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Research Article

The Development of a Flood Inundation Map: A Case Study of Karamustafa Village, Çankırı

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Abstract

Floods are severe natural disasters that affect many regions around the world, including developed countries, causing significant loss of life and property each year. In Türkiye, floods rank among the natural disasters causing the greatest losses after earthquakes. In order to prevent these damages, the generation of flood maps is of great importance. In the study, a flood inundation map for a 500-year flood event was formed for Çankırı-Çerkeş Karamustafa Village using HEC-RAS hydraulic modeling, followed by the design of a channel. The results showed that, under current conditions, 50 houses were inundated, substantial agricultural areas were affected, and a flood inundation area of 35864.5 m² was formed. Simulations showed that the proposed concrete trapezoidal channel would prevent Karamustafa Village from being affected by a 500-year flood event. It was noted that future studies would benefit from calibration with local data to obtain more accurate results. Flood inundation maps are vital for water resource management and urban planning. The use of updated data and optimized channel sections is essential for preventing potential flood disasters and minimizing future loss of life and property.

Keywords

Flood modeling, HEC-RAS, Karamustafa Village, Çerkeş, Çankırı, Flood inundation map

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1. Introduction

Floods are among the most significant hydrological natural disasters affecting many regions worldwide, including developed countries. These disasters occur due to insufficient water-carrying capacity in river channels for various reasons or the accumulation of more water than expected. Each year, many lives are lost due to floods and substantial financial damages occur in both infrastructure and buildings. One of the most important methods to prevent or mitigate the damages caused by floods is to create flood inundation maps and provide information on this focus (Merwade et al., 2008; Jain et al., 2006). These maps not only identify areas at risk of flooding in the future but also serve as a guide for rescue and relief operations related to floods. In our country, floods, which rank second after earthquakes in causing loss of life and property, result in an annual economic loss of approximately 100 million dollars (Özşahin, 2013; Şahin and Sipahioğlu, 2003). In contrast, the annual average investment in projects aimed at flood control and damage reduction is approximately 30 million dollars (Ya et al., 2006).

The availability of flood data is crucial for deciding the flood characteristics and sensitivity of a region and enhancing the accuracy of analyses in risk assessment studies (Haltas et al., 2021). Additionally, the generated flood inundation maps provide significant insights for land-use planning and zoning attempts. Understanding the impact of climate change on these maps is also of global importance. Technological advancements in remote sensing and geographic information systems (GIS) have enhanced precision in the fields of hydrological and hydraulic modeling, aiding in the creation of these maps. In our country, GIS techniques have been used in numerous flood assessment studies, starting in the early 2000s and continuing to the present day.

The Hydrologic Engineering Center River Analysis System (HEC-RAS) is a widely used tool for flood modeling and analysis. Numerous studies in Turkey demonstrate its effectiveness. For example, a study conducted on the Tigris River between the Diyarbakır-Silvan Road and the historic On Gözlü Bridge used HEC-RAS to evaluate flood zones and develop a flood hazard map, contributing to the Tigris River Rehabilitation Project (Ogras & Onen, 2020). Similarly, after the 2012 flood disaster in Samsun Mert River Basin, which caused significant financial damage and loss of life, HEC-RAS was used with GIS to prepare flood hazard maps for recurrence intervals of 10, 25, 50 and 100 years. The simulation results for the 10-year recurrence flood were found to align with the 2012 flood event (Demir & Kisi, 2016). In another study on the Mert River and its tributary Yılanlıdere in the same basin, flood modeling and damage estimation were conducted. The results showed that floods with 50- and 1000-year recurrence intervals could cause estimated damages ranging from 150 to 500 million ₺ in the study area (Demir & Ülke Keskin, 2022). A similar analysis evaluated the 2012 flood in Hatay Amik Plain, where 8,465 hectares of agricultural land, roads, bridges, residential areas and Hatay Airport were inundated (Üneş et al., 2020). Other studies have been carried out in various regions, such as Kırıkkale Çoruzözü Stream and Bingöl City Center, where flood inundation maps were generated, maximum water depths calculated and the inadequacy of existing cross-sections for peak discharges identified (Doğu & Yıldız, 2019; Çeliker et al., 2020). In western Turkey, flood analyses were conducted on Zeytinli Stream, producing water surface profiles for various return periods. Subsequently, flood prevention scenarios were proposed and risk analyses were repeated to develop flood prevention recommendations for the region (Yerdelen et al., 2023). Another study investigated the impact of potential dam failure on the Kapulukaya Dam on the Kızılırmak River. HEC-RAS revealed that the expected flood would raise the river water level by up to 27 meters, inundating downstream settlements (Duvan & Yildiz, 2020). A similar analysis was performed for the Darlık Dam in Istanbul, where the flood discharge, water velocity and depth were calculated in case of dam failure. The results showed that 80% of buildings fell into the very high-risk category, with over 3,000 buildings expected to be affected (Tilav & Gülbaz, 2024). In Mersin Kebendibi River sub-basin, 1-D flood risk analyses were conducted using HEC-RAS. Raster data from digital maps of Mersin were analyzed using NetCAD software and the results were utilized to generate flood risk maps (Altın et al., 2024).

This study aims to use HEC-RAS hydraulic modeling to generate a flood inundation map for Çankırı-Çerkeş Karamustafa Village based on a 500-year flood recurrence interval discharge and to design a channel for this discharge. The flood inundation areas and water levels obtained from this study are intended to provide valuable contributions to reducing potential flood risks in the region and supporting the development of socio-economic planning for the area.

2. Materials and Methods

2.1. Study Area and Data

The Çerkeş district of Çankırı features a rich geographical formation that reflects Turkey's diverse climate due to its location. It is predominantly situated within the Kızılırmak Basin but also extends into the Western Black Sea and Sakarya Basins (Figure 1(a)). Serving as a transition zone where the typical continental climate of Central Anatolia interacts with the humid air of the Black Sea, Çerkeş exhibits variable climatic characteristics depending on the season. Winters are generally cold, while summers are milder and drier. The region's high elevation highlights temperature differences, with cooler temperatures observed in mountainous areas and higher temperatures in lowly elevated regions (Mülayim, 2012).

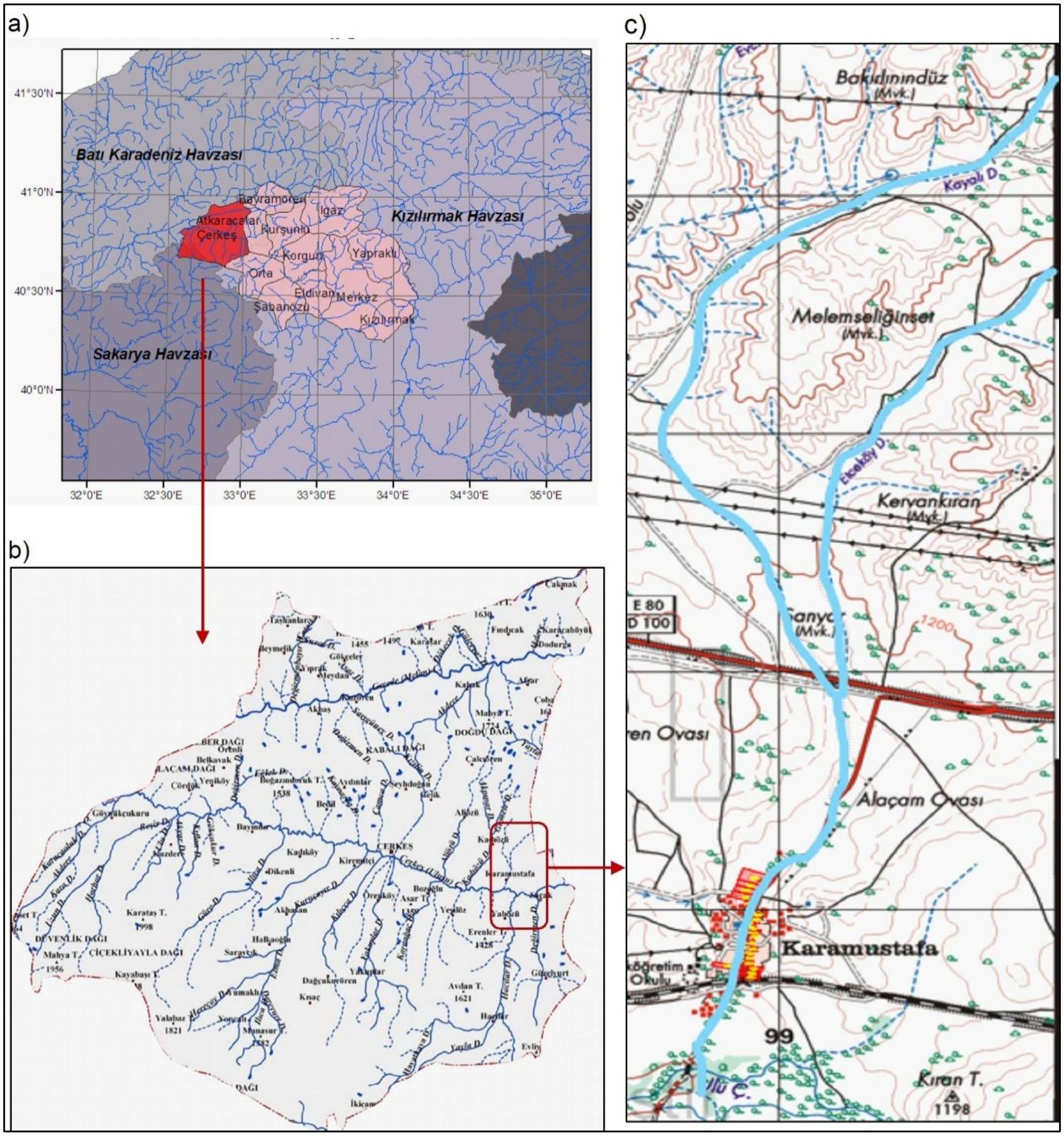

Figure 1. Study area (**(a)** Location of Çankırı province within the basins and its districts, **(b)** Çerkeş district and its river network, **(c)** Eceköy and Kayalı Streams along with Karamustafa Village)

Figure 2 illustrates the monthly rainfall and temperature values for Çankırı and the Çerkeş district. In general, rainfall levels in Çerkeş tend to be lower compared to the overall Çankırı province. While rainfall peaks in May for Çerkeş, it is observed that Çankırı receives higher amounts of rainfall during the same period. This can be attributed to Çankırı's higher elevation and more mountainous terrain. Throughout the year, rainfall in both the province and district is concentrated mainly in the spring and autumn months, while it decreases during the summer and winter seasons. Average temperatures in Çerkeş, particularly during the summer months, are observed to be lower compared to Çankırı. The seasonal concentration of rainfall in spring and autumn contributes to the replacement of water resources in the region, while the dry conditions of summer put pressure on these resources. Cengil and Kuşvuran (2012) highlighted the increase in the average monthly maximum temperatures in Çankırı and emphasized its significance on an agricultural scale.

The vegetation in Çerkeş reflects the region's climate and topography, displaying a diverse range of flora. Despite the arid steppe vegetation typical of Central Anatolia, the area also covers rich forests. These forests provide a crucial habitat for the region's biodiversity and support various forms of wildlife. The region's river network plays a critical role in meeting agricultural and drinking water needs. However, increasing pressure on water resources, particularly around Çerkeş Stream and its surrounding water sources, has led to declines in both water quality and quantity (Çelikoğlu, 2011).

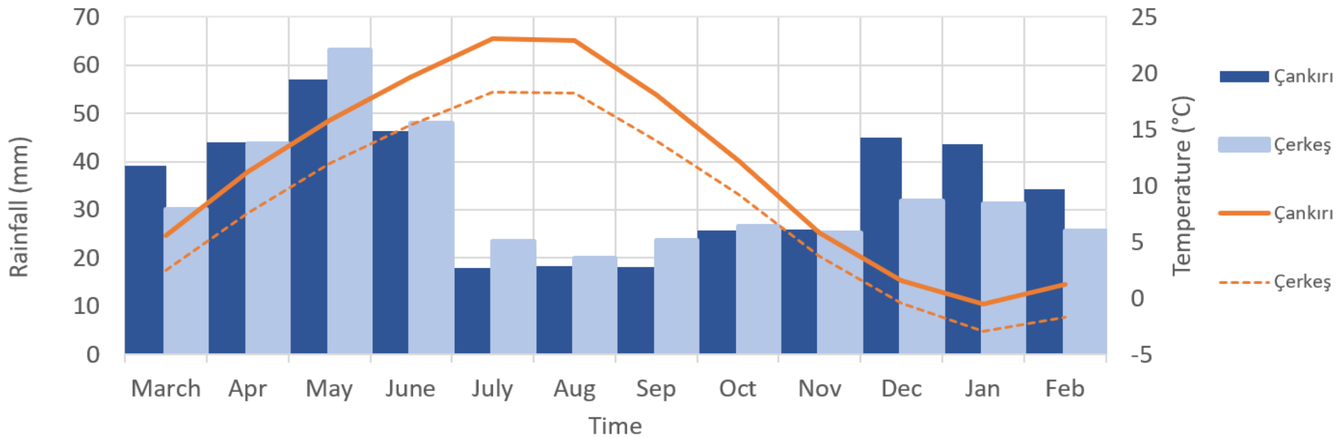

Figure 2. Average monthly rainfall and temperature values (Çankırı and Çerkeş)

The selected study area, Çerkeş-Karamustafa Village (Figure 3 (a)), is located 70 km away from Çankırı city center (Figure 1 (a)). The village experienced flood events on 5th July 2019 and 7th June 2022 (Figure 3 (b) and (c)). While no fatalities occurred during these floods, approximately 50 houses were indirectly affected. Many houses suffered partial damage, with belongings in basements and vehicles parked in front of houses being impacted. Additionally, the village's infrastructure was completely disrupted; concrete paving stones were displaced, the sewer system was clogged, and both the sewage pipes and the drinking water network sustained damage. Upstream of the village, the Kayalı and Eceköy Streams converge at the Senyar area, located just above the settlement. The combined stream flows through the center of the village and joins the Ulusu Stream downstream of the village (Figure 1 (c)).

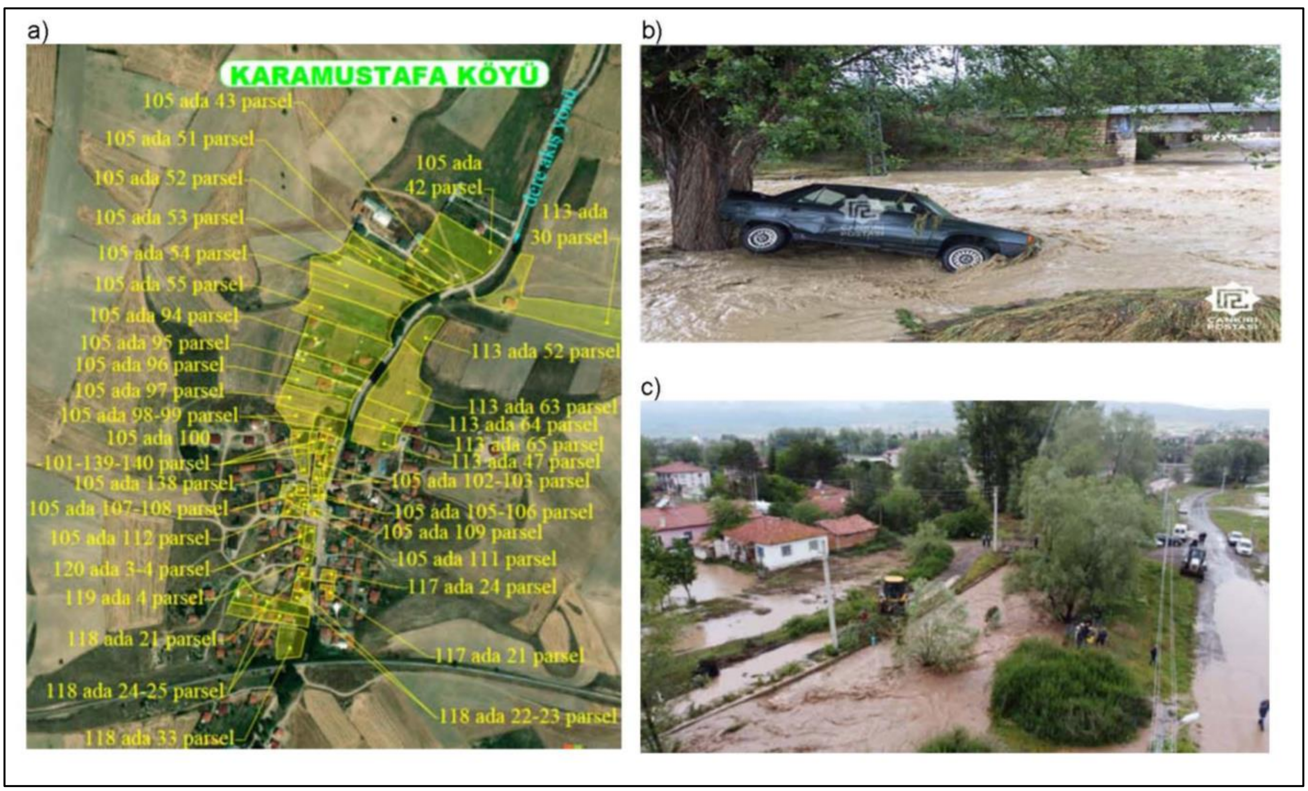

Figure 3. (a) Settlement and parcel view of Karamustafa village, **(b)** flood event on July 5, 2019, **(c)** flood event on June 7, 2022

2.2. HEC-RAS Modelling

The first step of the flowchart presented schematically in Figure 4, involves transferring settlement/parcel data obtained from the General Directorate of Land Registry and Cadastre into a CAD environment. This data will later be used to identify the affected settlement areas in the flood inundation map. The next step is to create a 3D representation of the study area using 1/25000 scale digital elevation maps (Figure 5 (a)). For this, it is essential to accurately position the digital elevation model. The project area lies in Zone 36 according to the UTM (Universal Transverse Mercator) projection (based on 6° intervals). Using ED 50 (European Datum), the EPSG (European Petroleum Survey Group) code 23036 was applied for the study area, completing the georeferencing process. In the CAD program, the stream's flow path and cross-section layers were defined. Subsequently, the basin boundary (Figure 5 (c)) and the stream

(Figure 5 (b)) were delineated. Following this step, cross-sections were assigned at 30-meter intervals (Figure 5 (d)), ensuring that the cross-sections were perpendicular to the stream and did not intersect one another. Finally, as shown in Figure 5 (e), the geometric data were loaded into the HEC-RAS program.

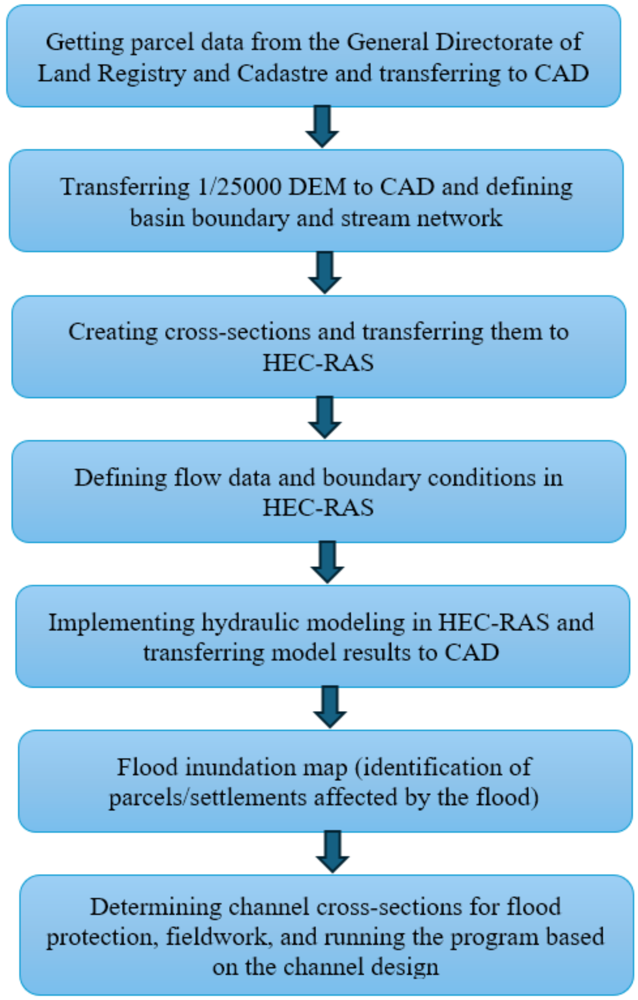

Figure 4. Flowchart of the study

With the HEC-RAS model, flow simulation was conducted for the section starting from the convergence of the Kayalı and Eceköy streams and extending to the exit of Karamustafa Village.

2.2.1 Calculation of the roughness coefficient (n)

In hydraulic calculations, the 'n' value represents the roughness coefficient, which indicates the resistance to flow. The Cowan method is considered a suitable approach for calculating this coefficient under Turkish conditions (Eryılmaz Türkkan, 2021). The revised Cowan method, as updated by the State Hydraulic Works (DSİ, 2016), is as follows:

$$n = m(n_1 + n_2 + n_3 + n_4 + n_b) \tag{1}$$

The coefficient m represents channel sinuosity (the ratio of stream length to straight-line distance); the coefficient n_1 represents the condition of the channel slope (e.g., bare, concrete, stone); n_2 represents channel cross-section changes (e.g., gradual, varying); n_3 represents obstacles in the channel (e.g., negligible, minor, severe); and n_4 represents channel vegetation (e.g., low, medium, high). In this study, considering the conditions of the bed material, channel slope, cross-section, obstacles, and vegetation, the following values were selected (Table 1): $n_1 = 0.01$, $n_2 = 0$, $n_3 = 0$, $n_4 = 0.005$ and $n_b = 0.025$. For the sinuosity calculation, the stream length was measured as 7717 m, and the straight-line length was measured as 7400 m, resulting in an m coefficient of 1. Based on these calculations, the roughness coefficient was determined to be 0.04.

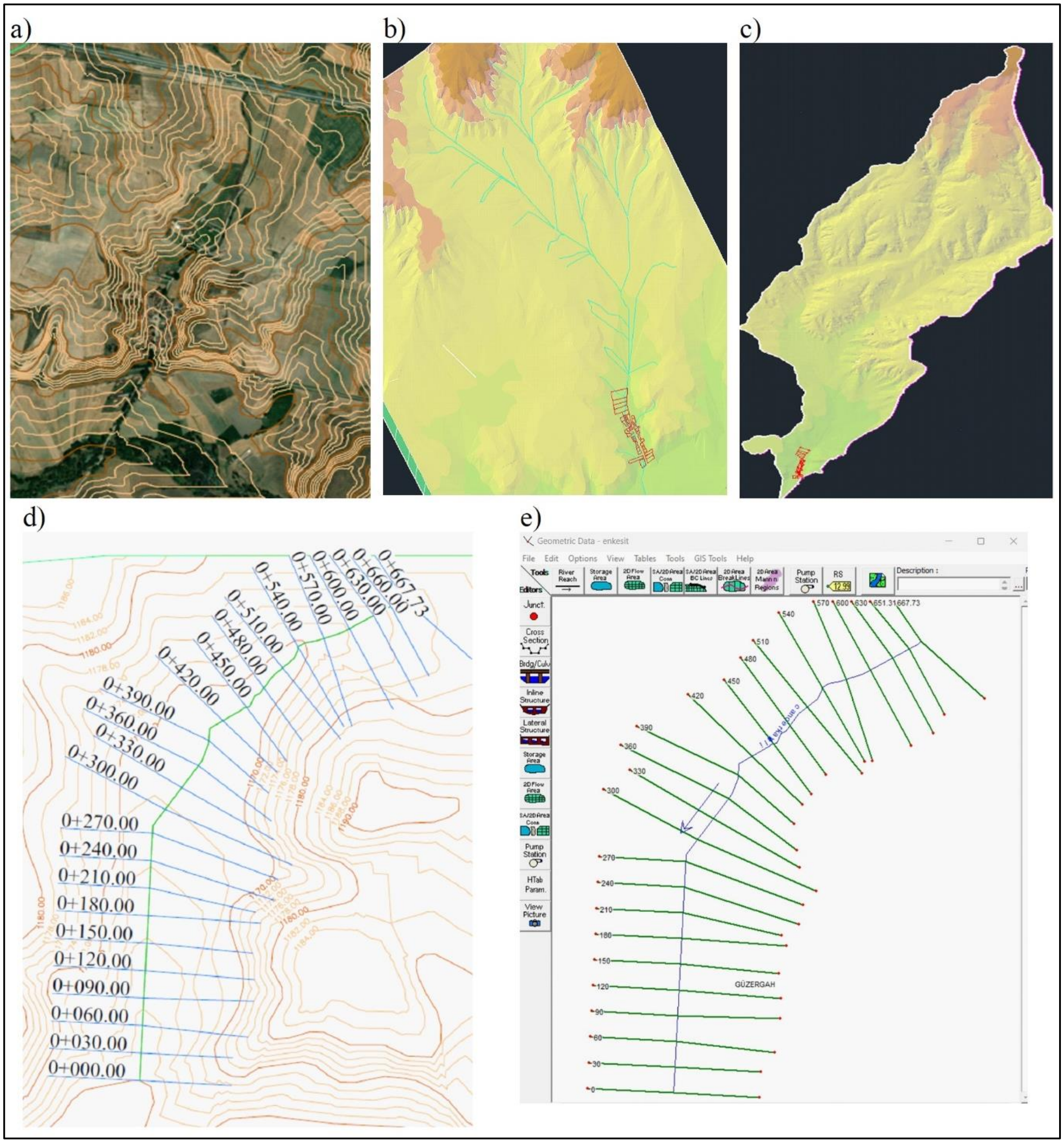

Figure 5. (a) 1/25000 Digital Elevation Map of the study area, **(b)** 3-D map, **(c)** basin area, **(d)** plan view of selected cross-sections in the study area **(e)** plan view in HEC-RAS

2.2.2 Determination of the maximum flow value

Since there is no observation station on the stream, meteorological rainfall data from the Çerkeş Meteorology Station in the Uluçay Basin was utilized. In synthetic unit hydrograph methods, the Rational Method is used for areas smaller than 1 km²; the DSİ Synthetic (SCS) Method is applied in drainage areas where the time of concentration (T_p) exceeds 2 hours and ranges between 10-1000 km²; and the Snyder Method is used for drainage areas larger than 1000 km² (Dikici & Aksel, 2019).

For this study, the drainage area is 17.2 km², and since the time of concentration (T_c) is less than 30 hours, the Mockus Method was used. The Mockus Method is preferred for its practicality in calculations and the ease of drawing a triangular hydrograph.

Table 1 "n" values according to the Cowan method (DSİ, 2016)

Category	Subcategory	n
Type of bed material (n_b)	concrete	0.012-0.018
	hard soil	0.025-0.032
	Coarse sand	0.026-0.035
	gravel	0.028-0.035
	Large stone	0.030-0.050
	boulders	0.040-0.070
Condition of channel slope (n_1)	smooth	0
	minor	0.005
	moderate	0.01
	severe	0.02
Channel cross-section variation (n_2)	gradual	0
	occasionally varying	0.005
	frequently varying	0.010-0.015
Obstacles in the channel (debris, mound, rock, bridge pier) (n_3)	negligible	0
	minor	0.010-0.015
	significant	0.020-0.030
	severe	0.040-0.060
Channel vegetation (n_4)	low	0.005-0.010
	medium	0.010-0.025
	high	0.025-0.050
	Very high	0.050-0.100
Channel sinuosity (m) (stream length/straight-line length)	minor (1-1.2)	1
	significant (1.2-1.5)	1.15
	Severe (>1.5)	1.3

Triangular hydrographs provide results as precise as curvilinear hydrographs in routing within reservoirs and stream channels (Ersoy & Kumanlıoğlu, 2018). The discharge calculations using the Mockus method are as follows:

$$t_c = 0.00032(L_h^{0.77}/S^{0.385}) \tag{2}$$

t_c, L_h and S represent the time of concentration, the hydraulic length of the drainage area and the average slope, respectively. By calculating the t_c value, the rainfall duration (D) is determined as follows:

$$D = 2\sqrt{t_c} \tag{3}$$

The time to peak discharge (t_p) and the flood recession time (t_r) are calculated as follows:

$$t_p = 0.5\,\Delta D + 0.6\,t_c \tag{4}$$

$$t_r = H_c t_p \tag{5}$$

The H_c value is an empirical coefficient that varies depending on the basin characteristics. For this study, this value is taken as 1.67. The calculation of maximum discharge (Q_p) for 1 mm of rainfall is as follows:

$$Q_p = K\,A\,h_a/t_p \tag{6}$$

K represents the basin coefficient, and h_a is the maximum rainfall depth. The unit hydrograph parameters calculated for the study area are presented in Table 2.

Table 2 Unit hydrograph parameters

S	t_c (hr)	D (hr)	t_p (hr)	t_r (hr)	Q_p (m^3/s/mm)
0.017	2.75	3	3.15	5.25	1.14

According to the DSİ Flood and Sediment Control Regulation, the 500-year recurrence flood discharge is used in residential areas. In this study, steady flow analyses were conducted using the peak discharge (Q_{500}) under the assumption of uniform flow for downstream and upstream flow conditions. The following equation was used to calculate the 500-year flood discharge:

$$Q_{500} = Q_{10} + (0.99 \log 500 - 0.98)\, Q_{100} - Q_{10} \tag{7}$$

Q_{100} and Q_{10} were calculated as 9.24 m³/s and 3.74 m³/s, respectively. Based on these values, the 500-year flood discharge was determined to be 26.1 m³/s. In this modeling, no changes in flow quantity are observed over time and the discharge remains constant across all cross-sections. However, variations in flow depth and velocity occur. The flood routing analysis was performed using the HEC-RAS program across all cross-sections.

3. Results

The flood water levels used in preparing the flood map were calculated using the water surface profile data provided by the HEC-RAS (Figure 6). According to the DSİ Flood and Sediment Control Regulation, when channel modifications are made for flood control in residential areas, an air gap (H_p) is added to the water height (h) corresponding to the Q_{100}. The resulting height is then compared with the water height corresponding to the Q_{500} and the larger value is taken as the basis. In this study, simulations were performed for both Q_{500} and Q_{100} (with an H_p value of 15 cm for Q_{100}) and it was found that the Q_{500} resulted in a larger value. Therefore, the flood inundation map (Figure 7 (a) and (b)) and the proposed concrete channel dimensions were developed using the Q_{500}. The maximum water level for Q_{500} was determined to be 1.02 m. According to the model results, the flood inundation area was calculated as 35864.5 m².

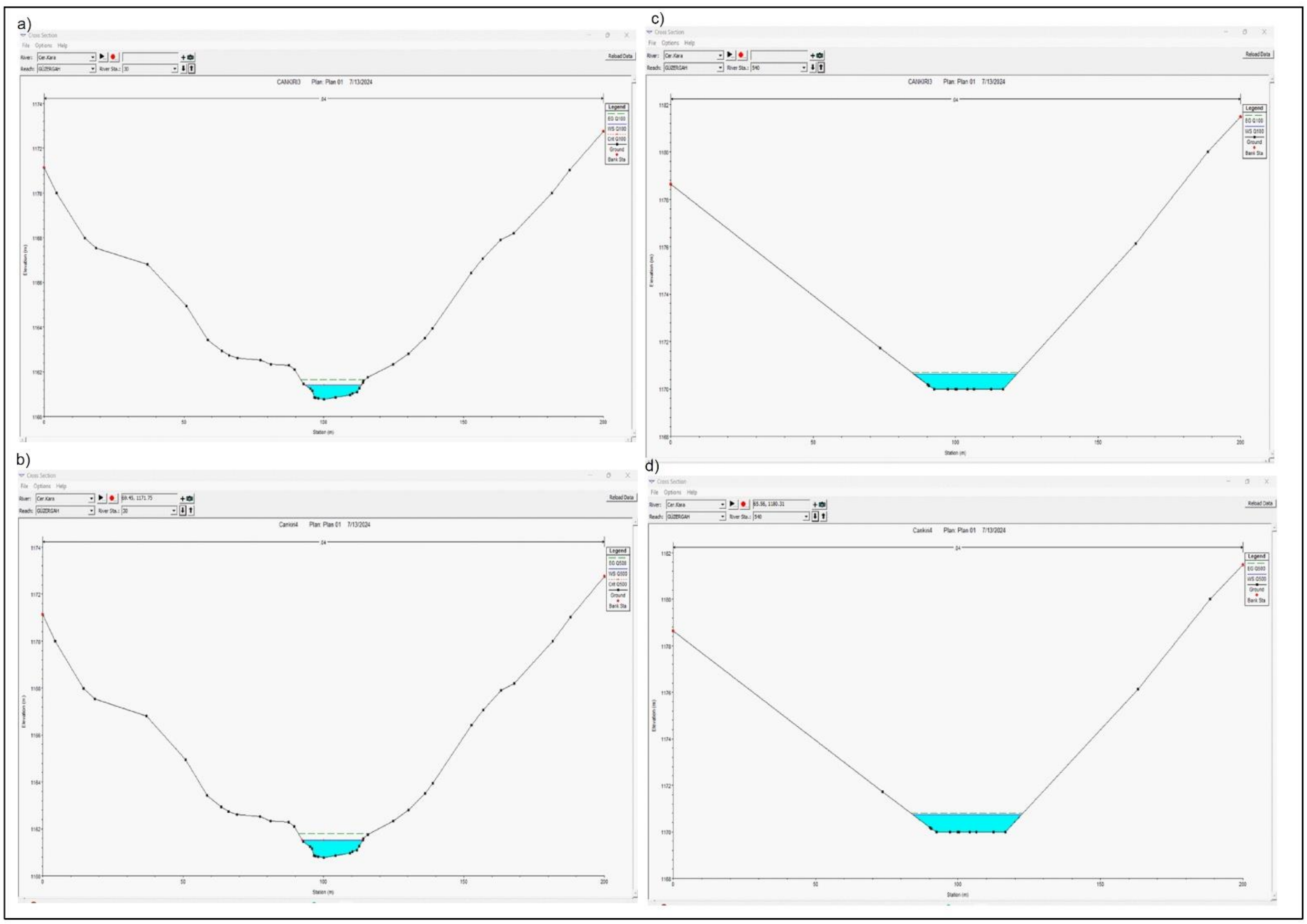

Figure 6. Channel cross-section examples **(a)** Q_{100} water surface profile at cross-section (30 m) with water level at 1161.40 m, **(b)** Q_{500} water surface profile at cross-section (30 m) with water level at 1161.59 m, **(c)** Q_{100} water surface profile at cross-section (540 m) with water level at 1170.65 m, **(d)** Q_{500} water surface profile at cross-section (540 m) with water level at 1170.78 m.

With the generated flood inundation map (Figure 8), it was determined that the entire village road, approximately 50 houses and a significant portion of agricultural lands are at risk of flooding. Considering the economic losses caused by past floods (Figure 3(b) and (c)), it is evident that rehabilitation of this stream is essential. For this reason, the flood simulation was rerun with channel dimensions designed for the same discharge.

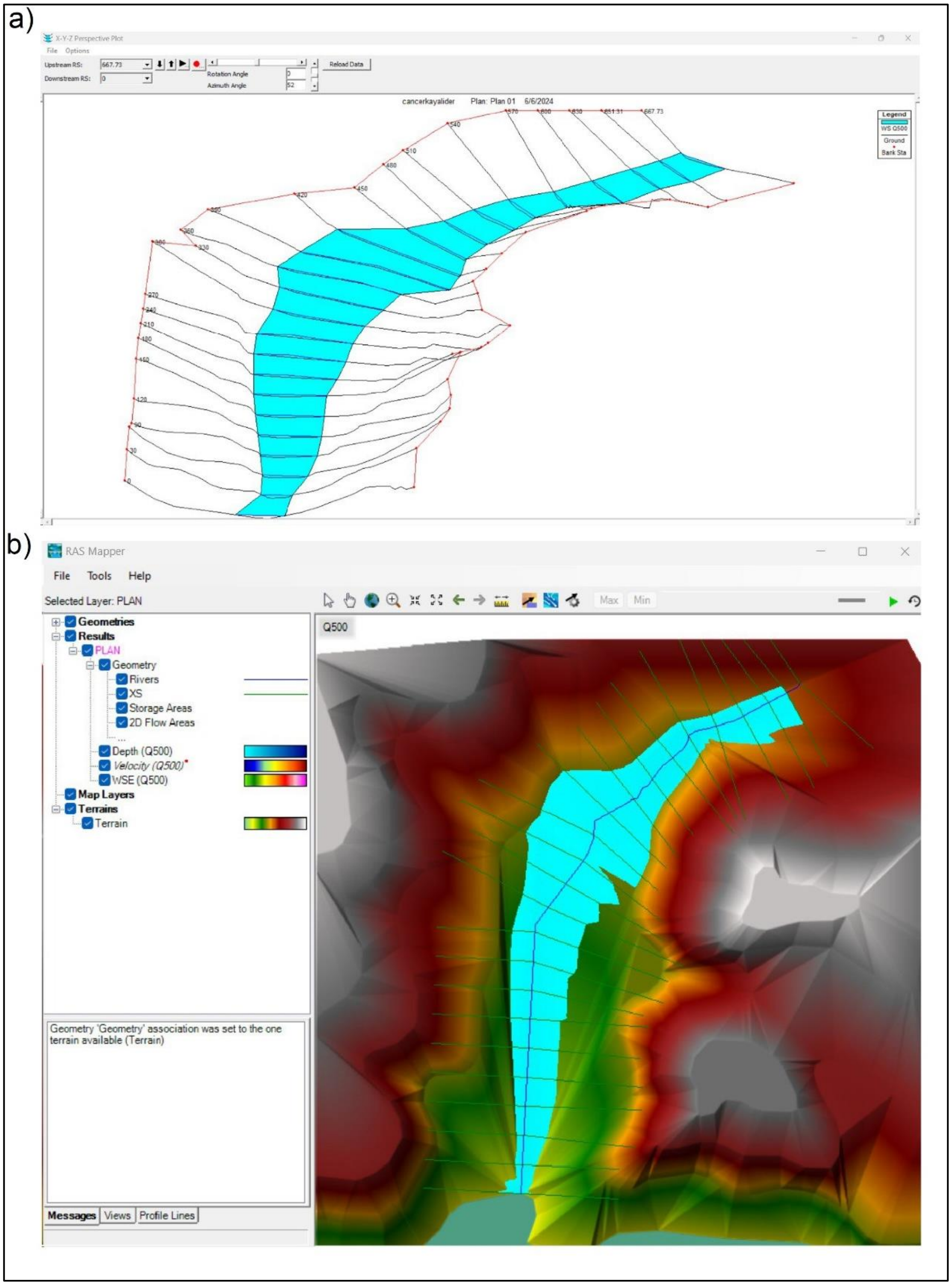

Figure 7. (a) Q_{500} water surface profile created with HEC-RAS, plan view, **(b)** RAS mapper view

The rehabilitation design, shown in Figure 9 (a), runs parallel to the road alignment. A site visit was conducted to determine the channel design route, revealing that the minimum cross-section width within the settlement area is 10.5 m (Figure 9 (c)) and the culvert cross-section on the railway line at the continuation of the road is 8 m wide and 3.5 m high (Figure 9 (b)). Since the culvert can easily convey the flood recurrence discharge, no additional dimensioning was performed for the culvert. As a part of the proposed rehabilitation work, a trapezoidal cross-section lined channel design (3.5 m bottom width, 3 m height) shown in Figure 9 (a) was recommended. For the concrete channel, a roughness coefficient of 0.016 was used. The hydraulic modeling based on the proposed cross-sectional dimensions was found sufficient to prevent flood risks. For the Q_{500} flood discharge, the maximum water level in the proposed channel cross-sections was calculated as 2.6 m (Figure 10 (a) and (b)).

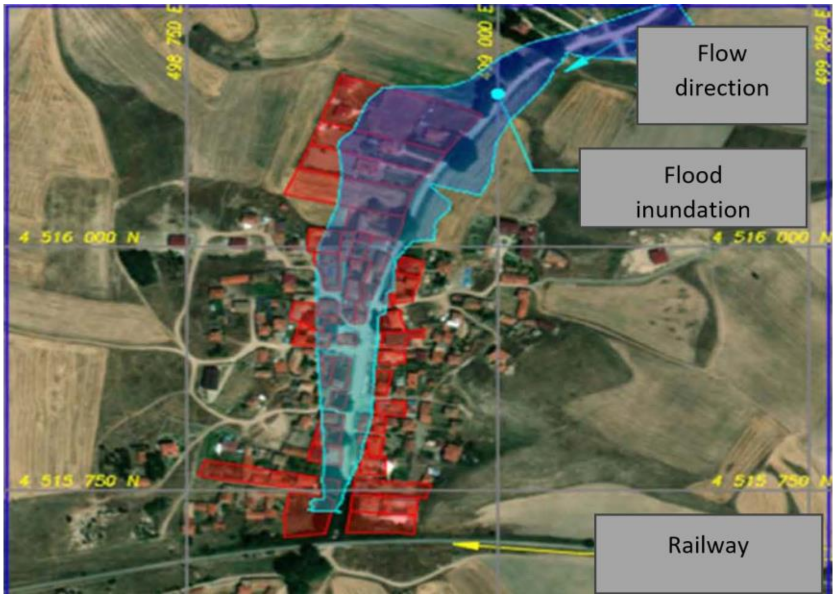

Figure 8. Flood inundation map for Q_{500} and affected settlements in Karamustafa village

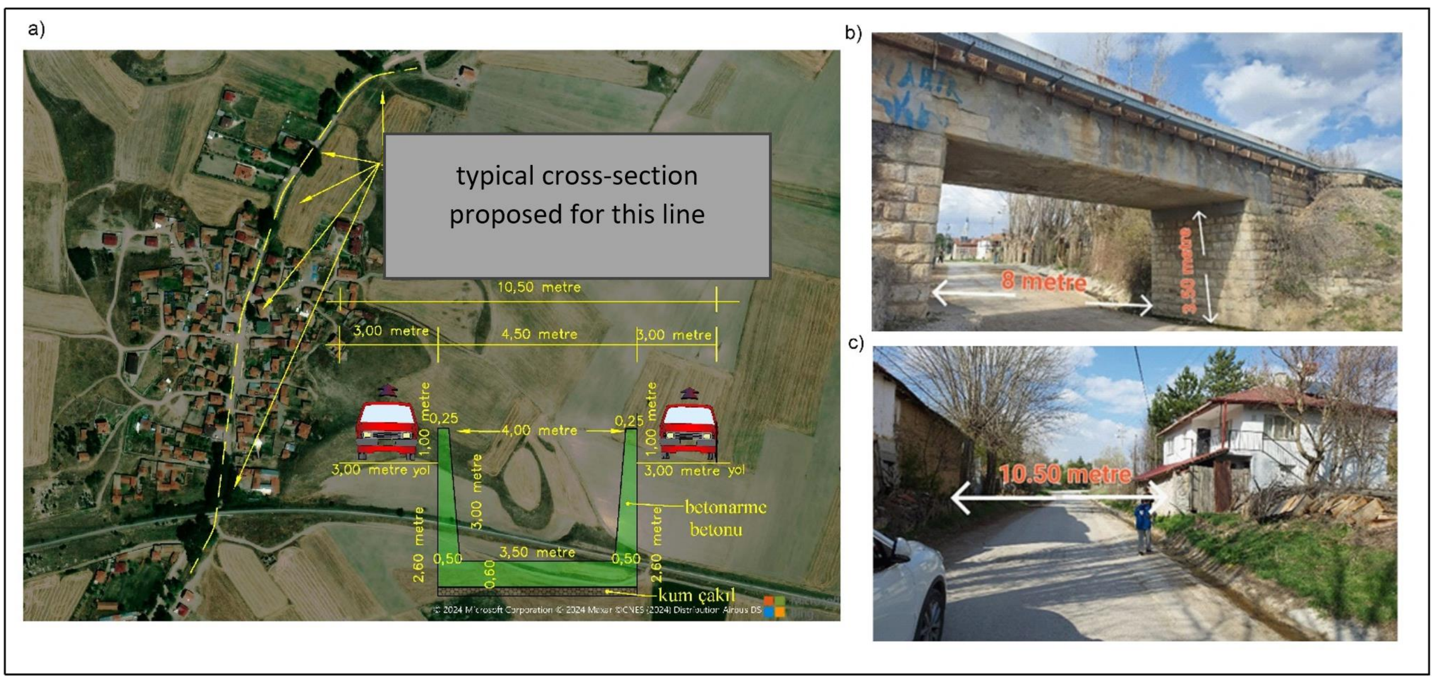

Figure 9. (a) Plan view of the designed channel, **(b)** railway culvert dimensions, **(c)** minimum road width

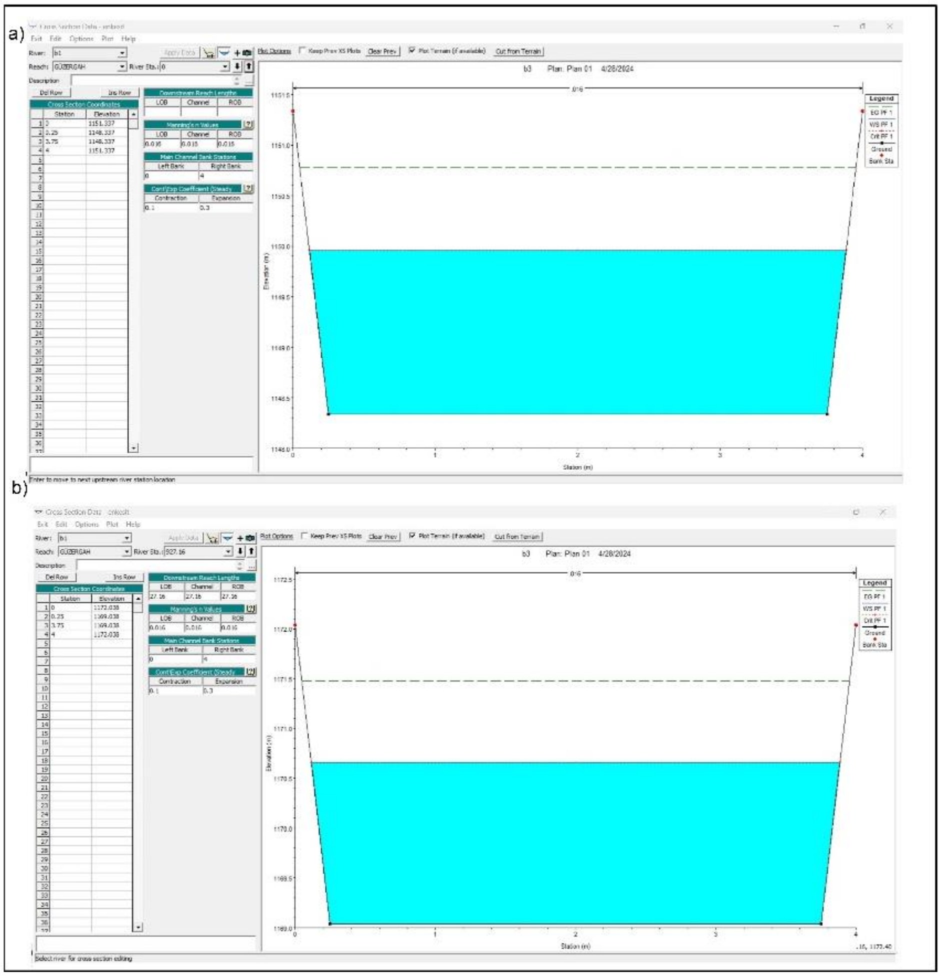

Figure 10. Cross-section view of the designed channel and flood level **(a)** upstream **(b)** downstream

4. Discussion and Conclusion

In this study, flood inundation maps for a 500-year recurrence interval flood were generated for Karamustafa Village in Çankırı-Çerkeş District, both before and after stream rehabilitation. Using the Non-Superposed Mockus Method, flood peaks were calculated, and the water surface profiles were determined with the HEC-RAS software. The development of flood inundation maps utilized HEC-RAS and Civil-3D programs. The identification of flood-prone areas revealed that structures in these regions face significant flood risks. Based on current conditions and incorporating GIS data, it was observed that 50 houses in Karamustafa Village were flooded and substantial agricultural land was affected during the 500-year recurrence interval flood. For this flood, the water level was calculated as 1.02 m and the flood inundation area was 35864.5 m². These findings are consistent with the impacts of past floods, such as those on July 5, 2019 and June 7, 2022. Simulations using the proposed concrete trapezoidal channel cross-section showed that Karamustafa Village was not affected by the 500-year flood discharge. However, estimating "n" values can influence the accuracy and reliability of results. This uncertainty poses risks in hydraulic calculations and flood modeling. Future studies should aim to use calibrated local data to achieve more accurate "n" values, leading to more reliable results. When determining the flood calculation method for a basin, rainfall amounts, flow measurements and the basin's characteristics must be carefully identified. Parameters such as basin size and drainage slope are critical in selecting the appropriate method. The Mockus Method, used in this study, is preferred for its practicality and ease of hydrograph generation. Applying this method in areas with a time of concentration of 3 hours or less and smaller drainage areas ensures more consistent results. Including basin slope and other specific coefficients further enhances result precision and helps avoid overestimations. Flood inundation maps are vital for water resource management and urban planning. For this region, using updated data and optimized channel cross-sections is critical in preventing potential flood-related loss of life and property in the future.

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