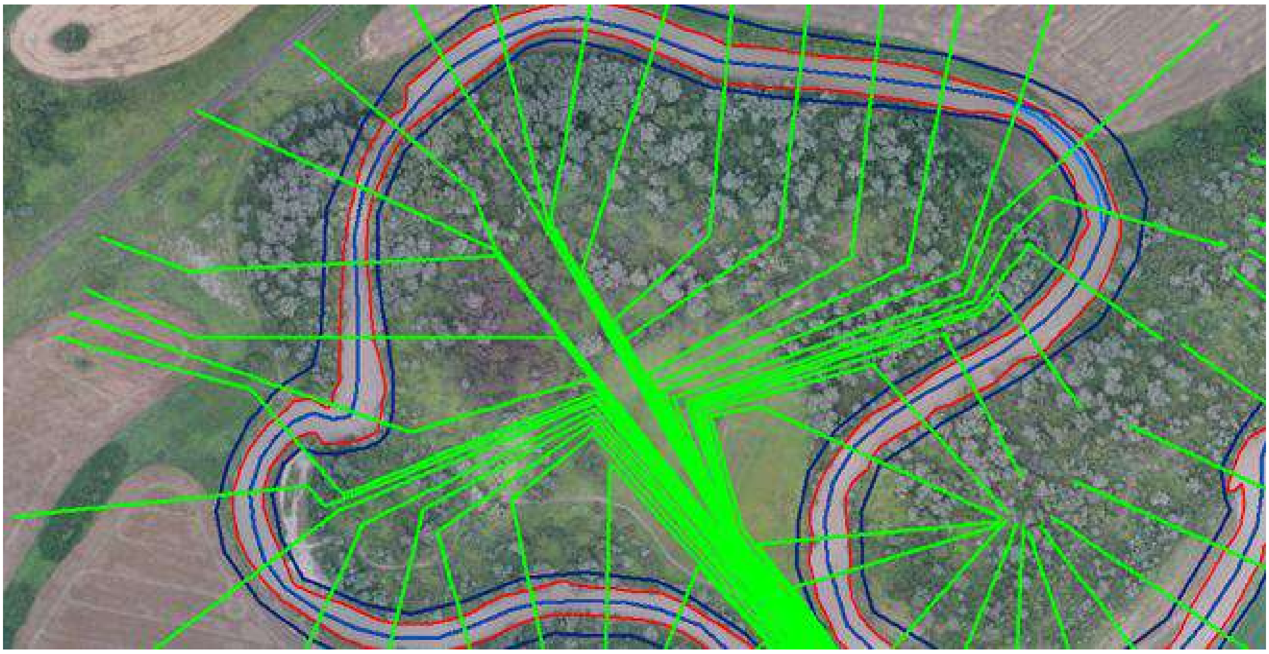

Fig. 6. Created profiles

Study of water discharge graphs

The regime of the rivers in the Dniester basin is characterized by considerable variability in the short time intervals. The analysis of annual hydrographs makes it possible to identify individual phases, periods or seasons in which the nature of flow fluctuations, its magnitude and genesis differ from the adjacent periods.

Such periods or seasons are particularly important for the rivers in the Dniester basin:

– meltwater runoff or spring floods (spring);

– the period of positive temperature predominance and underground feeding predominance, or the period of summer-autumn low flow (summer-autumn);

– the period of positive air temperature predominance and rainfall feeding predominance, or the period of summer-autumn floods (summer-autumn);

– the period of low air temperature dominance and the presence of ice or winter low temperatures (winter).

Throughout the year, in a multi-year context, the probability of high levels is the same as the probability of low levels. Even in dry years with generally low water levels throughout the year, there are sharp rises in water levels that reach 50–100 cm or more per day. There is no clear pattern in the distribution of floods and short standing low water levels on the Dniester. An example of the river level regime is the fluctuation of water level near Sambir as shown in Fig. 7.

The maximum annual levels are usually related to flood events. In some years, they are equal to those during spring floods.

The relatively low river channel capacity of the Carpathians contributes to the persistence of significant level rises in the Carpathians. The banks of the Dniester River are mostly steep and the floodplains are narrow or non-existent.

The distribution of level fluctuations during the year on the Dniester can be divided into three categories of years:

1) years with prevailing spring floods and relatively small floods during the rest of the year;

2) years with no pronounced flooding, with prevailing floods in the summer-autumn season;

3) years with continuous alternation of floods, equally large both in spring and in the summer-autumn period.

The analysis of the daily graphs for the years with the largest floods has shown that the maximum water discharge in the investigated section of the Dniester is up to 300 m^3 /sec.

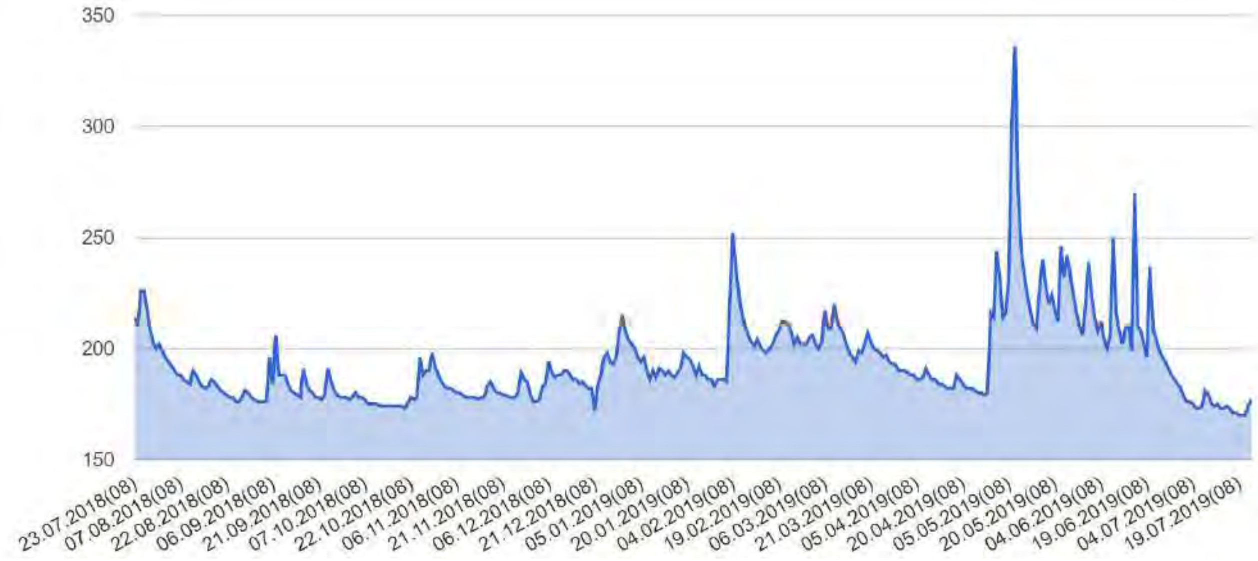

Fig. 7. Graph of the level regime of the Dniester River for the period 2018–19 near Sambir

Hydrological modelling and determination of flooded areas

The vector layers obtained using the HECGeo-RAS module have been exported to the HEC-RAS modelling software (Fig. 8).

In addition to the vector layers, hydrological modeling requires the presence of channel and floodplain roughness values, as well as water discharge values, which are typical for a river in its typical state and during flooding. The roughness coefficient characterizes the hydraulic resistance of the channel surface. They are determined from special tables, depending on the type of underlying surface.

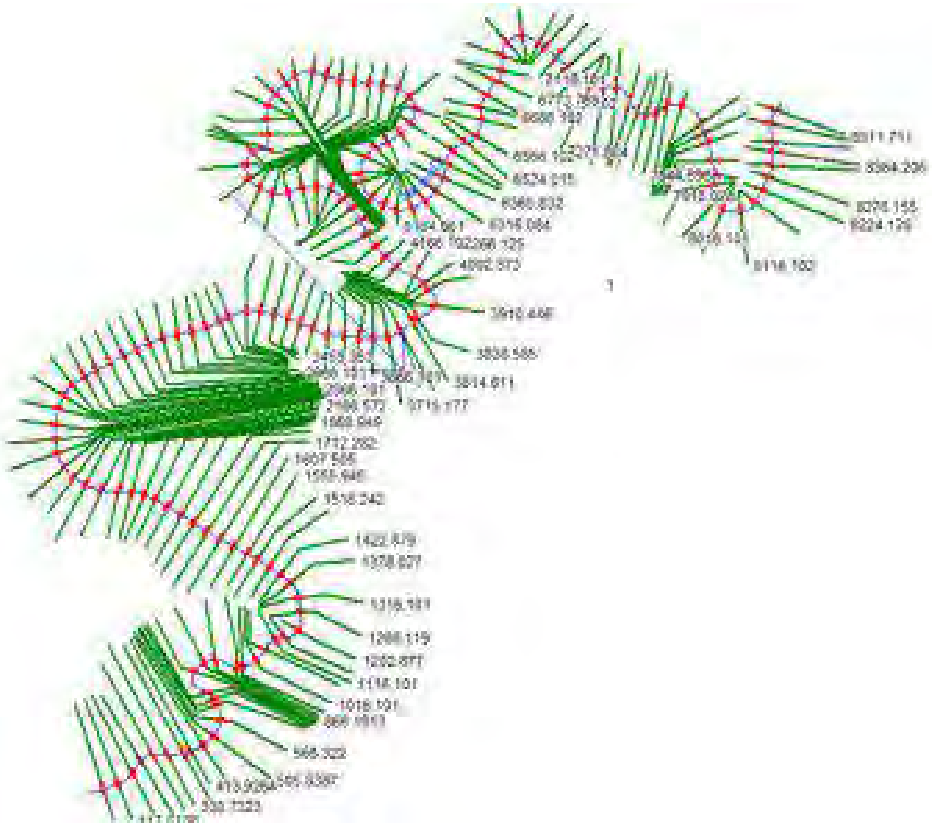

Fig. 8. Data visualization for modeling using HEC-RAS software

The water discharge for the study site bed in a low water level condition is on average 10 m^3/sec. Water discharge of 50 m^3/sec raises the river level by about 1 m. Modelling was carried out for flow rates of up to 300 m^3/s, which corresponds to a rise of approximately 4 m. These water levels were observed in this area during the summer floods (particularly in 2008). Figure 9 shows one of the profiles superimposed on the level of water rise after modelling. Figure 10 provides an orthoimage with a simulated flooded area for a water discharge of 300 m^3/s.

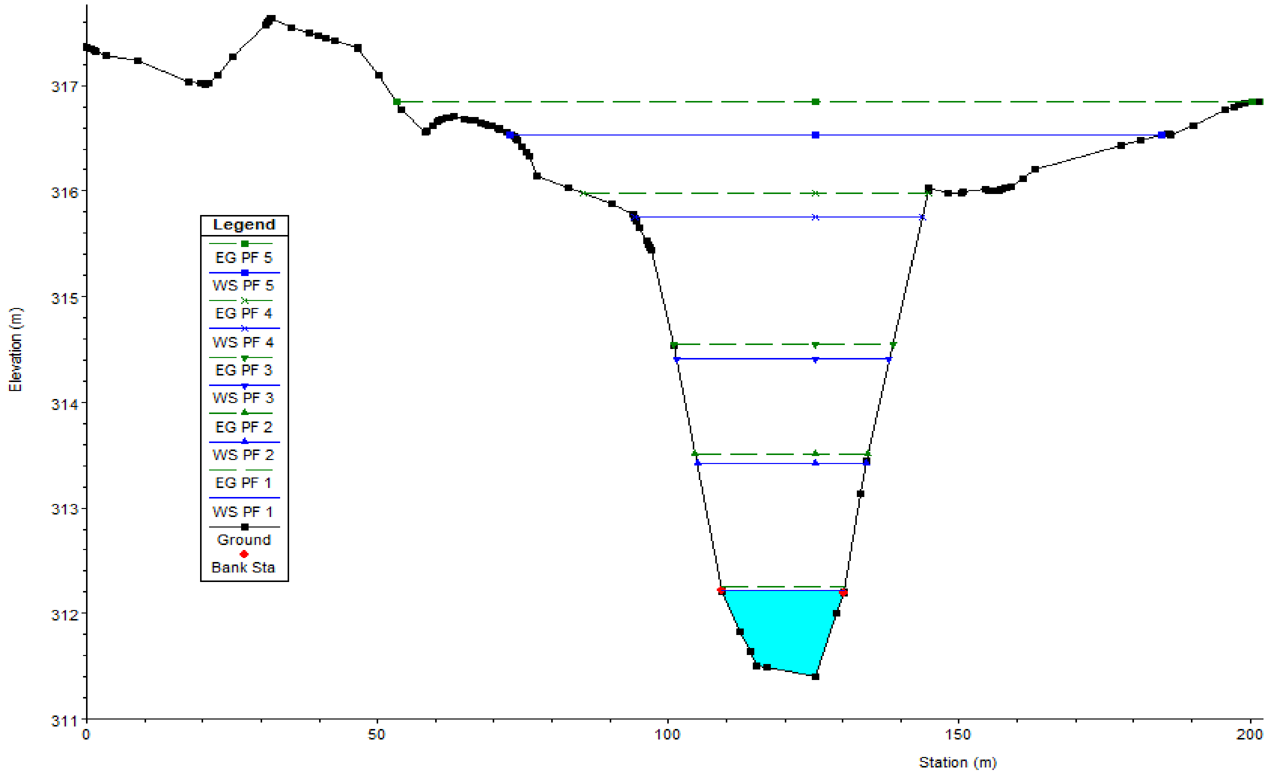

Fig. 9. Example of a river profile with marked levels of water rise for different discharges

Fig. 10. Flooded area for water discharge 300 m^3 /s

Table 2 shows the calculated flood area for the different water discharges of the river.

Table 2

Flooded areas at different discharges of water

Water discharges, m^3/s	Level of water rise, m	Projected flooded area, km^2
50	1	0.108
100	2	0.169
200	3	0.341
300	4	1.068

In summary, it should be noted that each river should be examined separately. The reliability of hydrological modeling depends on such main factors:

– the type of model adopted for modeling, which depends on the characteristics of the river (width of water surface, floodplain, river slope);

– accuracy of the digital elevation model, which serves as the basis for the selection of profile lines;

– water level rise associated with water discharge, based on a hydrograph obtained from a hydrometeorological station;

– underlying surface types obtained from ground surveys or topographic data.

Thus, for the selected study site with a complex type of meandering of the Dniester River, as well as the operation of erosion processes, it is particularly important to construct DEMs to determine the cross lines that form the basis of hydrological modeling. The type of underlying surface is taken into account within the riverbed and floodplain, with factors ranging from 0.35 to 0.8.

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Conclusions

1. In order to prevent material losses and timely inform the population about threatening flood events, modern technologies for determining the area of flooded lands may be use, for example hydrological modeling methods.

2. Automated hydrological modeling is based on the use of DEMs as a basis for determining floodplains. The choice of the type of model depends on the morphometric characteristics of the river and the type of bed and floodplain surface.

3. The object of the modeling was a section of the Dniester River with a length of about 9 km and a complex type of meandering in the transition from the mountainous part to the plain.

4. Taking into account the small width of the river (15–20 m), a one-dimensional model was chosen for modeling, on the theoretical principles of which an automated module HEC-RAS was created, which is widely used in world practice.

5. Unmanned survey data with the accuracy of 0.21 m were used for DEM construction having complex terrain and river type. A posteriori assessment of accuracy was carried out on the basis of control points measured in the process of GNSS-survey. It is established that in places with bushy and high herbaceous vegetation the accuracy of marks determination is 0.64 m. Therefore, the model was modified in the TerraScan module to specify the point heights.

6. In order to improve the model parameters in field conditions, river depth measurements were made and Manning coefficients for the channel and floodplain were determined.

7. The hydrological modeling of the selected section of the Dniester River was carried out for 4 levels of water discharge rise.

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МОДЕЛЮВАННЯ ГІДРОЛОГІЧНИХ ПРОЦЕСІВ З ВИКОРИСТАННЯМ ГІС ARCGIS ТА МОДУЛЯ HEC-RAS

Мета роботи полягає у визначенні площ затоплення земель згідно обраної гідрологічної моделі складної ділянки р. Дністер у місці переходу від передгірської частини до рівнини зі складним меандруванням та значними зміщеннями річки. **Методи.** Опрацьовано метод дослідження затоплених земель внаслідок підняття води до певного рівня. Він включає: знімання з БПЛА; геодезичні та гідрологічні роботи; створення ЦМР та аналіз її точності; гідрологічне моделювання з використанням програмного пакету HEC-RAS; визначення площ затоплення. Для отримання цифрової моделі рельєфу, яка є основою для гідрологічного моделювання, був використаний БПЛА Trimble UX5 з камерою Sony NEX-5R. Точність визначення планових координат за ЦМР становить 6 см; висотні позначки залежно від базису стереопари та підстильної поверхні становлять 0,21м. ЦМР створено за допомогою спеціалізованого програмного забезпечення Pix4D. **Результати.** ЦМР створено за результатами знімання з БПЛА з середньою квадратичною похибкою 0,2 м. Методику гідрологічного моделювання реалізовано на частині річки Дністер зі складною конфігурацією русла. Визначено зони затоплення за різних рівнів підняття води. **Наукова новизна** полягає у розробці методики визначення затоплених територій на основі гідрологічного моделювання за допомогою модуля HEC-RAS для ділянки річки Дністер, яка характерна значною ерозією прибережних ґрунтів, складним меандруванням та переходом від передгірської частини до рівнинної. Такі умови вимагають точного визначення параметрів моделювання. Для отримання вхідних даних для моделювання затоплень виконано знімання з БПЛА з попереднім обґрунтуванням параметрів точності. **Практичне значення.** Гідрологічне моделювання виконують з метою передбачення наслідків матеріальних втрат внаслідок повеневих явищ, які трапляються в Прикарпатському регіоні. Своєчасне отримання інформації про ці процеси, стеження на гідрологічних постах за рівнем води, яка наповнює русла і заплаву, дозволяють через відповідні адміністративні структури здійснити оповіщення населення і прийняти заходи для зменшення втрат, які виникають внаслідок цих руйнівних явищ. Запропоноване дослідження спрямоване на отримання інформації про площі затоплення внаслідок різних рівнів підняття води в річці Дністер.

Ключові слова: гідрологічне моделювання; HEC-RAS; затоплення; гідрологія; безпілотні літальні апарати; цифрова модель рельєфу.

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