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Application of Methodology for Defining the Adjoining Lands and Flooding River Strips in Bulgaria in a GIS Environment Upon Bridge Facility Designing

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Abstract: The "Methodology for defining the adjoining lands and flooding rivers stripes in Bulgaria" (MALFARS) has been developed in 2012 based on the requirements of the EU Water Framework Directive 2000/60. In this article we investigated another aspect of MALFARS application. We have reviewed the possibilities for methodology application upon designing of bridge facilities within the researched river section. The study presents the application of the Methodology for the designing of a bridge facility over the Dzherman River upon the maximum dimensional water quantities calculated for the studied section of the river. We have used GIS instruments to analyze and evaluate the results obtained for the parameters of the maximum runoff and the conductivity of the river section. The results present the defined flooding zones of the adjoining river areas/stripes, good conductivity of the road facility, hydraulic and geometric characteristics of the runoff in the investigated river section in cases of high water levels

Keywords: Floodable strips, Bridge equipment, Maximum streamflow, Dzherman river

Introduction

Determining the area of floodable riparian strips is a subject of research in engineering hydrology in the hydro technical design of bridge facilities, dikes, etc. Particularly prone to failure during high river levels are the riverine bridges and that is why it is important to determine the maximum streamflow of the river that crosses a given bridge (Vigil & Booker, 2023). The floods change river morphology (hydraulic and geometrical parameters of the riverbed), river depths, flow velocity, and load transport, negatively affecting the bridges as structurally and functionally impaired. (Sasidharan et al., 2023; Sasidharan et al., 2022). A lot of techniques can be applied like HEC-RAS (Popescu&Bărbulescu, 2023; Ghimire et al., 2022), FLO 2D, TELEMAC 2D, MIKE, etc. (Anees et al., 2016). Several studies analyze flood impact on bridges by flood-frequency analysis and hydraulic approach (Mondoro & Frangopol, 2018)

The aim of the present study is to apply a methodology for determining the floodable riverside areas (Methodology for Defining the Adjoining Lands and Flooding Rivers Stripes in Bulgaria – MALFARS) with GIS tools and suitable hydrological and hydraulic model for assessing the risk of flooding of the constructed bridge over the Dzherman river part of the "Struma" highway (Dupnitsa municipality). According to the regulations, the bridge is a Class I facility, which is dimensioned with a 1.0% probability of exceeding and hydraulically checked for 0.1% probability of exceeding. The methodology was applied in hydrological reports related to flooded river sections and mainly in the developed flood risk management plans of the basin regional directorates under the leadership of the Ministry of Environment and waters in Bulgaria. In the present research, the methodology is applied for the first time in such a case with a view to be included in technical reports for a new bridge design facilities and for the rehabilitation of existing ones.

Study Area

The present study covers the watershed of the Dzherman River (a left tributary of the Struma River), from the source area to Highway "Struma" in the area of the Dzherman village. The drainage basin of the Dzherman River is part of the northwestern sections of the Rila mountain range. The river's source is a lake at an altitude of 2,535 m and it is 47.8 km long (Hristova, 2012). Dzherman River influences the Struma River at an altitude of 369 m (Fig. 1). According to the River basin management plans for river basin directorates upon the Ministry of Environment and waters the river is considered as water body BG4ST600R036, type R5.

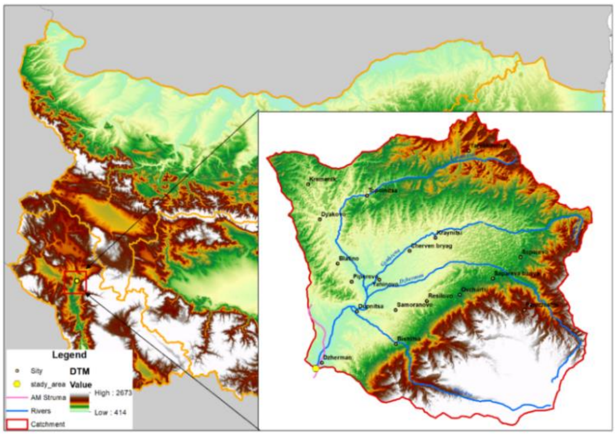


Figure 1. Location of the study area

Materials and Methods

The “Methodology for Defining the Adjoining Lands and Flooding River Stripes in Bulgaria” (MALFARS) is the official accepted methodology for assessing the boundary and the area of the river stripes. This approach includes nine steps – 1: digital input data provided in a GIS environment; 2: defining physio-geographical characteristics based on DEM (digital elevation model); short climate characteristics of the survived area; 4: hydrological calculation, etc. (Figure 2).

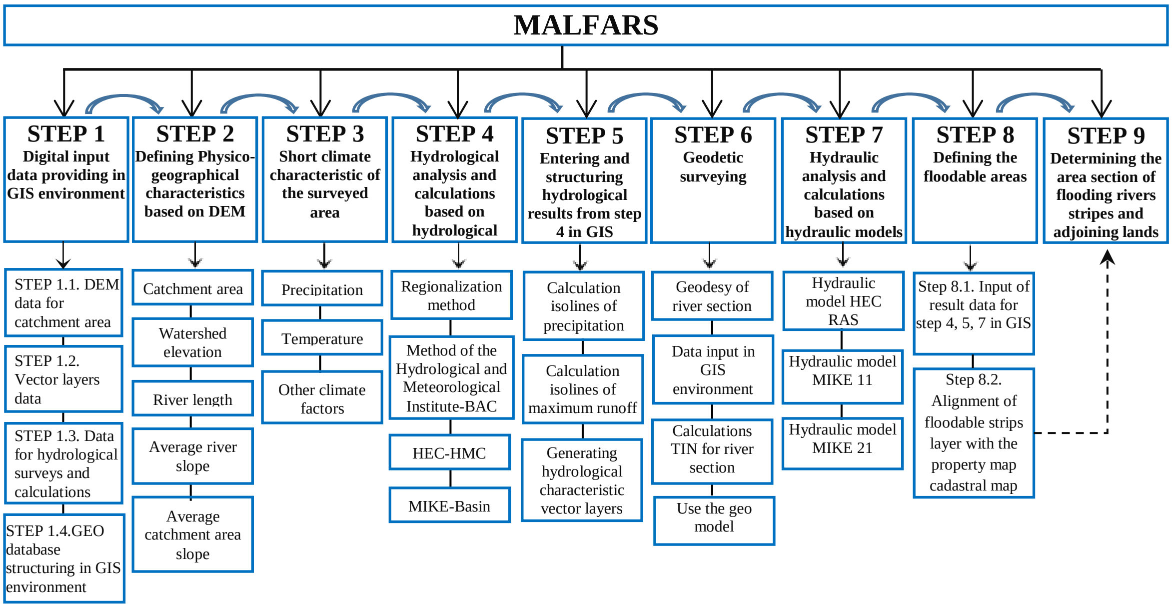


Figure 2. Methodology for defining the adjoining lands and flooding river stripes in Bulgaria” (MALFARS)

According to the first step of the methodology, input information is required to create a GIS database for the studied watershed, which is implemented with raster data - DEM and vector objects - rivers, springs and natural and artificial lakes, existing hydro-technical systems and facilities, forest cover, soil characteristics and others. The generated DEM of the studied watershed is the basis for the orographic characteristics (step 2): area (A, km^2) and altitude (H, m) of the river basin, length (L, km) and slope (i, ‰) of the river (river section) and others. The climatic characterization is performed on the basis of main climate data (air temperature and precipitation), as well as some features of the climate in the studied watershed (step 3). The selection of a hydrological model for the maximum runoff calculation (according to step 4 of MALFARS) is based on the availability of hydrometric and meteorological information in the study area. The studied section, a bridge facility part of Struma highway, does not coincide with a hydrometric station from the national reference hydrometric network. Therefore, the hydrological analysis and assessment is carried out under conditions of insufficient or total lack hydrological information. In this case, empirical relationships between the hydrological characteristics and the orographic characteristics of the studied watersheds are applied to estimate the maximum runoff to the studied area. In the present study, regressions between the modulus of the maximum runoff (M_{qmax}, $l/s/km^2$) and the mean altitude (H, m), between the coefficient of variation of the maximum runoff (Cv) and the catchment area (A, km^2) are used.

A logarithmic grid is used to plot the graphical dependencies. The resulting regressions were evaluated using the correlation coefficient (R) at a statistical significance level of 5.0% and evaluation criteria for the correlation coefficient. The information arrays of data on the maximum runoff observed in the hydrometric stations used in the study are subjected to processing through mathematical statistics. Parametric and non-parametric criteria for uniformity, representativeness and significance of hydrological series of maximum water quantities were used. The test was performed according to the Mann-Whitney, Pettit's test and Wilcoxon tests. The collateral curves for each HMS are calculated and constructed, on the premise of choosing the most appropriate theoretical distribution law based on minimal deviations of the empirical points from the theoretical ones (Mamdouh et al., 1993). The analysis was made to reach reliable results for the maximum runoff parameters used to construct regional dependencies. The method of analogy is applied to obtain maximum water quantities with characteristic probability of exceeding for the studied area. The adopted hydrometric station for analog is HMS 51430 on the Dzherman River, which is located about 6.5 km above the studied section. The station was opened in 1936 and has been operating until now and based on WMO requirements (WMO, 2017) a calculation period of 1961 to 2020 is assumed. The hydrological series of annual maximum water quantities is processed with the methods of mathematical statistics, the security curve is calculated and constructed, and the statistical parameters are calculated using the method of maximum likelihood under lognormal distribution. Based on the obtained ordinate deviations with a lognormal distribution at HMS 51430 and with the application of the method of moments, the theoretical probability curve for the studied section of the Dzherman River is obtained as

$$Q_{p,i} = \overline{Q_i}(\varphi_{p,i}.Cv + 1)$$

Where as

i is river section

$Q_{p,i}$ – annual maximum discharge with probability *P* for the river section

$\overline{Q_i}$ – average of the annual maximum discharges by the equation: $M_{max,av} = f(H)$;

C_v – coefficient of variation of the annual maximum discharge by the equation $C_v = f(A)$;

φ_p –conditional outflow coefficient of maximum runoff at probability of exceeding p%;

In step 5 of the methodology, the hydrological results are implemented in the developed GIS database. Thematic maps of the distribution of the annual maximum runoff, the coefficient of variation of the maximum runoff and others are created. In step 6, the topography of the studied river section is implemented in the developed database. Using AcrMap tools a digital terrain model of the river section is generated in TIN format. With the capabilities of HEC-geoRAS (HEC- GeoHMS, User's Mannual, 2013), based on the created TIN format, cross profiles along the length of the river bed are generated (Icaga et al., 2016). In step 7, a hydraulic model was selected. HEC-RAS was used for the purpose of the study. The results of step 6 and step 4 are implemented in the model and the bridge facility is designed (Ogras&Onen, 2020). The results of the hydraulic model, such as the water level elevation, the change in the average velocity and the depth of the water current, are implemented again in GIS to perform step 8 (8.1 and 8.2) of the methodology. From the processed information, thematic maps of the flooding river strips and the adjoining lands in the studied river section are prepared, and present the final result of the adopted methodology in step 9 (Figure 2).

Data Source

The DEM for the study catchment was generated from open-access raster data with a 30 m x 30 m grid cell size from the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Global Digital Terrain Model Version 3 (GDEM 003). Linear objects are vectorized from topographic maps at a scale of 1:25000 (https://www.cadastre.bg). For land cover, data from Corine Land Cover was used for two years – 2018 and 2022 (Radeva&Kirilova, 2023). For the climatic characteristics of the river catchment, data from meteorological observations in the city of Dupnitsa are used (Table 1). The initial data for constructing the degree dependences for determining the maximum runoff to the studied section are maximum runoff values in the catchments of the Dzherman River - Dupnitsa (HMS 51430), the Blagoevgradska Bistrica River - Slavovo (HMS 51450) and the Rilska River - village. Pasta (HMS 51470). Data on the physio-geographical characteristics of the HMS were taken from NIMH - MOEW (Table 2)

Table 1. Meteorological data (Dupnitsa city)

Climate parameters	Month												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
T_{av} (°C)	-0,9	1,3	4,7	10,6	15,3	18,8	21,0	20,5	16,7	11,4	6,5	1,5	10,6
T_{max} (°C)	3,1	6,2	10,5	16,7	21,5	24,9	27,6	27,8	24,1	18,1	11,3	5,3	16,4
T_{min} (°C)	-5,1	-3,3	-0,4	4,7	8,9	12,3	13,5	12,6	9,3	4,9	1,9	-2,3	4,8
Precip. (mm)	45	38	37	61	69	79	52	40	38	56	61	51	627

Table 2. HMS Physio-geographical characteristics

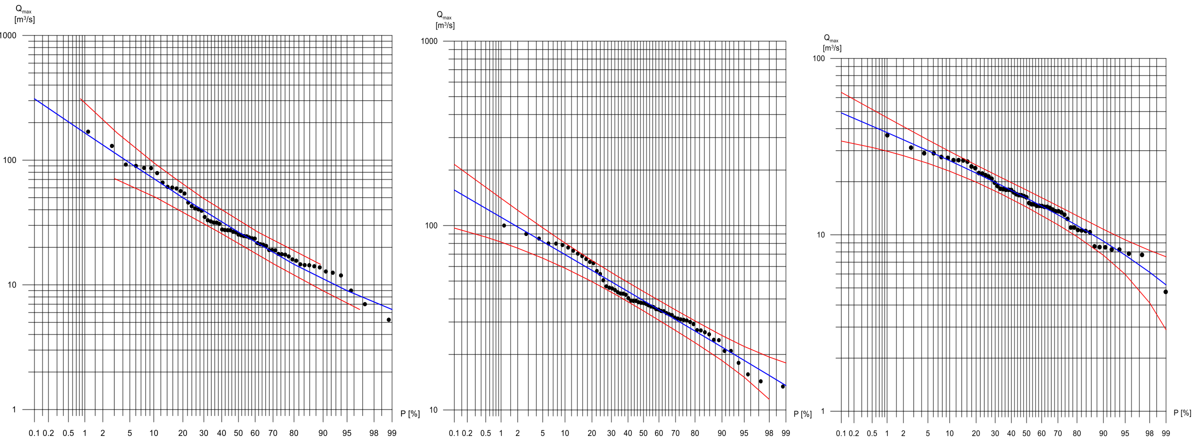
HMS №	River	A (km^2)	H (m)	L (km)	Average slope ‰	Average catchment slope
51430	Dzherman	396	1001	30	43.1	0.222
51450	Rilska	222	1918	24	50.3	0.519
51470	Blagoevgradska bistritza	105	1790	21	30,8	0,44

Results and Discussion

For the purpose of hydrological characteristics analysis and evaluation vector layers were generated and the physico-geographical characteristics of the studied watershed were calculated based on the developed DEM and with the help of the HEC-geoHMS modules in a GIS environment (Table 3)

Table 3. Orographic characteristics of the studied area

Section	River	A (km^2)	H (m)	L km	Average river slope ‰	Average catchment slope
Bridge from Highway Struma	Dzherman	492,8	955	37,2	40,8	0,2



a). b). c)

Figure 6. Theoretical probability of exceeding curves for maximum runoff observed in HMS 51430 (a), HMS 51450 (b) and HMS 51470 (c)

To determine the characteristics of the maximum outflow of the Dzherman River to the studied section of the bridge over the Dzherman River, three HMS with a period of the observed magnitude from 1961 until 2020 were used. The hydrological series are checked for homogeneity according to the accepted criteria, which confirm their significance. The probability of exceeding curves for the maximum runoff with an assumed lognormal distribution in a logarithmic-probability network were calculated and constructed (Figure 6).

The statistical parameters of the hydrological series of the used HMS were calculated by the maximum likelihood method with an assumed lognormal distribution. The results of the calculations are given in Table 4. Based on data on the statistical parameters of the maximum runoff calculated in table 4 for the studied hydrometric stations, regression of type $Y = a.X^b$ were constructed, where Y is the hydrological variable, and X is the orographic characteristic (catchment area - A (km^2) or the mean altitude of the watershed H (m)), a and b are coefficients of the non-linear regression.

Table 4. Statistics of Q_{max}

HMS	**River**	$\boldsymbol{M_{qmax}}$, **(l/s/km²)**	**Statistics**			
			Q_{max} (m^3/s)	σ	C_v	C_s
51430	Dzherman	0.09	36.0	29.8	0.83	3.35
51450	Rilska	0.192	42.6	20.4	0.48	1.16
51470	Blagoevgradska Bistritza	0.167	17.5	6.96	0.36	0.93

Figure 4a and 4b show the graphical relationships between the modulus of maximum runoff and mean elevation and coefficient of variation and catchment area.

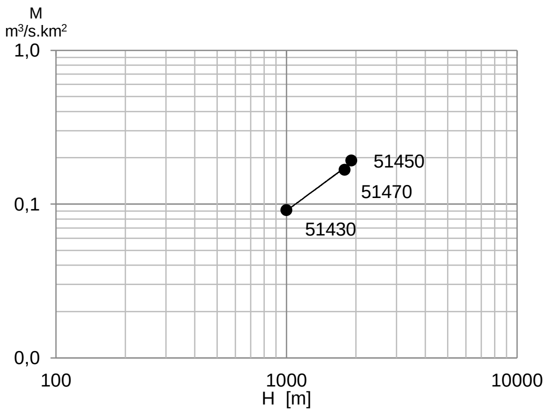


Figure 4a. Relationship between $M_{q\ max}$ and H

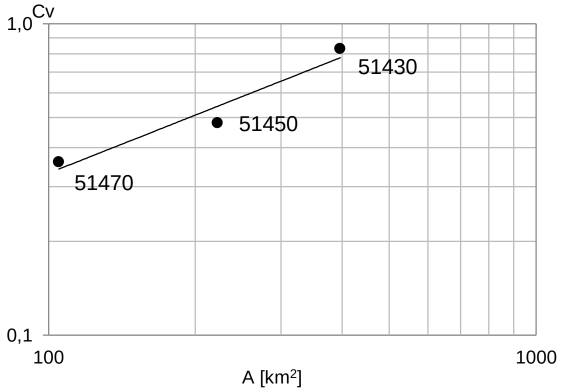


Figure 4b. Relationship between $C_{v\ max}$ and A

For each graphical dependence, the non-linear regression dependence for the individual hydrological parameter with the corresponding evaluation criteria is derived. For the maximum runoff modulus ($\boldsymbol{M_{qmax}}$), the following dependence was obtained:

$$\boldsymbol{M_{qmax}} = 4{,}32.10^5.H^{1{,}108}\ (m^3/s.km^2),$$

which is checked with the correlation coefficient R = 0,997 and reliability assessment of R by the probability error E_R = 2,6 % < 3.0% and by Fisher criteria F_R = 5,55 > 3.0. The following dependence was obtained for the coefficient of variation of the maximum runoff modulus:

$$C_{v,max} = 1{,}9.10^2.H^{0{,}62}$$

which is checked with the correlation coefficient R = 0,968 and estimate the reliability of R by the probability error E_R = 2,43 % < 3.0% and by Fisher criteria F_R = 4,15 > 3.

Applying the derived non-linear regression dependences for the studied section (the bridge over the Dzherman River), the maximum runoff Qmax, brige = 42.5 m^3/s and coefficient of variation Cv = 0.88 is obtained. To obtain the maximum water quantities with a specific probability of exceeding for the studied section, we have used the data on the maximum runoff from HMS 51430, which is accepted as an analogue. The calculation procedures carried out for the determination of the maximum water quantities with different probability of exceedings for the section along Dzherman River, with the applied hydrological model, give the following results, accepted as final for input information in the hydraulic model (Table 5).

Table 5. Dimensional maximum water quantities for the studied section of Dzherman River

Section	River	A (km^2)	H (m)	$Q_{0.1\%}$ (m^3/s)	$Q_{1\%}$ (m^3/s)
Bridge from HW Struma	Dzherman	492,8	955	353,0	188,7

To create the digital terrain model for the studied river section in TIN format (Figure 6), a captured topography of the river section (Figure 5) is used, according to step 6 of MALFARS.

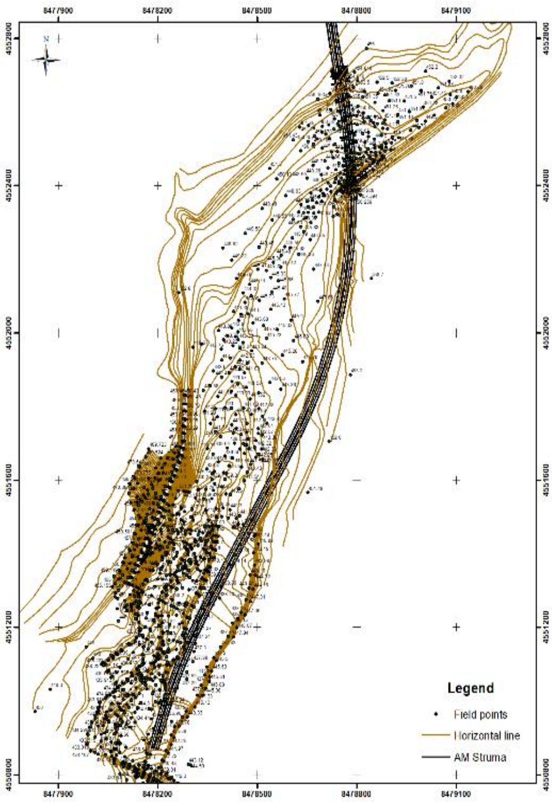


Figure 5. Geodetic surveying

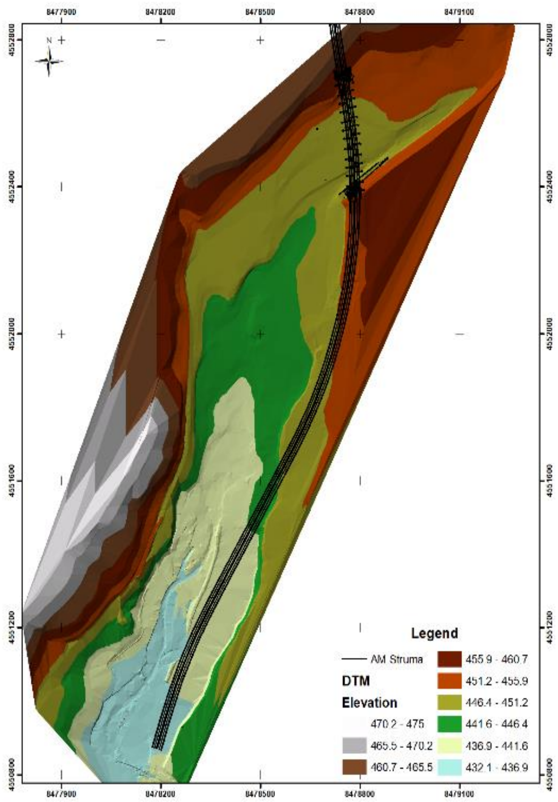


Figure 6. Digital terrain motel

With the capabilities of the HEC-geoRAS model, cross profiles along the length of the studied river section are generated (Figure 7). The results of the geometric characteristics of the river section of the Dzherman River are input information for the selected HEC-RAS hydraulic model, according to step 7 of the methodology. The selected hydraulic model make it possible to model the shape and dimensions of the bridge facility that is a subject of this study. The results of the hydraulic calculations for the modeled bridge structure over the Dzherman River and the position of the water level at the maximum water amount with 0.1% probability of exceding calculated in the hydrological model are presented in Figure 8. The obtained hydraulic parameters of the river current from the hydraulic model show that the calculated maximum water quantity with a 0.1% probability of exceeding does not create conditions for flooding the so designed bridge structure.

To create thematic maps representing the inundation strip and inundation area, hydraulic results such as flow depth change and average velocity change are implemented in the already designed DEM in a GIS environment. Figures 9 and 10 present thematic maps of the variation in river flow depth and variation in mean velocity at maximum water quantity with a 0.1%. probability of exceeding.

From figure 9 and 10, the outline of the water surface that shows the boundaries of the flooding strips has been defined. The outline of the water surface determines the area of the flooded territory. In the investigated computational section, the flooded area amounts to 0.28 km^2 at the maximum water quantity – $Q_{0.1\%} = 353\ m^3/s$.

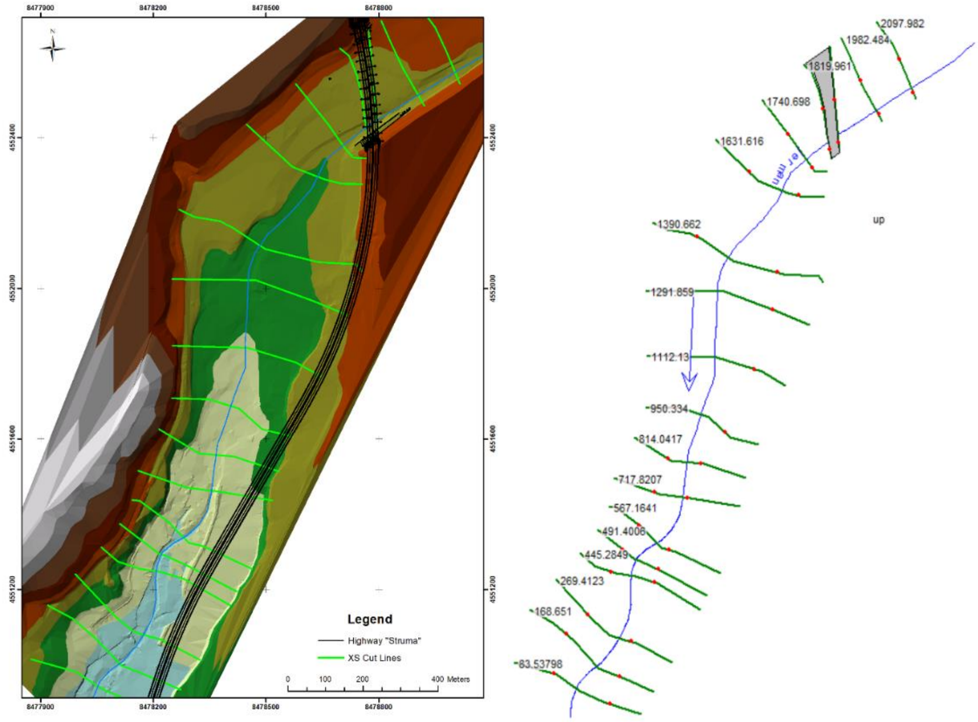


Figure 7. Location of the cross profiles along the river section (Dzherman River)

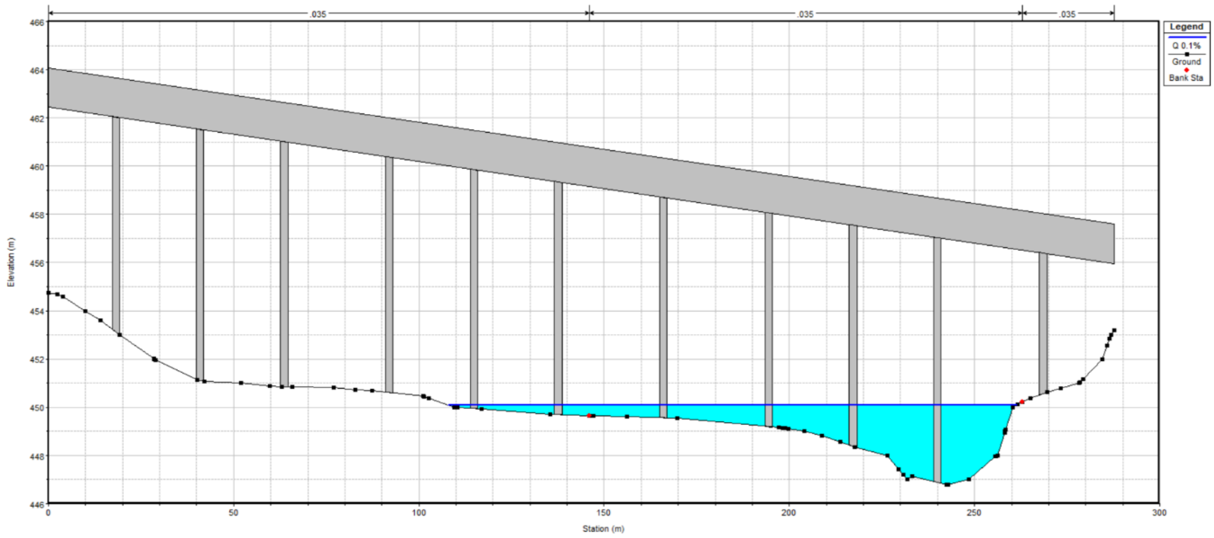


Figure 8. Cross profile of Dzherman river with longitudinally depicted the bridge facility part of HW Struma with a water quantity with a 0.1%. probability of exceeding

The obtained hydraulic parameters of the river current from the hydraulic model show that the calculated maximum water quantity with a 0.1% probability of exceeding does not create conditions for flooding the so designed bridge structure. To create thematic maps representing the inundation strip and inundation area, hydraulic results such as flow depth change and average velocity change are implemented in the already designed DEM in a GIS environment. Figures 9 and 10 present thematic maps of the variation in river flow depth and variation in mean velocity at maximum water quantity with a 0.1%. probability of exceeding. From figure 9 and 10, the contour of the water surface that shows the boundaries of the flooding strips has been difined. The water surface outline determines the area of the flooded territory. In the investigated computational section, the flooded area amounts to 0.28 km^2 at the maximum water quantity – $Q_{0.1\%} = 353\ m^3/s$.

The inspection carried out for the bridge, which is part of the Highway Struma, is not flooded and no destruction of the design structure of the bridge will be observed when the maximum amount of water passes with 0.1%

probability of exceeding in the Dzherman riverbed. In the lower section of the highway route, flooding of the roadway has been observed, which leads to taking construction measures for protection against flooding.

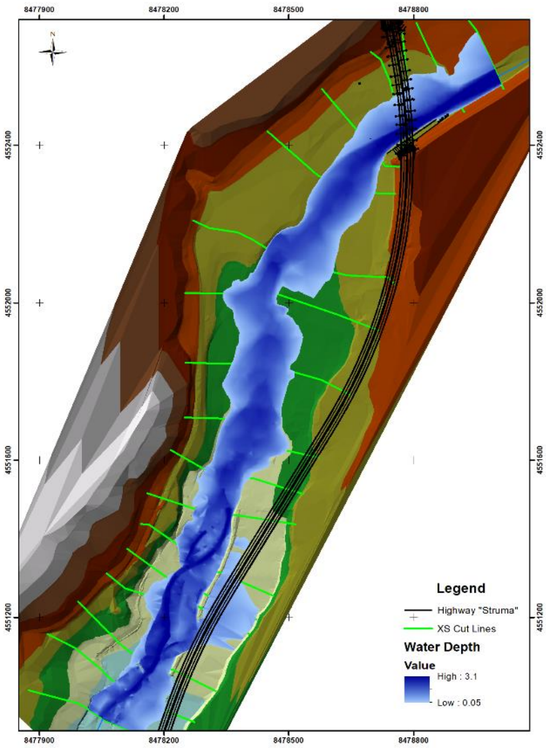


Figure 9. Water surface depth at $Q_{0,1\%}$ = 353 m3/s

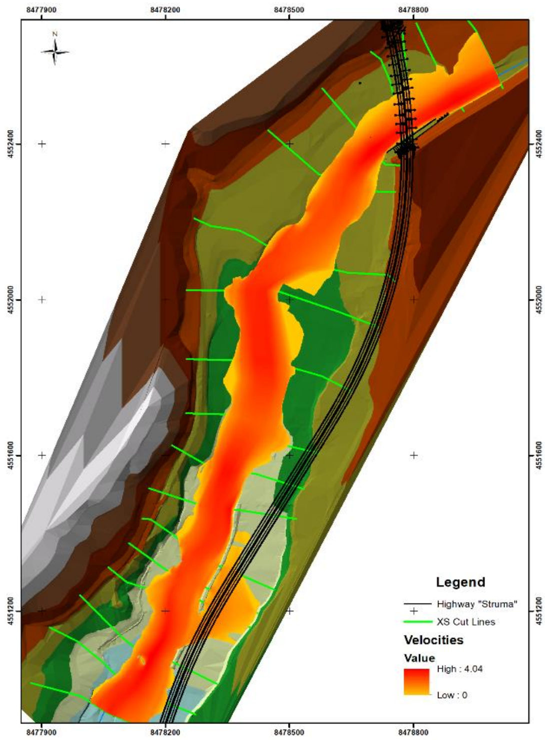


Figure 10. Average current speed at $Q_{0,1\%}$ = 353 m3/s

Conclusion

The results of the present study show that the "Methodology for Defining the Adoining Lands and Flooding River Stripes in Bulgaria" (MALFARS) is an important tool for assessing the risk of damage to bridge structures. The generated vector layers for the analysis and assessment of the hydrological characteristics based on the developed DEM and the HEC-geoHMS modules in a GIS environment provide objective information about the physicogeographical characteristics of the studied watershed. The Cross-sections in the surveyed river section are generated in a GIS environment using HEC geoRAS modules and the developed DEM derived from geodetic terrain surveying. The selected hydrological model and calculated maximum water quantities with 0.1% and 1.0% probability of exceeding based on the HEC-RAS model defines the accurate determination of water level elevations, bridge facility throughput and average river flow velocities at assumed maximum water quantities. According to the results of the present survey, a thousand-year high river wave is not possible to flood and destroy the built bridge over the Dzherman River. The methodology is applied for the first time to river bridges in the country and the results of the survey demonstrates its importance and contribution to define flooding riverside strips for other bridge structures built over water bodies.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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