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Identification of areas with potential significant flood risk using specialized software in the Vistula river basin within Ukraine

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In the period of climate change, the frequency of extreme hydrological phenomena increases, therefore, an extremely important problem in the hydrological study of the territory is the determination of areas with potentially significant risks of flooding, as well as the construction of maps of threats and risks of flooding. The basin of the Vistula river within Ukraine, located in the west of Ukraine, is in a zone of sufficient moisture and suffers from floods almost every year. A significant problem of the hydrological study of this basin is the identification of areas with potential significant flood risks, as well as the creation of flood hazard and risk maps. The paper presents the methodological principles and algorithm for using the HEC-RAS software in modeling the flooded territory with the corresponding calculated characteristics of the maximum runoff. The resulting maps of areas with potential significant flood risk (APSFR) in the area of Busk are also presented.

KEY WORDS: Vistula, flood, maximum runoff, HEC-RAS

Introduction

Floods on the Vistula river are a complex phenomenon, caused by several generating mechanisms, with a relative frequency of occurrence specific to the different parts of the basin (Cyberski et. al., 2006), particularly, for Upper Vistula is possible as spring such as rain floods. Flood zoning is one of the three components of Integrated Flood Management (IFRM). A detailed analysis of flood risk and flood damage assessment studies is available (Šugareková and Zeleňáková, 2021). In particular, it is shown, the IFRM method (Wang et. al., 2021) includes the identification, assessment, and management of flood risk with a focus on 3 objectives. First, it's the identification of significant areas with high flood risk. The second one is an assessment of economic damage caused by floods, and the third – is the use of flood risk management to select the best design measures to improve the capacity of the drainage system.
In Ukraine also, at the governmental level, the need to develop maps of flood threats and risks and flood risk management plans (Resolution of the Cabinet of Ministers of Ukraine, 2018). In 2022 was presented the first part of the Vistula river basin management plan (RBMP) was, which will help implement integrated water resources management on a basin basis. The plan was developed by a team of the Ministry of Natural Resources, the State Water Agency, and the Blue Rivers Environmental Consulting project together with experts, including specialists from the Basin Administration for Water Resources of the Western Bug and San rivers. Now presented is only the first part of the management plan for the Vistula river basin. The document contains information about: the characteristics of surface and ground waters; anthropogenic impact on surface and groundwater and their condition; areas to be protected; results of studies of surface and ground waters and their mapping; economic analysis of water use; measures to reduce water pollution.
Thus, the development of cartographic information about the flooding of the territory will play an important role in the further development of the RBMP, which also includes an assessment of areas of possible flooding during the passage of floods. The development of flood hazard and risk maps is carried out by hydrodynamic modeling. Based on the results of such modeling, it is possible to determine the inundation zones, water levels, and depths in the study area. Such maps make it possible to determine the potential damage from flooding in the future.

Material and methods

The Vistula river is the largest river flowing into the Baltic Sea. The Vistula river originates in the Western Beskids in Poland from the confluence of the Black and White Vistula rivers and flows into the Gulf of Gdańsk (Fig. 1). The basin of the Vistula river in Ukraine is located within the borders of the Lviv and Volyn regions; watersheds run along ridges and hills, so they are clearly defined. The area of the Vistula river basin within Ukraine is 12,892 km^2, which is 2.13% of the country's territory and has 3,112 rivers, the total length of which is 7,356 km. According to the modern hydrographic zoning of the territory of Ukraine, the basin of the Vistula river is represented in a separate district. Its characteristic feature is the only region of the river basin in Ukraine, the flow of which is directed to the Baltic Sea.

The area of the Vistula river basin is divided into two sub-basins: the Western Bug and San rivers. A part of the Poltva river basin, a tributary of the Western Bug river, was chosen for modeling the flooding zone (Fig. 2). The studied area was limited to the water gauging stations (WGS) of the Poltva river – WGS Busk and the Western Bug river – WGS Kamyanka Buzka. This area was chosen as characteristic of the areas with potential significant flood risk (APSFR), and according to the WRBM of the Western Bug and San, it regularly

Fig. 1. The Vistula river location in territory of Ukraine.

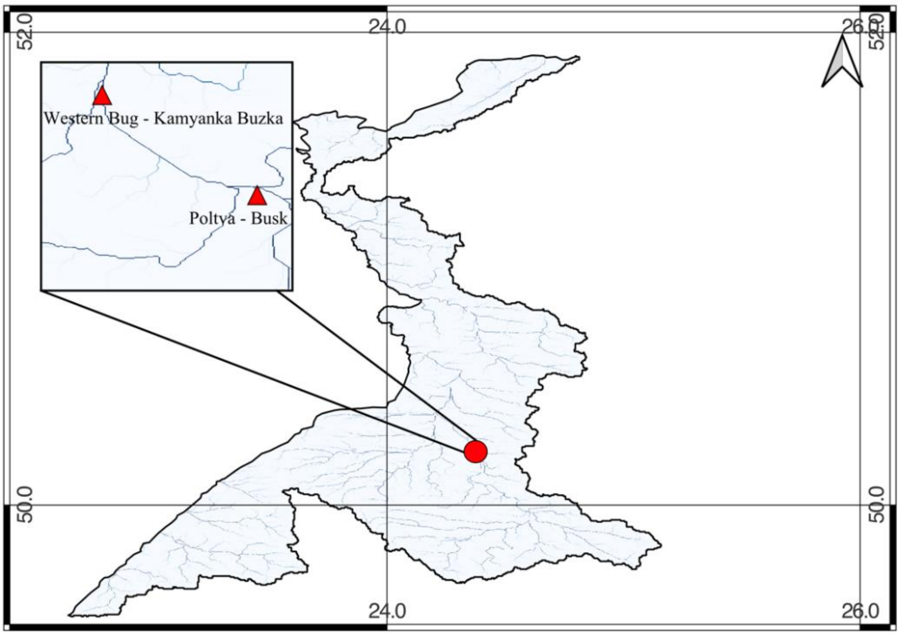

Fig. 2. The study area within Vistula river basin.

suffers from floods both during spring and rain floods.
For the construction, the calculated output data on the maximum runoff during the spring flood period, calculated hydrographs, transverse profiles, and the constructed digital elevation model of the terrain were used.
In this particular case, the water gauging stations located at Busk, which is located upstream, were taken as the upper reach for further calculations; therefore, the characteristics of the maximum runoff explicitly calculated for this WGS were used.
Calculations of the maximum water runoff with a rare probability of exceeding were performed under current regulatory documents (Manual, 1984).
Data on water flows, runoff layers, and runoff modules of the rare probability of exceedance were used, the calculation of which is given in the works (Martyniuk and Ovcharuk, 2020a; 2020b).
The estimated hydrograph is built based on data on the maximum discharges corresponding to the estimated probability of exceeding, in our case – 1%. Estimated hydrographs for spring floods are built based on the average daily water discharge, so it is necessary to switch from the calculated maximum runoff $Q_{1\%}$ to the average daily $Q_{1\%daily}$ using the transition coefficient K_τ according to the formula:

$$Q_{1\%daily} = Q_{1\%} K_\tau \qquad (1)$$

Transition coefficient K_τ is determined depending on the studied territory's natural zone, and for the Poltva river basin, $K_\tau = 1.2$ (Manual, 1984).
The form of calculated hydrographs depends on many factors, such as the morphometric characteristics of the basin and the distribution of water discharge time. However, the typical form of the hydrograph is accepted in hydrological calculations.
The hydrograph asymmetry coefficient K_s and the corresponding hydrograph shape factor λ are determined approximately, depending on the catchment area. Determination of the scheme of hydrographs, both for spring and rain floods, according to the equation proposed by Alekseev (1955):

$$Y = 10^{\frac{\alpha(1-x)^2}{x}} \qquad (2)$$

where
x – is the relative abscissa of the calculated hydrograph, expressed in fractions of the flood duration;
Y – is the relative ordinate of the calculated hydrograph, expressed as a fraction of the average daily maximum water discharge of a particular supply.

The absolute abscissas of the calculated hydrograph are determined by the formula:

$$\mathrm{t_i} = \mathrm{X_i} \mathrm{t}_r \qquad (3)$$

where
t_r – the duration of the rise of spring floods or rain floods is defined as:

$$\mathrm{t_r} = \frac{0.0116 \cdot \lambda \cdot \mathrm{Y}_{1\%}}{\mathrm{q}_{1\%}} \qquad (4)$$

where
$Y_{1\%}$ – is the calculated runoff layer of the flood (spring or rain) with a rare probability of exceeding [mm];
$q_{1\%}$ – module of the maximum runoff of flood (spring or rain) [m^3 skm^{-2}];
λ – hydrograph shape factor.

The absolute ordinates of the calculated hydrograph are calculated as follows:

$$\mathrm{Q_t} = \mathrm{Y_i} \mathrm{Q}_{1\%\mathrm{daily}} \qquad (5)$$

The calculated hydrograph of spring flood on the Poltva river – WGS Busk is shown in Fig. 3.
Transverse profiles of the upper reach (Poltva river – WGS Busk) and the lower reach (Western Bug river – WGS Kamyanka Buzka) were used in the modeling, which is given in special reference publications. Intermediate cross-sections were obtained by interpolating DEM and cross-sections of the upper and lower reaches using HEC-RAS software.

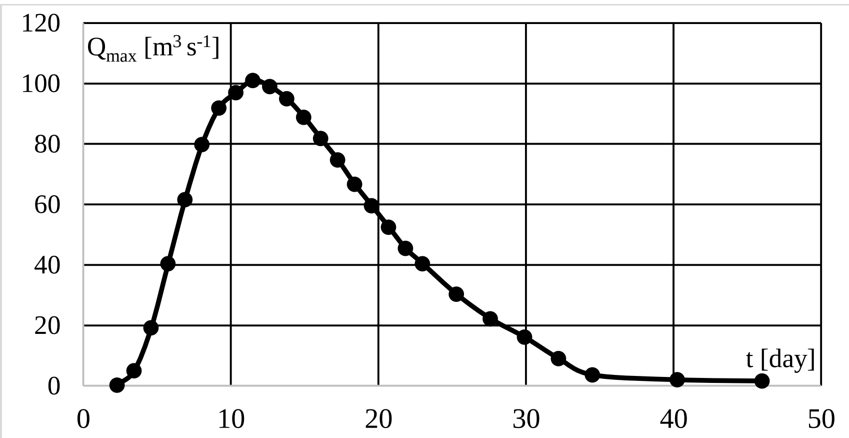

Fig. 3. Estimated hydrograph of the spring flood of the Poltva river – WGS Busk.

Results and discussion

A Digital Terrain Model (DEM) with sufficient accuracy for preliminary modeling of flood zones for large areas can be built from SRTM data. However, analysis of SRTM data accuracy indicates significant errors, up to 2.9 m for a flat area, as considered in (Karwel and Ewiak, 2008) and (Bildirici et al., 2007). The ability to use SRTM images of various resolutions to build a DEM is described by (Nagaveni, 2019). For an accurate study of APSFR, it is necessary to use refined DEMs obtained from LiDAR survey data and survey work directly in field studies. In subsequent calculations, in the absence of field observations and surveys, only SRTM data obtained from the USGS Earth Explorer resource and processed using Quantum GIS were used. The resulting map is shown in Fig. 4.

The HEC-RAS 6.2 software was used to create the flood model. HEC-RAS is a software developed by the US Army Corps of Engineers. The software allows the user to perform 1D steady flow calculations, 1D and 2D transient flow calculations, and other hydrological and hydraulic simulations.

HEC-RAS is also used for dam failure and land flooding simulations. The use of the application and its correctness in different conditions and on different rivers is confirmed by (Farooq et al., 2019; Parhi, 2018; Sathya and Thampi, 2021; Marko et al., 2019).

The first stage of work is creating a new project and working with the integrated GIS RAS Mapper. Importing a pre-prepared DEM and creating a one-dimensional (1D) flow model is necessary. For this purpose, the middle line of the river and coastlines are marked manually and using satellite images.

Next, the flow center lines (Flow Paths) are defined. They are used to calculate the length of sections between cross- sections and are plotted along the downstream coastline. The lines do not reflect and may not coincide with areas of possible flooding but are only an initial geospatial estimate of the relationship of the center of mass of the flow from one cross-section to another.

Cross sections of the river are also being built. They should be placed perpendicular to the flow, often enough for adequate modeling, covering an area considered potentially floodable from upstream to downstream. That is, such cross-sections reflect changes in the relief of the entire floodplain, and in the area of the channel bounded by the banks, they are automatically marked as cross-sections of the stream (Starodub and Havrys, 2015) (Fig. 5).

An example of the built cross section of the upper reach is shown in Fig. 6.

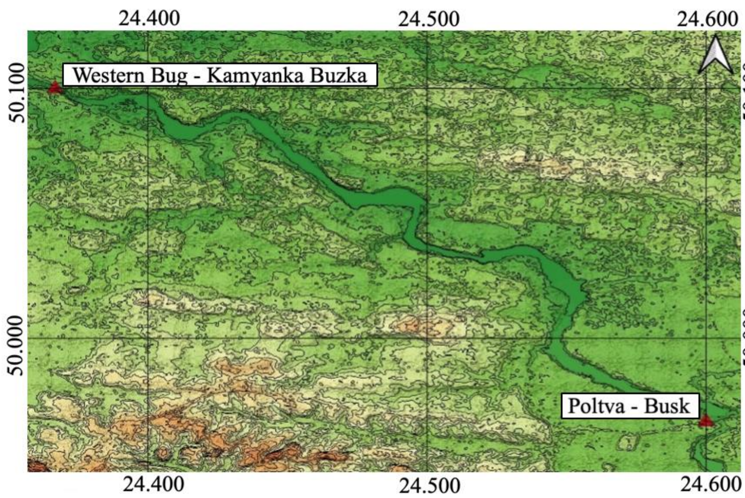

Fig. 4. DEM of the studied territory.

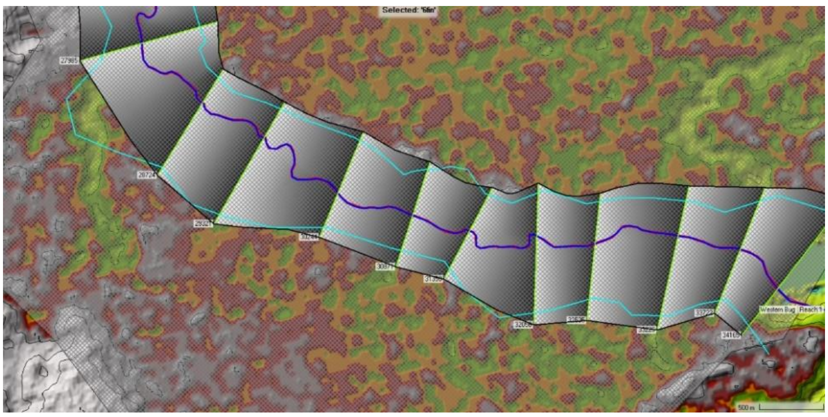

Fig. 5. One-dimensional flow model (HEC-RAS) Poltva river – WGS Busk

The next step is to build a two-dimensional (2D) flow model. At this stage, the territory for further analysis is determined by the polygonal layer, that is, in our case, the territory of the river's floodplain at the highest points of the terrain. In the constructed layer, it is necessary to specify the distance between the calculation points, which are the centers of the calculation cells. Choosing the smallest possible size is more expedient for greater calculation accuracy. For the study area, the distance between the plotted points is 5 m, respectively the number of calculated cells is about 500,000. It is also necessary to indicate the Manning roughness coefficients for individual sections, depending on the description of the watercourse and floodplain.

For the studied area, the Manning coefficients of the flow ranged from 0.06 for the channel to 0.10 for the floodplain. After entering all the necessary characteristics, the formation of the table of hydraulic characteristics of the calculation cells is started. Also, at this stage, the lines of limiting flow parameters are plotted on the map (Fig. 7)

To simulate flooding, enter the abscissa and ordinate values of the hydrograph and the river's slope in the "Unsteady flow data" tab.

After entering the input information, it is necessary to configure the parameters of the Unsteady Flow Analysis, namely, the calculation interval and the mapping interval. The calculation interval was chosen to be 1s, which corresponds to greater accuracy but is also more resource-intensive. The mapping interval has been adjusted to reflect the maximum runoff rate.

After processing the input information and checking for errors, a raster layer is created, showing the depth of flooding of the territory. For better display and the possibility of further processing, the flooding layer was imported into Quantum GIS (Fig. 8).

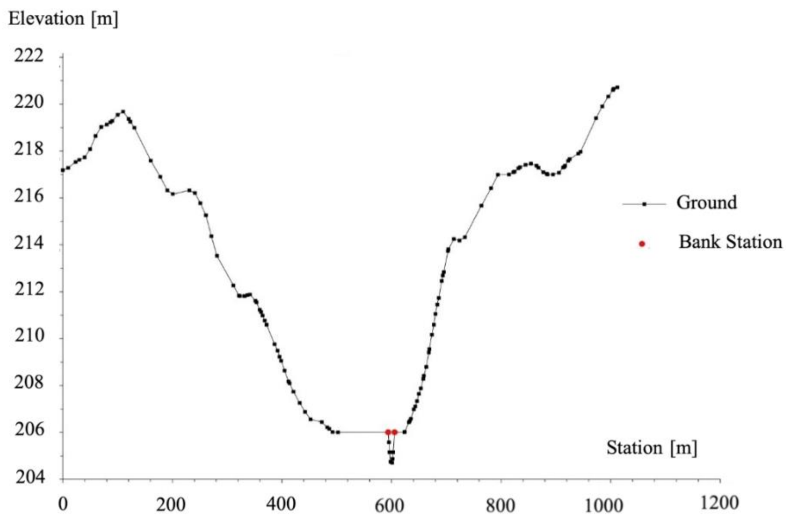

Fig. 6. Cross section of the Poltva river – WGS Busk.

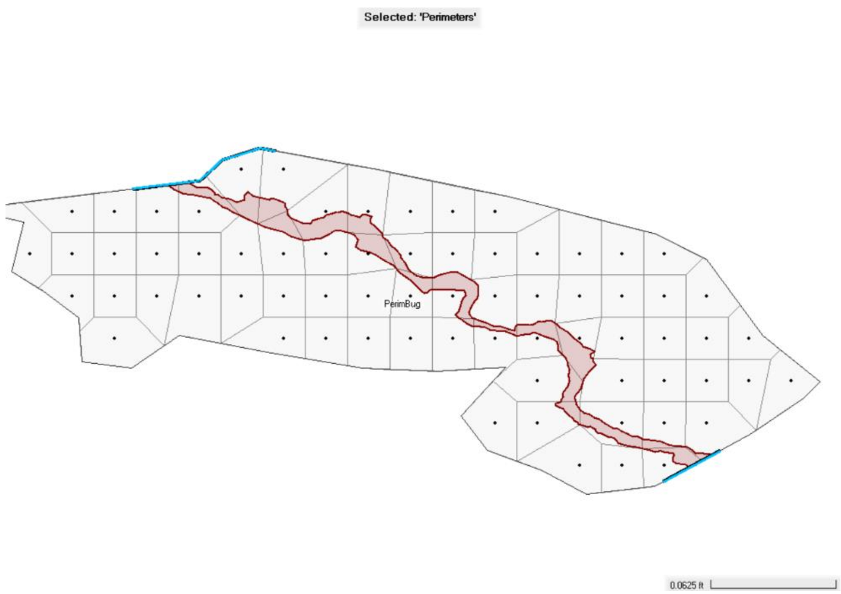

Fig. 7. Two-dimensional flow model (HEC-RAS) Poltva River – WGS Busk.

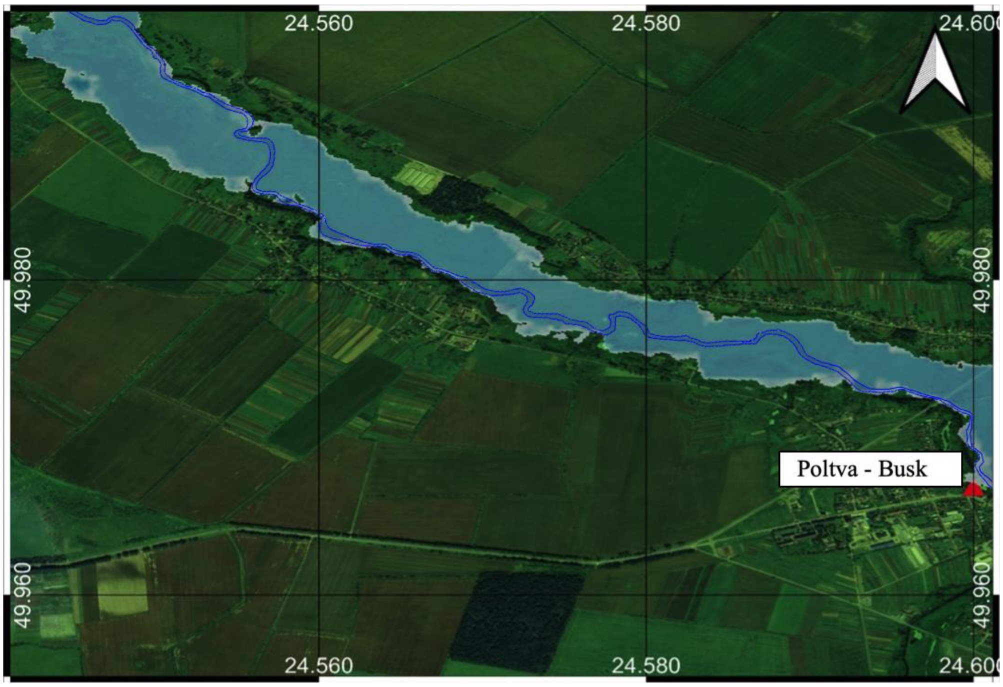

Fig. 8. Flood Hazard and Risk Map of Poltva river – WGS Busk.

Thus, flood zones were modeled in the study area. To further assess the threat of flooding and determine the possible damage, it is necessary to use cartographic data containing the coordinates and exact dimensions, including heights, of all infrastructure facilities (roads, bridges, power lines, dams), as well as agricultural land. To reduce the consequences of natural disasters, it is necessary to identify in advance many characteristics that affect the level of damage and determine the most effective and adequate measures to reduce it.

Conclusion

- Floods in the Vistula river basin are a dangerous hydrological phenomenon in all its sections, including the upper Vistula in Ukraine.
- Development and adaptation of modern methods for determining flood zones are part of the Integrated Flood Management and Vistula river basin management plans.
- As a result of the study, a method for determining inundation zones during spring floods using the example of the Poltva river within Vistula basin was justified.
- This methodology gives good results for a preliminary assessment of APSFR and can be used throughout the Vistula river basin within Ukraine. The constructed map allows identifying areas with potentially significant risks of flooding.
- In the future, such areas need to be carefully studied and the flood zones refined, taking into account field research data, particularly more accurate DEMs obtained from LiDAR images and actual sections of the stream.

References

Alekseev, H. (1955): Calculations of the flood runoff of rivers in the USSR. Leningrad: Gidrometeoizdat. 200 p. (in Russian).

Bildirici, I. O, Ustun, A., Ulugtekin, N., Selvi, H. Z., Abbak, R. A., Bugdayci, I., Dogru, A. O. (2007): SRTM Data In Turkey: Void Filling Strategy And Accuracy Assessment. In: The 4th Middle East Spatial Technology (MEST) Conference & Exhibition, 10–12 December, Bahrain.

Cyberski, J., Grześ, M., Gutry-Korycka, M., Nachlik, E., W. Kundzewicz, Z. W. (2006): History of floods on the River Vistula, Hydrological Sciences Journal, 51:5, 799–817, DOI: 10.1623/hysj.51.5.799

Farooq, M., Shafique, M., Khattak, M. S. (2019): Correction to Flood hazard assessment and mapping of River Swat using HEC-RAS 2D model and high-resolution 12-m TanDEM-X DEM (WorldDEM). Nat Hazards 97, 493. https://doi.org/10.1007/s11069-019-03644-x

Karwel, A. K., Ewiak. I. (2008): Estimation of the accuracy of the SRTM terrain model on the area of Poland, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII. Part B7. Beijing 2008, pp. 169–172.

Manual to Determining the Calculated Hydrological Characteristics (1984): edited by A. Rozhdestvensky and A. Lobanova. Leningrad: Gidrometeoizdat. 447 p. (in Russian).

Marko, K., Elfeki, A., Alamri, N., Chaabani, A. (2019): Two Dimensional Flood Inundation Modelling in Urban Areas Using WMS, HEC-RAS and GIS (Case Study in Jeddah City, Saudi Arabia). In: El-Askary, H., Lee, S., Heggy, E., Pradhan, B. (eds) Advances in Remote Sensing and Geo Informatics Applications. CAJG 2018. Advances in Science, Technology & Innovation. Springer, Cham. https://doi.org/10.1007/978-3-030-01440-7_62

Martyniuk, M., Ovcharuk, V. (2020a): Determining the characteristics of the maximum runoff of the rare probability of exceeding the Vistula River basin within Ukraine. Ecology, neo-ecology, environmental protection and sustainable use of nature: proceedings VIII international. Science. Conf. young scientists (Kharkiv, Ukraine, 229–231). (In Ukrainian).

Martyniuk, M., Ovcharuk, V. (2020b): Study the influence of zonal and azonal factors on the maximum flood runoff in the Vistula basin (within Ukraine). International Baltic Earth Secretariat Publication, 18, 209.

Nagaveni, C., Kumar, K. P., Ravibabu, M. V. (2019): Evaluation of TanDEMx and SRTM DEM on watershed simulated runoff estimation. J Earth Syst Sci 128, 2 (2019). https://doi.org/10.1007/s12040-018-1035-z

Parhi, P. K. (2018): Flood Management in Mahanadi Basin using HEC-RAS and Gumbel's Extreme Value Distribution. J. Inst. Eng. India Ser. A 99, 751–755. https://doi.org/10.1007/s40030-018-0317-4

Resolution of the Cabinet of Ministers of Ukraine on April 4, 2018 No. 247 On approval of the Procedure for developing a flood risk management plan / Official Gazette of Ukraine on April 24, 2018 – 2018, No. 32, p. 29, article 1116, act code 89821/2018

Sathya, A., Thampi, S. G. (2021): Flood InundationMappingof Cauvery River Using HEC-RASandGIS. In: Singh, R. M., Sudheer, K. P., Kurian, B. (eds) Advances in Civil Engineering. Lecture Notes in Civil Engineering, vol 83. Springer, Singapore. https://doi.org/10.1007/978-981-15-5644-9_2

Starodub, Y. P., Havrys, A. P. (2015): Use of HEC-GEORAS and HEC-RAS assistant software in territorial security projects. Project management and development of production, 1(53), 30–35. Luhansk. [In Ukrainian].

Šugareková, M., Zeleňáková, M. (2021): Flood risk assessment and flood damage evaluation–The review of the case studies, Acta Hydrologica Slovaca, vol. 22, no. 1, 156–163 DOI: https://doi.org/10.31577/ahs-2021-0022.01.0019

Wang, H., Zhou, J., Tang, Y., Liu, Z., Kang, A., Chen, B. (2021): Flood economic assessment of structural measure based on integrated flood risk management: A case study in Beijing. Journal of Environmental Management, 280, 111701

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