CARTOGRAPHY AND AERIAL PHOTOGRAPHY

UDC 528.7

Khrystyna BURSHTYNSKA[1], Andrzej MAZUR[2], Maksym HALOCHKIN[3], Yevhenii SHYLO[4], Iryna ZAYATS[5]

[1] Department of Photogrammetry and Geoinformatics, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine, tel. +38(067)2561130, e-mail: khrystyna.i.burshtynska@lpnu.ua, http://orcid.org/0000-0002-6013-0873
[2] Department of Environmental Engineering and Geodesy, Faculty of Production Engineering, University of Life Sciences in Lublin, 7, Leszczyńskiego Str, 20-069 Lublin, tel. (+48)815248128, e-mail: andrzej.mazur@up.lublin.pl
[3] Department of Photogrammetry and Geoinformatics, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine, tel. +38(095)8284467, e-mail: maksym.k.halochkin@lpnu.ua, http://orcid.org/0000-0002-2778-3602
[4] Department of Engineering Geodesy, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine, tel. +38(067)1631917, e-mail: yevhenii.o.shylo@lpnu.ua, http://orcid.org/0000-0002-3838-5431
[5] Department of Photogrammetry and Geoinformatics, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine, tel. +38(097)2470009, e-mail: iryna.v.dolynska@lpnu.ua

https://doi.org/10.23939/istcgcap2022.95.053

USING IMAGES OBTAINED FROM UAVS TO CONSTRUCT A DEM OF RIVERBED TERRITORIES WITH COMPLEX HYDROMORPHOLOGICAL CHARACTERISTICS

The aim of the work is to investigate the accuracy of the DEM of nearshore areas using UAV material. One of the important issues in hydrological flood modelling is the high accuracy of the DEM. In the case of a complex relief type, which is associated with meandering riverbeds, it is proposed to use UAV surveys to create a DEM. Hydrological modelling involves the following main steps: creation of high precision DEMs, determination of Manning coefficients to account for the influence of the underlying surface and determination of water level changes based on the water level graph derived from observations at hydrometeorological stations. This research presents the construction of a high-precision DEM, based on a UAV survey. For high-precision modeling, the fundamental issue is the consideration of vegetation in the nearshore areas and the choice of the optimal time period for the survey. The aim of the study is to develop a methodology for the construction of a high-precision DEM from UAV data, investigate the possibilities of eliminating the influence of vegetation on point marks using software methods, determine planned channel shifts and compare the accuracy of DEM construction for surveys conducted in June 2017 and in November 2021. The section at the transition from the mountainous to marshy-hilly part of the Dniester River near the town of Stary Sambir, with complex morphometric and hydrological characteristics of the channel and banks at the site of the complex meandering of the river in a rugged ravine area was the study object of this work. Results. It was found that for 4 years between two surveys, the planned displacements of some points are up to 25–31 meters. A priori estimation of coordinates determination by points from the GNSS-receiver was carried out, the accuracy of point coordinates determination is 2-3 cm. The a priori estimate of the accuracy of determining the coordinates of points from the input survey data is: for plan coordinates – 4–6 cm for two survey periods, the error in determining the marks of points for different values of the baseline – 21–31 cm. It has been established, that the program methods of accounting of influence of high vegetation do not give the possibility of its full accounting, the average square error, in places of such vegetation makes 0.64 m. Therefore, it is necessary to carry out UAV survey in the leafless period of the year, early spring or late autumn. Scientific novelty consists in the study of the possibility of constructing a high-precision DEM for different types of vegetation from materials obtained from UAVs. The results can be used for hydrological modeling of river channels with complex hydromorphological characteristics.

Key words: DEM accuracy, channel processes, Dniester River, UAV, hydrological modeling.

Introduction

The problem of determining changes in river channels and conducting their monitoring is relevant, as evidenced by a number of state and administrative regulations and recommendations, as well as numerous research papers.

In 1995, the Water Code was approved in Ukraine; in 2001 – Land Code; Cabinet of Ministers resolutions of different types, related to water protection activities, were adopted in 1996 and 2009. In the Land Cadastre, the study of channel processes is associated with the definition of protection zones and in the establishment of regulatory restrictions.

This issue is actual in Europe. Thus, in 2000, the EU Water Framework Directive was accepted, which defines the main principles of water resources management and ways to achieve good water quality and safe condition of rivers and reservoirs. One of the main principles set forth in the EU Water Framework Directive is the integrated water resources management model which implies joint actions of all riparian countries. Directive No. 2007/60/EC of the European Parliament and of the Council on Risk Assessment and Management and the Flood Risk Assessment and Management Action Plan are aimed at reducing the negative effects of flood events on human health, the environment, cultural heritage and economic activity.

The Danube River Flood Protection Expert Group of the International Commission for the Protection of the Danube River is working on the Danube River Flood Protection Plan.

In Poland the ISOK project “Program system of protection of the country from extreme threats” was developed, aimed at creating a system that will improve the protection of the economy, the environment and society from extreme threats, in particular from floods and flooding. The project determines areas where there is a threat to life and property, which will ultimately lead to limiting economic expansion in areas related to the operation of river systems. The end result is an electronic information platform with the necessary registry directories as an important tool for crisis management [ISOK].

Due to insufficient study of the issues of channel processes, in particular due to the lack of data on the morphodynamical characteristics of river channels, geological and hydrological features of rivers, there are cases of destruction of hydraulic engineering facilities, accidents of various structures and communications associated with river crossings, there are material losses due to flooded and waterlogged agricultural land and settlements.

Considering the periodicity of floods in Ukraine and their negative impact on channel systems, it can be argued that continuous monitoring of water bodies and forecasting of flooded areas as a result of floods is important and is necessary to solve applied problems.

Such observations are based on the use of remote sensing and GIS-technologies, which makes it possible to regularly monitor the state of territories, provides a wide overview, repeatability, high efficiency of obtaining and processing information. Besides, the use of ERS data and GIS-technologies opens up new opportunities for obtaining operational forecasts of possible flooding zones, preliminary evaluation of flooding scales, modeling of geographical objects, determination of the most optimal places for location of protective structures, and control of riparian territories.

Today there is a need for a detailed elaboration of methods for organizing monitoring of river channel shifts, the study of the processes of meandering, which is associated with changes in water protection zones, as well as the definition of flooded lands. Modern geoinformation systems, in particular special modules, allow determining flood zones according to certain hydrological models and conducting prediction of such zones, making thematic maps related to flooding and inundation of lands. Studying of channel processes determines measures that allow preventing catastrophic situations and avoiding significant economic losses.

In complex river channel sections and free meandering, which leads to channel shifts, first of all it is necessary to determine all deformations of the river. Permanent changes of channel configuration most often occur with rapidly eroding soils on complex morphometric landforms. To carry out hydrological modeling with determination of flooded land areas, it is necessary to use on such sites a scheme, which consists of two technologically related techniques: determination of horizontal displacements of the river channel and creation of high-precision DEM and on its basis carrying out of hydrological modeling of flooded land areas.

Literature analysis. The creation of a digital elevation model (DEM) of streamside areas is complicated by the action of the hydro morphological process as a determining factor that affects the horizontal displacement of the alluvial river channel within the floodplain. The special literature [Hooke, 2006; Krzemień, 2006] indicates that the hydromorphological direction of the theory of channel processes is based on generalizing channel forms and formations and determining their movement rates in order to develop predictions related to channel processes. It is noticed that the hydromorphological process significantly depends on changes in the general morphometry of the relief and changes in its character when the channel length is considerable.

As noted in [Korpak et al,. 2008], channel processes depend on natural and anthropogenic factors, physical conditions and environment that characterize the watershed landscape. The study of channel processes determines measures that prevent catastrophic damage and avoid significant economic losses. This type of assignment includes assessment of losses due to flooding of channel areas due to surface or flood events.

In accordance with the demands of practice, river channels have become the subject of research in the natural science disciplines of hydrology and geomorphology and technical hydraulics and hydrodynamics, on the basis of which many problems of channel processes have been solved. The study of channel processes is of great importance for solving the problems put forward by numerous requests of practice, they are closely related to the environment, the forms of manifestations of channel processes, channel and floodplain morphology [Burshtynska, et al., 2016]. The authors [Krzemień, 2006; Lawler, 1993] investigate the problems of soil erosion and channel processes. Problems of fluvial and dynamic geomorphology related to the reformation of channels, in particular the conditions of formation of small river channels are presented by the author [Hooke, 2006]. In [Burshtynska et al., 2019] the stability of river channels is investigated, the influence of hydrological regime and geological factors on river stability is analyzed [Bubnyak et al., 1997]; erosion-accumulative processes and their creation of landforms are presented in [Lawler, 1993].

Attention is drawn to natural meandering rivers, which are located in large fertile valleys, in the most valuable areas for agriculture and settlements, which are often subject to demographic and economic pressures [Rudko, & Petryshyn, 2014; Samoilenko, et al., 2009; Krzemień, 2006]. Full-flowing rivers affect human settlements and the environment. This demonstrates the need for systematic flood protection measures and increased control over bank erosion and meander migration. Any sector of the economy must consider the activities of the river. Construction of bridge crossings, water intakes, embankments and other structures cannot do without taking into account channel processes. In addition, these structures change the conditions of the river flow and cause a number of new phenomena in the channelforming activity, which should be provided to ensure the preservation and functioning of the structure itself. An important sphere of application of the theory of channel processes is related to agriculture, since the richest grasslands are located on river floodplains; river activity should be taken into account in the development of land reclamation projects. The development of works on regulation of channels, various construction on the banks and in river channels should be justified by forecasts of channel shifts, based on knowledge of conditions and regularities of formation of river channels. Engineering calculations can be sufficiently justified only if they take into account the direction and intensity of channel processes, their possible changes and specificity of manifestation in different conditions. Economic use of rivers leads to significant changes in their hydrological regime, up to the appearance of qualitatively new channels.

There are known cases where the plowing of floodplains has caused the soil to be washed away and meadows to become unproductive areas. These problems occur not only in Ukraine, but also in many European countries, such as the Netherlands, Italy and France. Some municipalities have decided to plan settlements without coordinating these measures with river channel activity, which has created significant future costs for flood control measures and emphasized the need and importance of taking channel stability into account in the long term, as discussed in the works [OSCE/UNECE project, 2015]. Further development of floodplains leads to even higher flood levels. Therefore, the priority of the new land use policy is to establish maximum protection boundaries, taking into account the future meandering of rivers.

The last decades in Ukraine are marked by a sharp increase in catastrophic floods and the social and economic losses associated with them. Damage is to some extent a consequence of natural phenomena, as well as the imbalance of the territorial natural resource system of the regions [Obodovsky, 1997].

In recent decades, unmanned aerial vehicles (UAVs) have been used to solve various thematic tasks requiring high accuracy in determining the coordinates of points on the earth's surface. The accuracy of determining the coordinates of points and the peculiarities of the UAV survey are devoted to the works [Hlotov et al., 2014; Hlotov et al., 2017].

In [Villanueva et al., 2019; Ruiz et al., 2013], it is noted that the use of UAVs must take into account the significant changes in the photographic heights and tilt angles of the images. Therefore, it is necessary to perform shooting with significant longitudinal and lateral overlap.

Specific features of using UAVs to construct high-precision DEM in urban built-up areas are considered in [Tokarczyk, et al., 2015].

Purpose of work

The purpose of this work is to investigate the accuracy of DEM construction of riverbed territories using UAV materials and satellite images.

Due to insufficient study of river channel processes, in particular due to the lack of data on morphodynamic characteristics of river channels, geological and hydrological features of rivers, there are cases of destruction of hydraulic engineering facilities, accidents of various structures and communications related to river crossings, there are material losses due to flooded and waterlogged agricultural land and settlements.

In the present conditions in Ukraine the issue of additional research of rivers, taking into account the hydrological and morphological analysis and intensity assessment of channel reformation, as well as the modeling of flooded lands to predict and reduce the risks associated with emergencies has risen sharply.

One of the important issues of hydrological modeling of flooding is the highly accurate creation of a DEM. In case of a complex type of relief, which is connected with meandering of the river channel, the influence of vegetation, it was proposed to use UAV imagery for creation of a DEM.

Methodology and results

Hydrological modeling involves the following basic steps: creating a high-precision DEM, determining Manning`s coefficients to account for the influence of the underlying surface, and determining water level changes based on the graph derived from observations at hydrometeorological stations. This study presents the construction of a high-precision DEM based on a UAV survey. For high-precision model building, the fundamental issue is the consideration of vegetation in the coastal areas and the choice of the optimal time period of the survey.

The essence of the study is to develop a methodology for constructing a high-precision DEM based on UAV data, the use of software to eliminate the influence of vegetation on point marks and to compare the accuracy of DEM construction for surveys conducted in June 2017 and in November 2021.

The object of the research was the section at the transition from the mountainous to marshy-hilly part of the Dniester River near the town of Stary Sambor, about 15 km long, with complex morphometric and hydrological characteristics of the channel and banks at the meandering of the river. The area is characterized by a branched system of ravines and gullies. The character of the channel banks at the study site is presented in Fig.1. In this place the river has rather steep banks, the left bank is especially steep with the difference of marks between the bottom and the bank up to 7 meters.

The main causes of channel behavior are climatic, physiographic, and anthropogenic factors, such as frequent flooding, weakly resistant rocks and soils, deforestation, and the removal of gravel and sand materials from river channels.

Fig. 1. General view of the banks of the Dniester River near Stary Sambor: a-left bank, b-right bank

Observation and analysis of long-term studies of the results of losses through floods indicate that the occurrence of floods and other dangerous natural phenomena in Ukraine comes as a result of the interaction of a number of hydrometeorological and morphometric factors. The most important of them are: global climate change, which leads to heavy torrential rains, steepness and magnitude of slopes, shallow depth of bedrock, low water-accumulative capacity of thin soils, ruggedness of the relief.

In addition, economic activity in the Dniester basins in recent decades has significantly increased the influence of these natural factors, which has increased the severity of floods and the scale of the damage caused. The formation of such high floods, which occur in the Carpathian region, in addition to purely morphometric and meteorological factors, is also affected by a number of anthropogenic factors, in particular the damming of river channels, which changes the conditions of water flow and the state of economic activity on the slopes of river valleys. One of the main reasons for the intensification of natural disasters in the Carpathian region is uncontrolled deforestation, particularly during the second half of the 20th and early 20th centuries, when more than 100.000 hectares of forest were destroyed.

Use of remote sensing data and GIS-technologies opens new possibilities for research of channel processes and flood phenomena.

Monitoring of river channel processes and, most importantly, determination of the horizontal and vertical displacements of the river should be carried out after catastrophic floods, since they can change the type of channel and be accompanied by significant erosion and deformation processes of both the river itself and the territory of its basin.

General morphometric characteristics of the Dniester river section are presented in Table 1.

The technological scheme for determining channel displacements and constructing a DEM based on data obtained from the UAV is shown in Fig. 2.

The technological scheme includes: field work, UAV survey, creation of orthophoto to determine the shifts of the river bed and the creation of a DEM to determine the zones of flooded land.

Monitoring of rivers in areas with complex geological structure, morphometric and hydrological characteristics requires surveys with a higher accuracy than can be obtained from space images of medium resolution. Images from drones make it possible to determine detailed horizontal changes in the riverbed.

Table 1

General morphometric characteristics of the Dniester river section

Morphometric characteristics of the investigated section of the Dniester	Dniester
Length, km	14.7
Length of the straight line (between the endpoints of the section), km	7.2
Speed, m/s	3
Elevation drop, m	27
Slope of the river, m/km	1.8
Sinuosity	2

UAV imaging to clarify horizontal displacements of the channel and to build a DEM was carried out in the years: May 2017, November 2021.

Among the main input data for hydrological modeling are: data of DEM representation in the form of cross-sections; data on the bedding of the channel and coastal territory in the form of Manning`s coefficients; data on water level rise due to heavy precipitation for a certain time, obtained from the hydrograph.

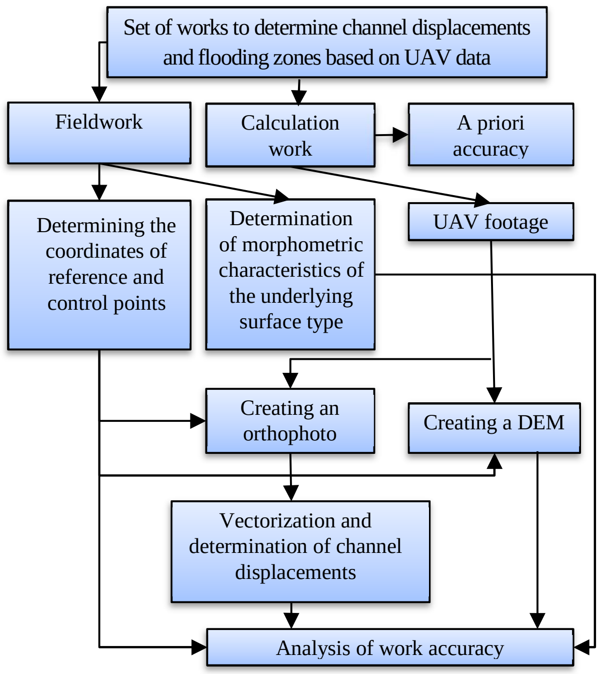

Fig. 2. Technological scheme for determining channel displacement and constructing a DEM using data obtained from UAV

The use of UAVs is effective in carrying out operational forecasting of flooding, including lands of settlements. According to the requirements [Hlotov et al., 2017] for forecasting flood zones for rivers 50–200 m wide, topographic plans are drawn at a scale of 1:2000-1:5000 with the image of the relief by horizontals in 0.5–1 m. For these scales the mean square errors of marks should be within 1/3 of the relief section, that is, the mean square error of determining the marks for predicting flooded areas should be within 0.16–0.30 m. According to the results of research the a priori accuracy of point heights determination on orthophoto using UAVs varies depending on the survey height, digital survey basis, camera focal length, accuracy and density of points for geodetic referencing of orthophoto.

In order to experimentally verify the possibility of applying the technology based on the UAV survey for land flooding forecasting, a study was conducted based on the survey of a 3 km^2 area of the Dniester. To construct the DEM, the photogrammetric method of determining the plan and altitude coordinates of points was used.

In 2017 the aerial surveys were carried out using the Trimble UX5 UAV with a Sony NEX-5R camera, and in 2021 - Abris Dg Arrow with a Sony QX1 camera. Technical characteristics of the UAV, digital cameras and the basic parameters of the survey are presented in Table 2.

Table 2

Trimble UX5 (Sony NEX-5R camera) and Abris dg arrow (Sony QX1 camera) specifications

Features	Trimble UX5	Abris Dg Arrow
Flight speed, (km/h)	70	60–80
Camera sensor	23.5×15.6 mm, 16.1 MP, CMOS	23.9×15.9 mm, 20.1 MP, CMOS
Shooting height, H, (m)	200	250
Sensor size (l_x x l_y), (mm)	23.5×15.6	23.9×15.9
Focal length, f, (mm)	15.3	25
Pixel size, Δ, (mm)	0.005	0.004
Image overlap (%)	80	80
Error of height determination at different values of the base, (m)	0.32/0.21	0.31/0,21
Accuracy of the determination of plan coordinates (cm)	3	2

Estimating the accuracy of point coordinates.

The error of determining the planned coordinates of the terrain points is calculated according to the formula (1) [Lobanov, 1984]:

$$M_x = M_y = \frac{H}{f} \cdot m_x, \qquad (1)$$

where H – height of photographing, f – ocal length of camera, m_x – root mean square error in determining the plan coordinates of points on the image.

Proceeding from the fact that the RMS of coordinate determination is half a pixel [Shavuk, 2009], we obtain that $m_x = \frac{1}{2} \cdot \Delta = 0.002$ mm., where Δ – pixel size.

The accuracy of determining the planned coordinates of the model points is calculated:

$$M_x = M_y = 0.002 \frac{250}{25.0} = 0.02 \text{ m} = 2 \text{ cm}.$$

The error in determining the point marks is determined by the formula (2).

$$h = \frac{H}{b} \cdot \Delta p, \qquad (2)$$

where Δp – difference of longitudinal parallaxes, H – height of photographing.

$$\Delta p = p - p_0, \qquad (3)$$

where p – longitudinal parallax, and obtained by formula (4):

$$p = x_l - x_r, \qquad (4)$$

where x_l – the coordinate of the point in the left image, x_r – the coordinate of the point in the right image.

The RMS of parallax is written by the following equation (5):

$$mp^2 = m_x^2 + m_x^2 = 2m_x^2 = m_x\sqrt{2}, \qquad (5)$$

where m_x – RMS of the definition of plan coordinates.

The RMS of the parallax difference is calculated by formula (6)

$$\begin{cases} m_{\Delta p}^2 = m_p^2 + m_{p_0}^2 = 2m_x + 2m_x^2 = 4m_x^2 \\ m_{\Delta p} = 2m_x \end{cases}. \qquad (6)$$

The basis is calculated according to the formula (7):

$$b = l\frac{100 - p\,\%}{100}. \qquad (7)$$

Substituting the values into formula (7), obtain (8):

$$\begin{cases} b_1 = 15{,}9\dfrac{100 - 80}{100} = 3{,}18 \text{ mm}; \\ b_2 = 23{,}9\dfrac{100 - 80}{100} = 4{,}78 \text{ mm}. \end{cases} \qquad (8)$$

The error of determining the excess at different values of the basis is:

$$\begin{cases} m_{h1} = \dfrac{250}{3{,}18}0{,}004 = 0{,}31 \text{ m}; \\ m_{h2} = \dfrac{250}{4{,}78}0{,}004 = 0{,}21 \text{ m}. \end{cases} \qquad (9)$$

Thus, depending on the survey basis, the a priori accuracy of determining the coordinates of point marks is 0.31–0.21 m, the accuracy of determining the plan coordinates is 2–3 cm.

Taking into account the fact that the surveys are carried out at low altitudes, where there are possible deviations from the calculated survey altitude, as well as deviations of inclination angles, the longitudinal and transverse overlapping of images are chosen so as to avoid photogrammetric discontinuities.

Aerial surveys were performed in May 2017 at an altitude of 200 m, and in November 2021 at an altitude of 250 m. The longitudinal overlap of images is 80 %, the transverse overlap is 80 %. The coordinates of the ground geodetic base were determined using a Trimble R7 dual-frequency GNSS receiver by RTK method using differential corrections from the "Geoterrace" network of active GNSS stations of Lviv Polytechnic National University. The nearest permanent GNSS station SAMB was in Sambor at a distance of 3 km from the object. Accuracy of determination of horizontal coordinates of geodetic base was within 2–3 cm and height component within 5 cm. Preliminary construction of the network phototriangulation was carried out. Processing of survey materials was carried out with binding of centers of images projections to the geodetic base in the program Pix4D.

Fig. 3 and 4 show schemes of survey routes with the centers of projections of digital images and geodetic base points determined by the GNSS method.

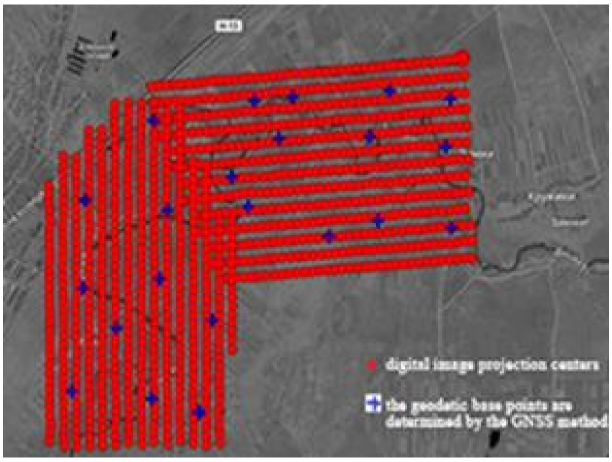

Fig. 3. Scheme of the location of the centers of projections of digital images and points of geodetic base 2017

Fig. 4. Scheme of the location of the centers of projections of digital images and points of geodetic base 2021

Based on the results of digital images processing orthophotomaps of the site and DEM were built (Fig. 5, 6).

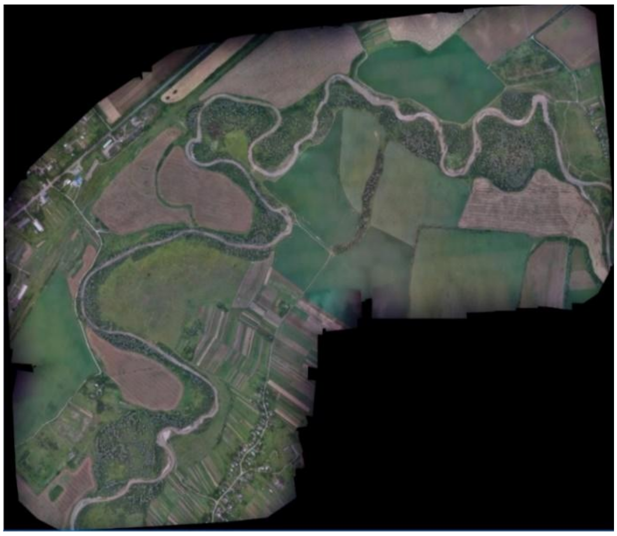

Fig. 5. Orthophotomap of the Dniester River according to Trimble UX5

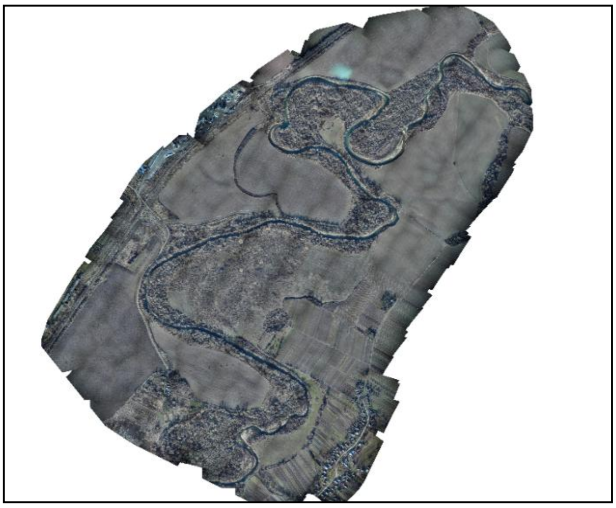

Fig. 6. Orthophotomap of the Dniester River according to Abris dg arrow

To estimate the accuracy, the coordinates measured in the field with a GNSS receiver at sites with different types of underlying surface were used.

Figure 7 shows a DEM built with Pix4D.

In order to determine the accuracy of the DEM of the study area on the ground, the identification of characteristic points was carried out and the planning and elevation coordinates were determined. Fig. 8 shows the location of these points on the ground. Particular attention is paid to the accuracy of determining the heights of the landmarks, since the DEM is used for hydrological modeling of point heights.

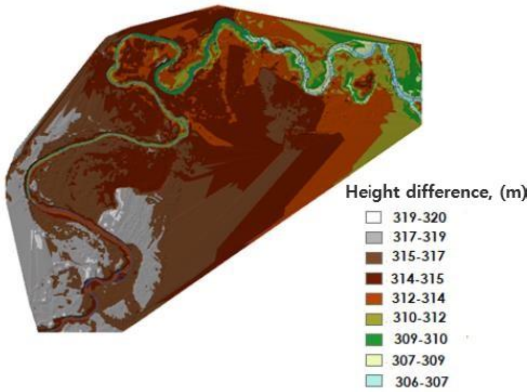

Fig. 7. Digital elevation model of the study area of the Dniester River: 2017

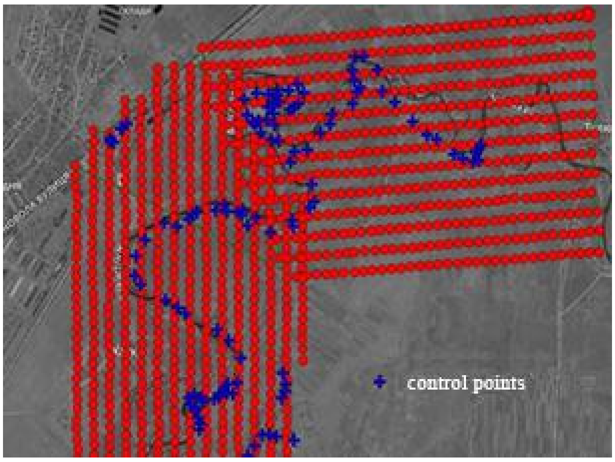

Fig. 8. Location of control points: Survey 2017

The digital terrain model with the purpose of elimination of high vegetation (trees, bushes) was processed with the help of Terra Modeler and Terra Scan modules. However, the model could not be corrected completely due to high grass and dense bush vegetation, the average quadratic error taking into account such vegetation was 0.64 m.

Based on the results of the determined control point elevations and those obtained from the DEM constructed using the Pix4D software, the differences of Δh elevations presented in Table 3 were calculated.

The mean square error in determining the marks from the DEM compared to GNSS data for the entire data sample (44 points) is 0.64 m, and according to the data determined from the sample for the underlying surface of sand and low grass (28 points) is 0.31 m. These results indicate that the real use of UAVs for predicting flooding of territories is not possible to survey during a period with significant foliage cover.

Table 3

The results of determining the marks of the control points by the method of GNS and with DEM, built with the help of Pix4D software

Object of survey	Number of control points	Mean square error *mh* (*m*)
Sand, low grass	28	0.31
Grass, bushes	44	0.64

It should be noted that the mean square errors of determining the altitude component we obtained are approximately two times larger compared to the results, which refer to surfaces without vegetation. Obviously, this is associated mainly with the identification of control points on the ground surface covered with dense and high vegetation.

Since the results of the DEM accuracy study based on the 2017 materials failed to correct the model by software, the same area was resurveyed in November 2021, when the trees and bushes had shed their leaves and tall grass had shriveled or been mowed. The constructed DEM with control points to determine the posterior accuracy estimate is shown in Fig. 9.

The results of the comparison of the GNSS survey reference points and the constructed DEM are shown in Table 4.

The RMS definition of the points is calculated by the expression:

$$m = \sqrt{\sum \Delta h_i^2 / n}. \qquad (10)$$

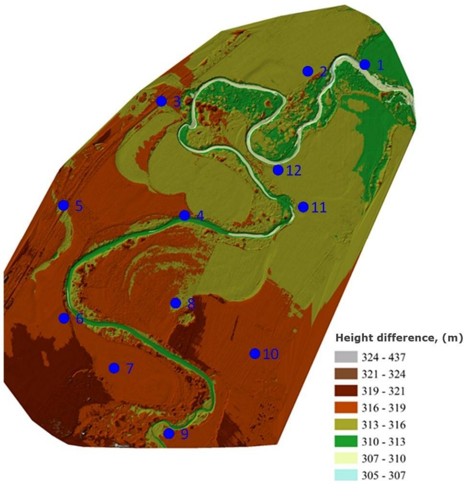

Fig. 9. Digital elevation model with control points for the 2021 survey.

Table 4

Comparison of differences in elevation

Point number	GNSS (m)	2021 (m)	Δh (m)
1	312.891	313.248	-0.357
2	315.251	315.410	-0.160
3	317.862	317.931	-0.069
4	316.699	316.903	-0.204
5	319.060	318.546	0.514
6	318.329	318.785	-0.457
7	316.352	316.364	-0.012
8	315.894	315.809	0.084
9	317.801	317.937	-0.136
10	317.157	316.857	0.300
11	314.202	314.160	0.042
12	314.609	314.736	-0.127

The root mean square error of point elevations, calculated based on a comparison of the corresponding elevations of control points obtained from GNSS observations and data from measurements of the constructed DEM, is 0.26 m.

Scientific novelty and practical significance

Scientific novelty lies in the study of the possibilities of constructing a high-precision DEM for different types of vegetation using materials obtained from UAVs. The results can be used for hydrological modeling of river channels with complex hydromorphological characteristics.

According to the results of the calculations, it was found that the accuracy of the DEM construction corresponds to the a priori accuracy estimate. Therefore, when surveying the land surface with high herbaceous and bush vegetation, it is necessary to survey in early spring or autumn when there is leafless cover and no herbaceous vegetation.

Conclusions

The conducted research leads to the conclusion about the expediency of UAV aerial survey of riverine areas with complex morphometric and hydrological characteristics.

Evaluation of the accuracy of the constructed digital elevation model by the results of the survey in May 2017 in the presence of high grass and shrub vegetation was carried out on 44 control points is: SCP = 0.44 m.

This indicates that the model development using Terra Modeler and Terra Scan modules does not give satisfactory results to improve the accuracy of the DEM suitable for further hydrological modeling.

Aerial survey of the same area in the leafless period in November 2021 with the subsequent evaluation of the accuracy of 12 control points, the SCP = 0.26 m, indicates that the accuracy of determining the marks in 2.5 times higher than for the survey in the late spring. This allows us to state that the period of survey is fundamental for obtaining a highly accurate DEM for the purpose of further hydrological modeling, so aerial surveys should be performed in early spring or late fall when there is no leaf cover and reduced influence of herbaceous vegetation.

REFERENCES

Bubnyak, I., & Bubniak, A. (1997). On the nature of the Stryi Jurassic depression. *Researches NTSh* T 1. Geology, geophysics, chemistry, biochemistry, materials science, mechanics of materials. pp. 69–72. (in Ukrainian).

Burshtynska, Kh., Shevchuk, V., Tretyak, S., Vekliuk, Vekliuk. (2016). Monitoring of the riverbeds of rivers Dniester and Tisza of the Carpathian region. XXIII ISPRS Congress, Commission VII (Vol. XLIB7) 12–19 July 2016, Prague, Czech Republic. p. 177–182, https://doi.org/10.5194/isprs-archives-XLI-B7-177–2016. (in Ukrainian).

Burshtynska, K. V., Babushka, A. V., Bubniak, I. M., Babiy, L. V., & Tretyak, S. K. (2019). Influence of geological structures on the nature of riverbed displacements for the rivers of the Dnister basin upper part. *Geodynamics*, (2 (27)), 24–38. https: //ena.lpnu.ua/handle/ntb/ 52220.

Hlotov, V., Hunina, A., & Siejka, Z. (2017). Accuracy investigation of creating orthophotomaps based on images obtained by applying Trimble-UX5 UAV. *Reports on Geodesy and Geoinformatics*, *103*, 106–118.

Hlotov V., Tserklevych, A., Zbrutskyi, O., Kolisnichenko,V., P rokhorchuk, O., Karnaushenko, R., Haletskyi, V., Zbrutskyi, O., Kolisnichenko, V., Prokhorchuk, O., Karnaushenko, R., & Haletskyi, V. (2014). Analysis and prospects of aerial photography from unmanned aerial vehicles. *Modern achievements of geodetic science and production*, I (27), 131–137. https://vlp.com.ua/node/12295. (in Ukrainian)

Hooke, J. (2006). Hydromorphological adjustment in meandering river systems and the role of flood events. Sediment Dynamics and the Hydromorphology of Fluvial Systems. (Proceedings of a symposium held in Dundee, UK, July 2006). 306. 127–135.

ISOK (Informatyczny System Osłony Kraju przed nadzwyczajnymi zagrożeniami). http://www.gugik.gov.pl/projekty/isok.

Korpak, J., Krzemien, K., & Radecki-Pawlik, A. (2008). Wpływ czynników antropogenicznych na zmiany koryt cieków karpackich. *Infrastruktura i ekologia terenów wiejskich*, (04). 1-88. file:///C:/Users/%D0%93%D0%B0%D0%BB%D0%B8%D0%BD%D0%B0/Downloads/Wp%C5%82yw_czynnik%C3%B3w_antropogenicznych_n.pdf.

Krzemien, K. (2006). Badania struktury i dynamiki koryt rzek karpackich. *Infrastruktura i ekologia terenów wiejskich*, (4/1). 131–142. file:///C:/Users/%D0%93%D0%B0%D0%BB%D0%B8%D0%BD%D0%B0/Downloads/Krzemien.pdf.

Lawler, D. M. (1993). The measurement of river bank erosion and lateral channel change: a review. *Earth surface processes and landforms*, *18*(9), 777–821. https://doi.org/10.1002/esp.3290180905.

Lobanov, A. N. Phogrammetry. Moskov: Nedra, 1984. p. 552. (in Russian).

Obodovskyi, O. H. (1997). Estimation of stability of riverbeds of the Middle and Lower Dnieper. *Land* *reclamation and water management*, 84, 131–137. (in Ukrainian).

Pix4D. Hands Free Solutions for Mapping and 3D Modeling, 2013. Access mode: http://pix4d.com/.

Project OSCE/UNECE: Transboundary cooperation and sustainable management of the Dniester river basin (November 2015. https://www.osce.org/files/f/documents/d/6/104060.pdf.

Rudko, H. I. & Petryshyn, V. Iu. (2014). Characteristics of boulder-gravel-sand deposits in Lviv region and their impact on the ecological state of the environment. *Mineral resources of Ukraine*, 1, 39–47. (in Ukrainian).

Ruiz, J. J., Diaz-Mas, L., Perez, F., & Viguria, A. (2013). Evaluating the accuracy of DEM generation algorithms from UAV imagery. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci*, *40*, 333–337. https://doi.org/10.5194/isprsarchives-XL-5-529-2014.

Samoilenko, L. I., Kolos, L. M., Pidhorodetska, L. V., (2009). Information technology of flood monitoring using remote sensing data. *Space science and technology*, 15(3), 50–55. (in Ukrainian).

Shavuk, V. S. (2009). Theoretical substantiation of a digital photogrammetric system for processing high-resolution satellite images: abstract of dissertation., 25.00.34 “Aerospace research of the Earth, photogrammetry”. M., p. 24. (in Russian).

Tokarczyk, P., Leitao, J. P., Rieckermann, J., Schindler, K., & Blumensaat, F. (2015). High-quality observation of surface imperviousness for urban runoff modelling using UAV imagery. *Hydrology and Earth System Sciences*, *19*(10), 4215–4228., https://doi.org/10.5194/hess-19-4215-2015, 2015.

Villanueva, J. K. S., & Blanco, A. C. (2019). Optimization of ground control point (GCP) configuration for unmanned aerial vehicle (UAV) survey using structure from motion (SFM). *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, 167–174. https://www.researchgate.net/publication/331410976.

Христина БУРШТИНСЬКА[1], Анджей МАЗУР[2], Максим ГАЛОЧКІН[3], Євген ШИЛО[4], Ірина ЗАЯЦЬ[5]

[1] Кафедра фотограмметрії та геоінформатики, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, тел. +38(067)2561130, ел. пошта: khrystyna.i.burshtynska@lpnu.ua, http://orcid.org/0000-0002-6013-0873

[2] Кафедра інженерії навколишнього середовища та геодезії, Університет природничих наук, вул. Лещинського, 7, Люблін, Польща, тел: (+48)815248128, ел. пошта: andrzej.mazur@up.lublin.pl

[3] Кафедра фотограмметрії та геоінформатики, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, тел. +38(095)8284467, ел. пошта: maksym.k.halochkin@lpnu.ua, http://orcid.org/0000-0002-2778-3602

[4] Кафедра інженерної геодезії, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, тел. +38(067)1631917, ел. пошта: yevhenii.o.shylo@lpnu.ua, http://orcid.org/0000-0002-3838-5431

[5] Кафедра фотограмметрії та геоінформатики, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна, тел. +38(097)2470009, ел. пошта: iryna.v.dolynska@lpnu.ua

ВИКОРИСТАННЯ ЗОБРАЖЕНЬ, ОТРИМАНИХ З БПЛА, ДЛЯ ПОБУДОВИ ЦМР ПРИРУСЛОВИХ ТЕРИТОРІЙ ЗІ СКЛАДНИМИ ГІДРОМОРФОЛОГІЧНИМИ ХАРАКТЕРИСТИКАМИ

Метою роботи є дослідження точності побудови ЦМР прируслових територій із використанням матеріалів БПЛА. Одним із важливих питань гідрологічного моделювання затоплень є високоточне створення ЦМР. За складного типу рельєфу, який пов’язаний із меандруванням русла річки, запропоновано для створення ЦМР використовувати знімання з БПЛА. Гідрологічне моделювання передбачає такі основні етапи: створення високоточних ЦМР, визначення коефіцієнтів Маннінга з метою врахування впливу підстильної поверхні та визначення змін рівня води на підставі графу, отриманого із спостережень на гідрометеорологічних пунктах. В цьому дослідженні подано побудову високоточної ЦМР на підставі знімання з БПЛА. Для високоточної побудови моделі принциповим питанням є врахування рослинності в прибергових ділянках і вибір оптимального часового періоду знімання. Завдання дослідження полягає в опрацюванні методики побудови високоточної ЦМР за матеріалами, отриманими з БПЛА, дослідження можливостей усунення впливу рослинності на позначки точок з використанням програмних методів, визначенні планових зміщень русла та порівнянні точності побудови ЦМР за зніманнями, проведеними у червні 2017 року та у листопаді 2021 року. Об'єктом досліджень слугувала ділянка при переході від гірської до болотисто-горбистої частини річки Дністер поблизу міста Старий Самбір, із складними морфометричними та гідрологічними характеристиками русла та берегів в місці складного меандрування річки в перетятій ярами місцевості. Результати: встановлено, що за 4 роки між двома зніманнями планові зміщення деяких точок становлять до 25–31 метрів. Здійснено апріорну оцінку визначення координат за точками з ГНСС-приймача, точність визначення координат точок якого становить 2–3 см. Апріорна оцінка точності визначення координат точок за вхідними даними знімання становить: для планових координат – 4–6 см для двох періодів знімання, похибка визначення позначок точок для різних значень базису – 21–31 см. Встановлено, що програмні методи врахування впливу високої рослинності не дають можливості повного її врахування, середня квадратична помилка, у місцях такої рослинності становить 0,64 м. Тому, знімання з БПЛА необхідно проводити в безлистяний період року, ранньою весною або пізно восени. Наукова новизна полягає у дослідженні можливостей побудови високоточної ЦМР для різного типу рослинності за матеріалами, отриманими з БПЛА. Результати можуть бути використані для гідрологічного моделювання русел рік із складними гідроморфологічними характеристиками.

Ключові слова: точність ЦМР, руслові процеси, річка Дністер, БПЛА, гідрологічне моделювання.

Received 12.03.2022