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# Application of the Monte Carlo Method to Determine of Evacuation Parameters from Settlements

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***Abstract*— This paper examines a potential application of the Monte Carlo method for estimating the number of people subject to evacuation during floods. Software for the simulation modelling of water disasters is utilized. The proposed method can also be applied to other crisis situations, supporting the planning of response activities and the allocation of necessary resources.**

***Keywords*— crisis, evacuation, simulation modelling.**

## INTRODUCTION

Examining the Bayesian approach to risk assessment reveals that the primary methods for risk management involve reducing the probability of a hazardous event occurring and mitigating the resulting damages. When considering large-scale crises—particularly from the perspective of planning response activities by the responsible authorities—the primary practical objective is minimizing the consequences. One of the main measures in this regard is the evacuation of people from endangered areas. Evacuation, in turn, can be preventive, or it can occur during and after the onset of the crisis. Each of these types has its own specifics and characteristics, which depend on the type of crisis, the size of the endangered areas, and the propagation time of the hazard.

This paper addresses a flood-type crisis caused by a dam failure. Depending on the size of the dam, this is most often a local or regional crisis that can threaten up to several populated areas. The characteristics of the crisis indicate that the required evacuation is more likely to occur concurrently with the crisis rather than preventively. For this type of evacuation, the most critical factors are the response time and the number of endangered people who must be evacuated. The purpose of this study is to verify the feasibility of determining precisely these factors through crisis modelling. For this purpose, the HEC-RAS software package is used [1].

## CRISIS SIMULATION

For the purposes of the study, a relatively large dam with a volume of approximately 80 million m³ was selected. A map featuring a Digital Terrain Model (DTM) with a 5 x 5 m resolution was obtained from the Military Geographic Service. Files necessary for accurately determining global projections are available at http://spatialreference.org/. This information is provided free of charge. Furthermore, a land cover map for the entire continent with a resolution of 100 x 100 m, developed under a European Commission project, can be accessed at:

https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/land-cover.

This data is required to determine the hydraulic resistance (roughness) of the earth's surface within the crisis zone.

Figure 1 illustrates the terrain and dam model used for the current study. It is assumed that the event occurs at 00:00 on April 20th, and the dam wall breaches within 30 minutes, as depicted in Figure 2. In this figure, the gray area represents the dam wall, the dark gray line indicates the terrain elevation in this section, and the trapezoidal line denotes the final stage of the breach.

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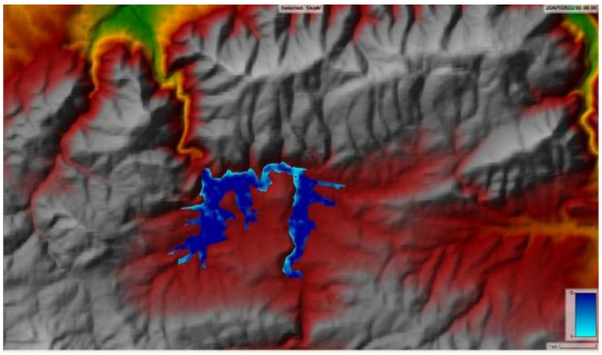

Fig. 1. Dam and terrain model.

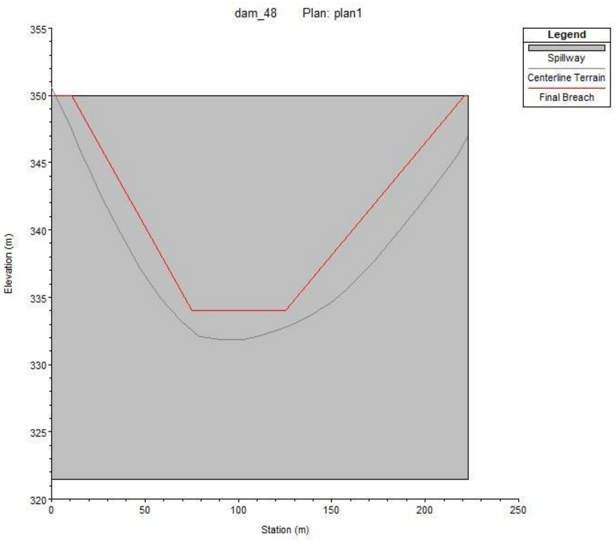


Fig. 2. Dam failure.

The HEC-RAS package utilizes a finite element approach for inundation modelling, dividing the area into cells of user-defined dimensions [2]. At a specified time step, it calculates the processes occurring within each individual cell based on the conditions of its neighbouring cells. For the purposes of this study, a cell size of 10 x 10 m and a time step of 1 second were selected. Figure 3 illustrates the inundation extent generated by the simulation within the first 24 hours following the onset of the crisis.

Along its path, the water passes through a tourist site situated at the foot of the mountain, as well as through several populated areas. The software package allows users to visualize the water level dynamics at any selected point during the simulation. Figures 4 and 5 depict the state of the tourist site before and after the flood, with an accompanying graph showing the variation of the water level over time.

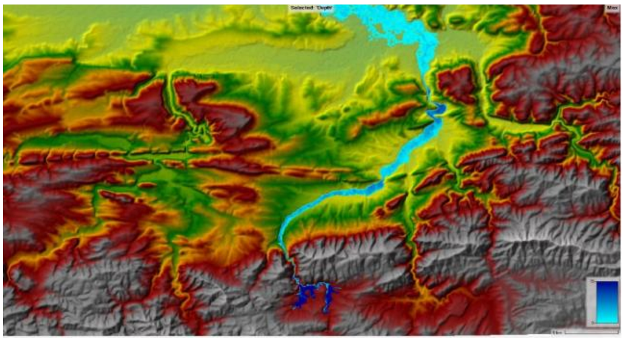

Fig. 3. Flood extent within the first 24 hours.

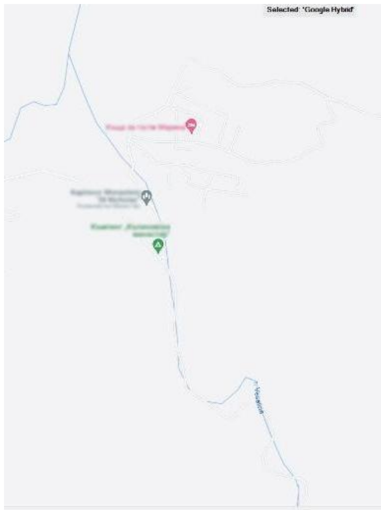

Fig. 4. Tourist site before the flood.

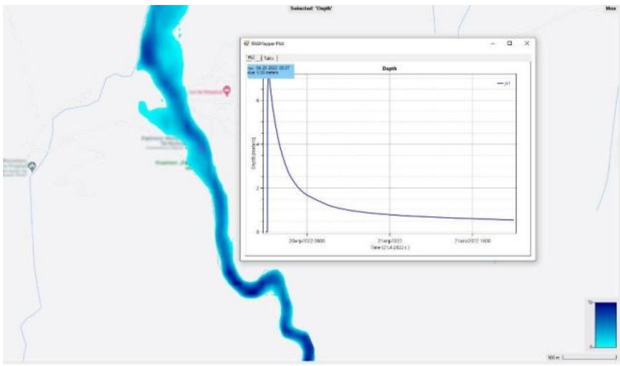

Fig. 5. Tourist site after the flood.

The graph in Figure 5 indicates that the flood wave will reach this location 27 minutes after the onset of the crisis, and its height will be approximately 7 m. On the one hand, 27 minutes is insufficient to organize an evacuation for the visitors and staff at the tourist site; on the other hand, since the inundation zone is relatively narrow, each individual could independently exit the endangered area, even on foot. However, this can only occur if they are alerted to the crisis in a timely manner. In other words, efforts here should be directed toward ensuring a timely and reliable early warning for the occupants at any time of the day or night.

To illustrate the simulation results and the possibilities for determining the factors for evacuation planning, two populated areas along the inundation path are presented. Figure 6 shows the boundaries of the populated zone (black line) for Settlement 1, as well as a graph depicting the water level dynamics.

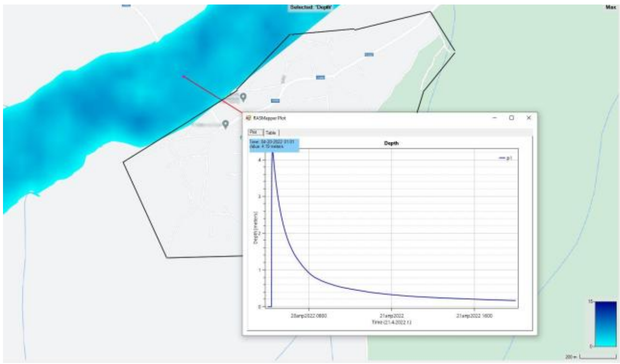


Fig. 6. Settlement 1 during the flood.

It is evident that the height of the flood wave here will be approximately 4.5 m, with an arrival time of 1 hour. Here too, the response time is short, but the residential area is only marginally affected by the flood. As with the tourist site, efforts should be directed toward alerting the people living along the riverbank and in the lower-lying areas. Local authorities and law enforcement agencies should plan to assist in the evacuation of individuals with limited mobility from the endangered areas.

Figure 7 presents the condition of Settlement 2 during the flood. Once again, the populated zone is outlined by a black line. The graph indicates that in the lower section, the water level will reach 2.5 m, which will occur 6 hours and 39 minutes after the onset of the crisis. It is evident that a significant portion of the residential area here will be endangered; however, the available response time is sufficient to prevent casualties, provided that a well-planned evacuation of the population is conducted.

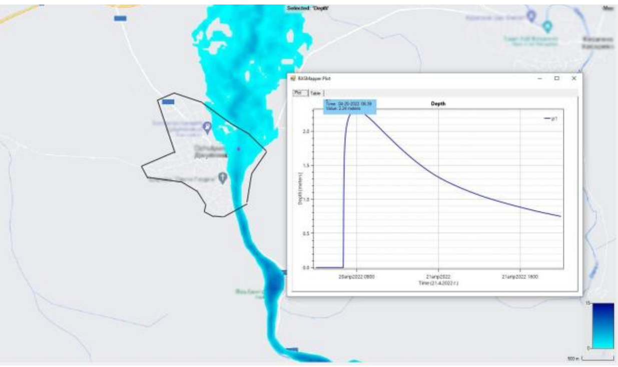


Fig. 7. Settlement 2 during the flood.

## EVALUATION OF EVACUATION PARAMETERS

Information regarding the number of residents in the populated areas can be obtained from official sources (e.g., the National Statistical Institute). It remains to determine the number of people living in the endangered zone. The settlement is of a "village" type, where people live in houses with yards. An assumption is made that the population density is relatively uniformly distributed across the area of the settlement. This allows for an approximate estimation of the number of endangered people by comparing the area of the settlement with that of the flooded section. Using modern GIS systems, the area of specific sections of the earth's surface can be determined with high precision; however, the software used for the simulation does not support these functions. Therefore, the Monte Carlo method was utilized to solve this problem [3].

In a separate image (Fig. 8), the territory of the settlement is outlined and colored yellow, while the endangered zone is colored blue.

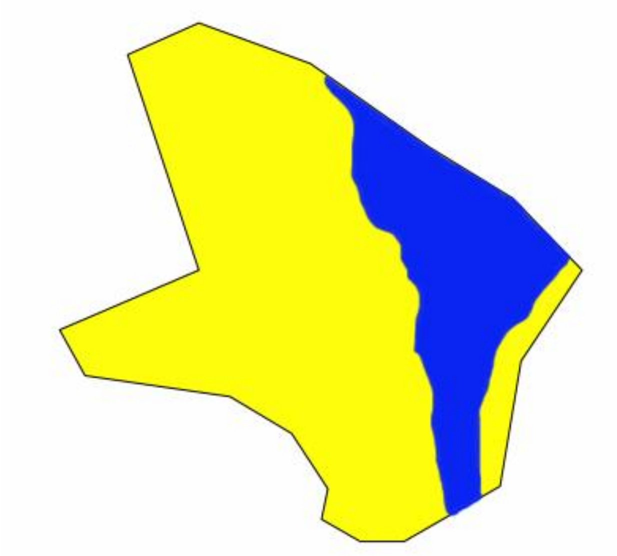

Fig. 8. Settlement area (yellow) and endangered zone (blue)

Using a script developed in Python, 1,000 points with random coordinates were generated within the image, followed by a count of the points falling into each of the colored zones. This procedure was executed 10 times. The averaged results are presented in Table 1.

TABLE 1: NUMBER OF POINTS

| Zone color | Number of points |
|---|---|
| White – outside the settlement | 605 |
| Yellow – settlement | 291 |
| Blue – endangered zone | 104 |

Figure 9 illustrates the points from one of the executions of the Monte Carlo procedure.

The total area of the settlement encompasses both the blue and yellow zones; therefore, a total of 395 points fell within this combined area. The ratio of the number of points located in the endangered zone to the total number of points in the settlement area provides an estimate of the ratio between the two areas.

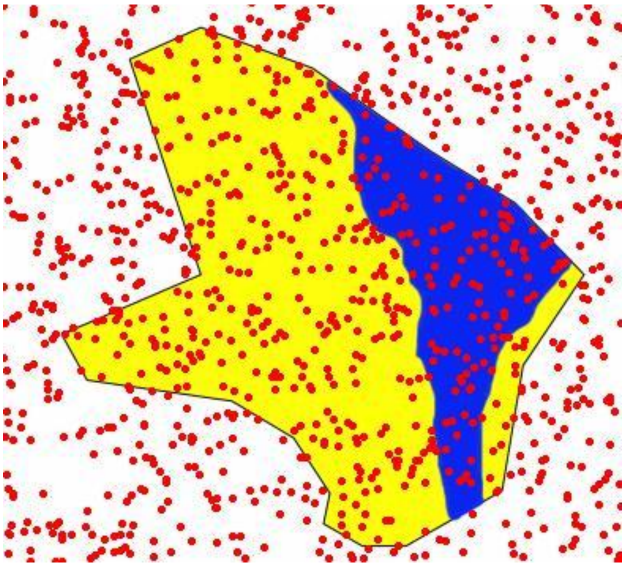

Fig. 9. Settlement area and endangered zone with 1,000 random points.

$$R = \frac{S_{flood}}{S_{village}} \cong \frac{N_{blue}}{N_{blue}+N_{yellow}}, \quad (1)$$

...where R is the ratio between the two areas;

$S_{flood}$ – area of the endangered zone;

$S_{village}$ – area of the settlement;

$N_{blue}$ – number of points located within the blue zone;

$N_{yellow}$ – number of points located within the yellow zone.

Calculated according to the formula using the numerical data from Table 1, the result is **R = 0.263**, or expressed as a percentage, **R = 26.3%**. This means that the endangered zone covers 26.3% of the settlement's total area.

Let assume that 3,000 people live here. Based on the assumption of a uniform population density distribution, we can calculate 26.3% of 3,000, which equals 789 individuals. This serves as an estimate for the number of people endangered by the flood who are potentially subject to evacuation.

The assumptions made work well for small settlements, where the housing stock predominantly consists of houses and low-rise buildings. For larger cities, a similar approach can be applied by dividing them into neighbourhoods with relatively homogeneous housing types, or in other words, with a relatively uniform population density. Furthermore, evacuation planning should account for the concentration of people in various areas of the settlement at different times of the day.

The overall results of investigating the feasibility of determining the factors necessary for the proper planning of civilian evacuation from populated areas through crisis simulation modelling are presented in Table 2.

TABLE 2. RESULTS

| Location | Total Population | Endangered Area | People to Evacuate | Available Response Time |
|---|---|---|---|---|
| Tourist site | 500 | 93% | 465 | 27 min. |
| Settl. 1 | 4500 | 2.5% | 113 | 1 h. |
| Settl. 2 | 3000 | 26.3% | 789 | 6 h. 39 min. |

## CONCLUSIONS AND FUTURE WORK

Based on the conducted research, the following conclusions can be drawn:

Modern software technologies enable the creation of models for various crisis situations with a relatively high degree of accuracy. Through these models, endangered areas can be identified, along with the threat arrival times at various settlements.

Various assumptions were utilized in the present study, which could be bypassed given precise data regarding the respective simulation elements. In this manner, the data required for planning evacuation operations can be obtained—if not to the exact individual, then at least to the correct order of magnitude. This enables the planning of necessary resources and activities tailored to both the available time and the number of people requiring evacuation.

The current study demonstrates that the simulation modelling of various types of crises can and should serve as the foundation for local governments and relevant authorities in drafting contingency plans regarding the resources and actions required for crisis response.

In this paper, the authors propose a methodology based on free software and well-established scientific methods, which can be applied to solve problems related to crisis planning and management. Despite the expected large margin of error, the obtained results can serve as a basis for planning the necessary resources, equipment, and activities required to rescue people from populated areas and regions threatened by disasters.

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