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Effect of Breach Parameters and Progression Curves on Dam Failure Hydrograph

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Abstract

Understanding the failure mechanisms of embankment dams due to overtopping is vital for flood protection, covering planning, design, and flood defence zone management. Typically, dam failure-induced flood wave propagation is modeled in 1D using Saint-Venant's equations. The breach itself is often simplified as a trapezoid defined by its final height, average width, side slopes, and the time required for complete formation. Often overlooked is the dynamic process of breach formation and its correlation with the outflow hydrograph during dam failure. This research scrutinizes the impact of breach parameters and progression curves on the outflow hydrograph. Two approaches were formulated: one crafting new equations for average breach width and formation time using global dam failure data and regression analysis, and the other employing these equations in 2D HEC-RAS dam failure modeling, comparing them with literature recommendations. The derived equations yield results similar to those in the literature. This study introduces a novel aspect by examining the mutual influence of results and floodplain areas on the outflow hydrograph, offering a comprehensive perspective on dam failure dynamics and its hydraulic consequences.

Keywords: Dam Break Analysis; Breach Parameters; Breach Progression Curve; Overtopping; 2D HEC-RAS Model.

1. Introduction

The failure of dams has significant implications for both human communities and the environment. Overtopping stands out as a predominant cause, accounting for approximately 48% of dam collapses, as confirmed by the International Commission on Large Dams. This problem is observed in about one-third of dam failures globally [1, 2]. Earth- or rock-fill dams represent the most widespread types of dams worldwide. Comprehensive studies on dam failures, mapping flood-affected regions, and evaluating risks in vulnerable areas are pivotal for comprehending the far-reaching consequences of dam failures [2].

In the event of a dam breach, there is practically insufficient time to warn people living near the dam of the danger [3]. Dam failure releases a substantial volume of water downstream, leading to potential loss of life, property destruction, and environmental degradation [3]. Studying the dam breach process is crucial for designing flood risk management plans, issuing flood warnings, and facilitating evacuation procedures. Areas downstream of the dam may be marked as vulnerable, allowing for the definition of hazard zones [4]. Knowledge of these flood-prone areas aids in the development of evacuation plans. Various models or software, with HEC-RAS being the most commonly used, are typically employed for floodplain delineation. HEC-RAS, developed by the Hydrologic Engineering Centre (HEC) of the U.S. Army Corps of Engineers in 1981, is widely utilized for this purpose [5, 6].

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Many researchers focus on modeling the spread of a flood wave resulting from dam failure using both 1D and, increasingly, 2D models [6–8]. For instance, in 2023, Jiang et al. [9] modeled the flood wave after the Pingshuijiang dam collapse in southeastern China using a 2D HEC-RAS model. The results of this study suggest that, due to the gradual dam failure, there is a possibility of evacuating the population within 45 minutes. Additionally, many researchers have studied the process of breach formation itself and the definition of its parameters.

Fread & Harbaugh [10] addressed the dam failure issue in 1973, developing an empirical model based on historical data and providing equations for calculating the average breach width and formation time. Similar equations were later proposed by researchers such as VonThun & Gillette (1990) [11] and MacDonald & Langride-Menopolis (1984) [12] for cases of overflow and seepage through the dam. Froehlich (2008) [6] derived an equation for calculating the average breach width and formation time, which has proven to be one of the most commonly used and recommended in the literature [13–16]. Ashraf et al. (2018) developed new equations for calculating breach width and formation time using regression analysis based on 126 historical data points for seepage through the dam. These equations were experimentally validated, and the results showed strong agreement with the experimental findings.

In all mentioned studies, breach width and formation time depend on dam height and reservoir volume. Most researchers assume instantaneous dam failure without considering the dynamics of breach formation. Linear and sinusoidal models of the breach progression curve are commonly recommended in the literature and in the HEC-RAS program. The choice of equations for calculating breach parameters and the progression curve shape undoubtedly influence the results. For example, in a study on flood wave propagation in a semi-arid area due to dam overtopping failure, Karim et al. (2021) [2] used a sinusoidal progression curve and Froehlich's equation for breach parameter calculation. The question arises about how much the progression curve shape affects the output hydrograph during dam overflow compared to the equations for calculating average breach width and formation time.

Based on the aforementioned, the main goal of this research is to validate the output hydrograph of a flood wave using different equations for calculating breach parameters recommended in the literature, coupled with various progression curves. The case study involves the Medjedja dam in Bosnia and Herzegovina. As an additional verification, the total floodplain areas downstream of the dam over a length of approximately 3.50 km were analyzed. An advantageous aspect of this study is that it focuses on the overflow case of a homogeneous earthen dam, for which data for the Medjedja dam were available. Historical dam failure data, isolating 79 instances related to dam failure due to overflow, was used in this study to create new equations for calculating the average breach width and formation time. In addition to the newly created equations, the validity of the results was checked against other equations recommended in the literature [6, 12]. For all equations, different forms of progression curves were employed, including linear, sinusoidal, quadratic polynomials, and a custom-defined progression curve (see Equation 12). The progression curve proposed by the authors of the paper represents a curve positioned between a sinusoidal and quadratic shape, aiming to further demonstrate the influence of the progression curve on the output hydrograph. The subsequent sections of the paper present the obtained research results.

2. Research Methodology

Modeling dam failures in the HEC-RAS program necessitates the collection of relevant data about the dam itself, a digital elevation model (DEM), downstream land use and purpose, hydrological characteristics, and the like. Challenges arise in cases of insufficient data. In this research, alongside data collection for the HEC-RAS model, historical dam failure data worldwide was processed to formulate new equations for calculating the average breach width and breach formation time in the case of overtopping from an earth-fill homogeneous dam. Various breach progression curves and equations for breach parameters were employed in the modeling, assessing the influence of the breach progression curves and breach parameters on the output hydrograph. The methodological approach to the research is schematically presented in the following:

2.1. Medjedja Dam and Reservoir

Medjedja is a homogeneous embankment dam, standing at an overall height of 28 meters. Constructed in 1984 to cater to the needs of the Omarska mine, it is situated in northern Bosnia and Herzegovina on the Gradina River, a left tributary of the Gomjenica River. The Gomjenica River, in its course, converges with the Sana River near the town of Prijedor. The exact coordinates of the Medjedja dam are a geographic latitude of (44°50'48.36" N) and a geographic longitude of (16°54'40.86" E). It is located approximately 22 km west of Prijedor and about 24 km east of Banja Luka. The accompanying Figure 2 depicts the precise location of the Medjedja dam.

On the right side of the dam, there is an overflow structure made of conventional concrete with a capacity of 100 m^3/s, serving for the controlled release of large volumes of water. The fundamental characteristics of the Medjedja dam and reservoir are outlined in Table 1. The cross-section of the Medjedja dam is illustrated in Figure 3.

Table 1. Dam main parameters

Parameter	Value
Dam height	28.0 m
Width crest	8.0 m
Crest level	202.0 m
Crest length	485.0 m
Reservoir volume at the crest	$8 \times 10^6\ m^3$

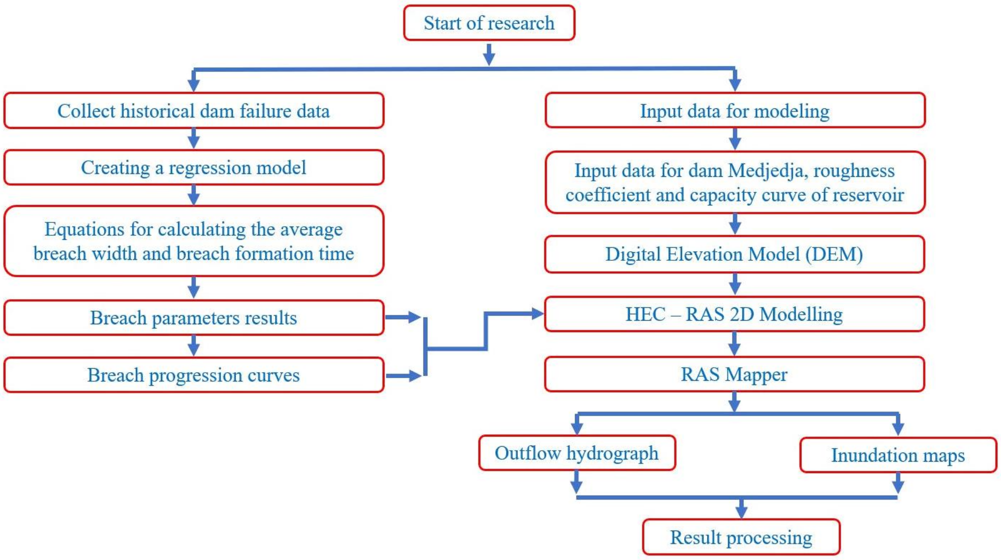

Figure 1. Flowchart of the methodology

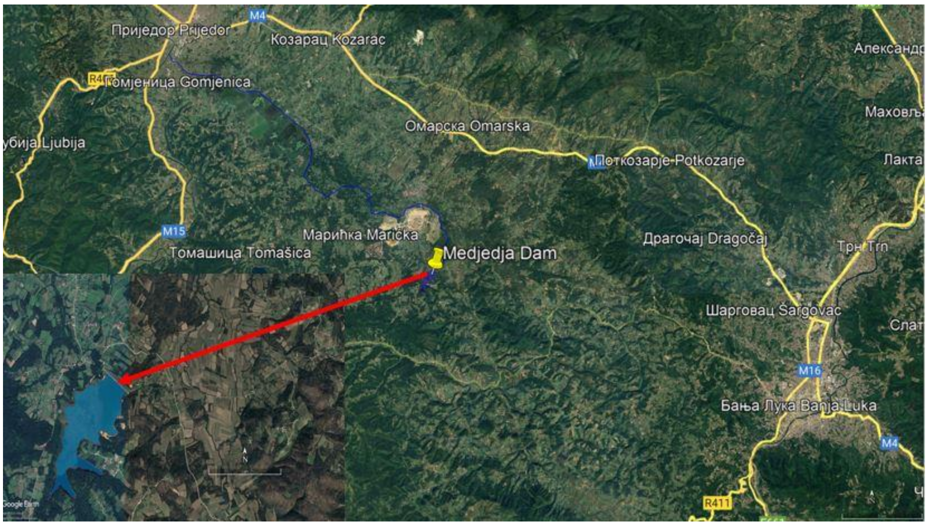

Figure 2. Location of the Medjedja dam

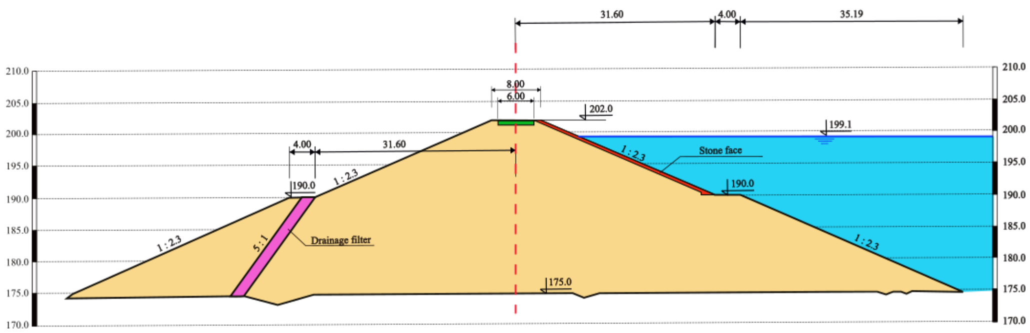

Figure 3. Dam cross section

The Omarska mine, together with various facilities, is located downstream of the dam. Water from the reservoir is transported to the mine site for industrial purposes. Downstream, the analyzed area is 3.50 km long and covers an area of 5.0 km^2. The capacity curve of reservoir is illustrated in the following Figure 4.

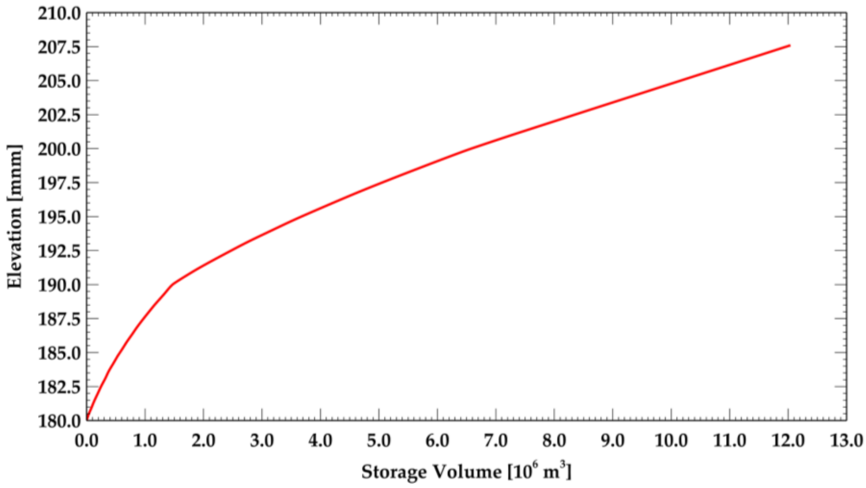

Figure 4. Capacity curve of reservoir dam Medjedja

2.2. Breach Parameters Estimation

Typically, breach parameter estimation relies on empirical equations and the specific characteristics of the dam [2, 12, 16]. The breach shape is commonly modeled as a trapezoid, with key geometric parameters including the width of the breach bottom, breach depth, and side slope. The trapezoidal form of the breach is depicted in Figure 5.

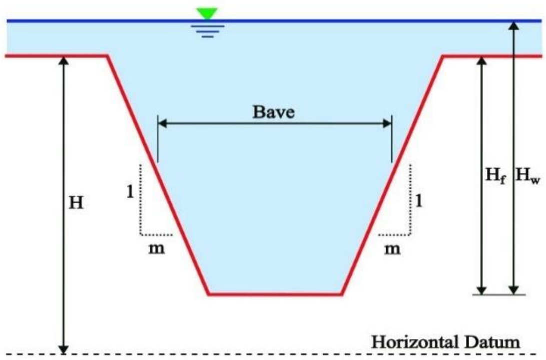

Figure 5. Example sketch of trapezoidal breach cross-section

Several empirical equations are utilized for several variables associated with dam break. In this research, the dam breach estimation was done based on the following equations [3, 10 15]:

Froehlich (2008) [6]:

$$B_{ave} = 0.27 \cdot K_o V_w^{0.32} \cdot H_f^{0.04} \tag{1}$$

$$T_f = 0.0176 \cdot (V_w / gH^2)^{0.5} \tag{2}$$

where B_{ave} is average breach width (m) (Figure 3), K_o is constant (1.30 for overtopping failures), V_w is reservoir volume at time of failure (10^6 m^3), H_f is height of the final breach (m), (Figure 3), g is gravitational acceleration (m/s), T_f is breach formation time (h), H is dam height.

Von Thun & Gillette (1990) [11]:

$$B_{ave} = 2.50 \cdot H_w + C_b \tag{3}$$

$$T_f = 0.015 \cdot h_w \tag{4}$$

where H_w is depth of water above the bottom of the breach (m) (Figure 3), C_b is coefficient, which is a function of reservoir size, in this study it used C_b = 54.9.

MacDonald & Langridge-Menopolis (1984) [12]:

$$W_b = \frac{V_{eroded} - H_f^2 \cdot (C \cdot m + H_f m Z_3/3)}{H_f (C + H_f Z_3/2)} \tag{5}$$

$$V_{eroded} = 0.00348 \cdot (V_w \cdot H_w)^{0.852} \tag{6}$$

$$T_f = 0.0179 \cdot V_{eroded}^{0.364} \tag{7}$$

where V_{eroded} is volume of material eroded form the dam embankment (m^3), W_b is bottom width of the breach (m), C is crest width of the top of dam (m), $Z_3 = Z_1 + Z_2$, Z_1 – average slop (Z_1:1) of the upstream face of dam, Z_2 is average slop (Z_2:1) of the downstream face of dam, m is side slopes of the breach (1 : m).

In addition to the equations presented as recommendations from the literature, this study, based on historical data of 1443 collapsed dams worldwide published by Zhang et al. (2009) [13], isolated only those data related to the failure of earth-fill dams due to overtopping. In the end, a total of 79 data points were available, upon which a regression analysis was conducted. The regression analysis involved selecting variables that could lead to a robust regression model for calculating the average width of the breach and the time of breach formation. The primary objective was to formulate a simple regression model that would best fit the observed historical data. Based on this, the following general form of the regression model was derived:

$$M = a \cdot A_1^b \cdot A_2^c \tag{8}$$

where M is dependent variable, A_i is independent variables, i = 1, 2, a, b, and c is constants.

The selection of parameters for establishing the regression model for calculating the average breach width and breach formation time depended on the extent of the available data. After exploring several combinations of different variables, it was concluded that the best results were achieved when the equation incorporated the height of the final breach and the reservoir volume at the time of failure. By employing a genetic algorithm for defining constants (a, b, c) in equation (8) (using the Generalized Reduced Gradient (GRG) nonlinear method), the following forms of equations for calculating the average breach width and breach formation time were obtained:

$$B_{ave} = 0.60370 \cdot H_f^{0.38421} \cdot V_w^{0.21813} \tag{9}$$

$$T_f = 0.02011 \cdot H_f^{-0.73949} \cdot V_w^{0.34527} \tag{10}$$

The regression model proposed by Ashraf et al. (2018) [1] based on a larger dataset that includes various types of earth-fill dams, differs in that the equations involve parameters, H is dam height, and V is reservoir volume. Ashraf's derived equations have not been compared with equations from the literature, such as the Froehlich (2008) [6] equations, which are considered recommended for use. For these reasons, the equations obtained in this study are compared with the Froehlich (2008) [6] equations. The comparative results are detailed in the results section.

Based on the provided equations for calculating the average breach width and breach formation time, Table 2 presents the computed results for the Medjedja dam.

Table 2. Average breach width and breach formation time for dam Medjedja

Method	Average breach width B [m]	Side Slopes (H:V)	Breach formation time T_f [h]
Froehlich (2008) [6]	42.0	1:1	0.72
Von Thun & Gillette (1990) [11]	109.90	0.5:1	0.69
MacDonald and Langridge-Menopolis (1984) [12]	48.0	0.5:1	0.97
Equations 9 and 10	63.4	1:1	0.49

2.3. Breach Progression Curve

In the literature, various curves are recommended as the shape of the breach progression curve. Different forms of the breach progression curve can be employed for distinct breach parameters [2, 6, 12]. Most models share the initial assumption that the breach progression starts from the top of the dam, and the time zone advances towards the bottom of the dam, forming a trapezoidal shape, as illustrated in Figure 6.

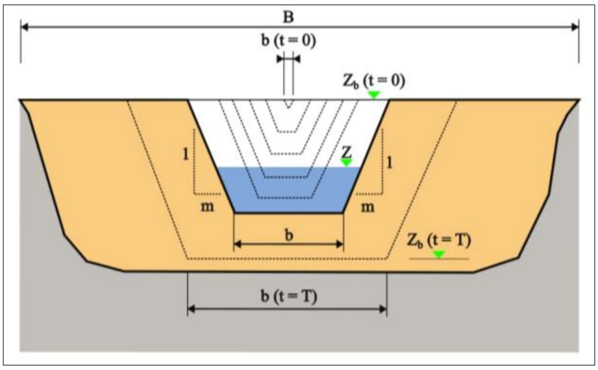

Figure 6. Example of empirical breach formation models

Two curves are available in the HEC-RAS software: a linear curve and a sinusoidal curve. In order to compare the results obtained based on the equations for calculating the width of the breach, various forms of the progression curve were utilized, in addition to the linear and sinusoidal curves [1, 6]. The square polynomial and the equation proposed by the authors of this paper were employed as non-dimensional forms, represented by the following equations:

Square polynomial breach progression curve:

$$b(t)/B_{ave} = [b - b(0)] \cdot (t/T_f)^{a_1} \tag{11}$$

The present study breach progression curve:

$$b(t)/B_{ave} = B_1 \cdot \left(\frac{t}{T_f}\right)^{b_1} + B_2 \cdot \left(\frac{t}{T_f}\right)^{b_2} + B_3 \cdot (t/T_f) \tag{12}$$

where *b(t)* is breach width for duration, B_{ave} is average breach width, calculation used Equations 1, 3, 9, *b(0)* is the initial breach width, t is duration. T_f is the duration of breach development, calculation used Equations 2, 4, 7 and 10, a_1, B_1, B_2, B_3, b_1, b_2, is constants, hears the value amount 2.0, -2.2296, 3.3444, -0.1199, 3.35 and 2.35 respectively. Forms breach progression curve show on Figure 7.

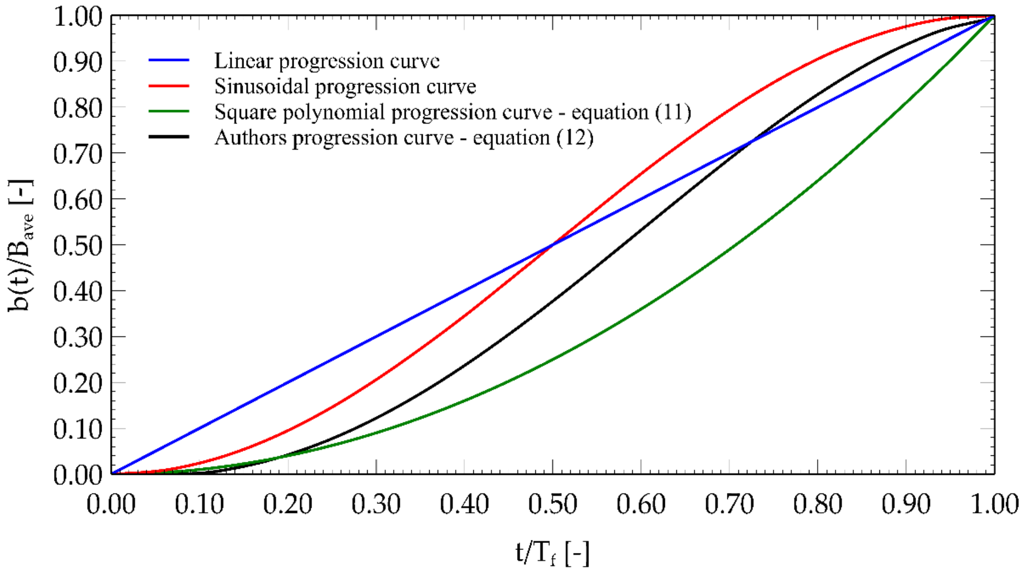

Figure 7. Show of used breach progression curves

2.4. 2D HEC–RAS Model

The flood routing models done in 2D HEC-RAS, using Saint-Venant equations for shallow water equation. The mass conservation and momentum equations [2, 14, 17-20]:

$$\frac{\partial Z}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} + q = 0 \tag{13}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial Z}{\partial x} + \frac{1}{h}\frac{\partial}{\partial x}\left(\vartheta_x h\frac{\partial u}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(\vartheta_y h\frac{\partial u}{\partial y}\right) - c_f u + \frac{\tau_{s,x}}{\rho h} \tag{14}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial Z}{\partial x} + \frac{1}{h}\frac{\partial}{\partial x}\left(\vartheta_x h\frac{\partial v}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(\vartheta_y h\frac{\partial v}{\partial y}\right) - c_f v + \frac{\tau_{s,x}}{\rho h} \tag{15}$$

where Z is the water surface elevation ($Z = z_d + h$), z_d is the bottom surface elevation, h is the water depth, u and v are the velocity components in the x and y directions, q is a source/sink flux term, g is the gravitational acceleration, ϑ_x and ϑ_y is the horizontal eddy viscosity coefficients in the x and y directions, c_f is the bottom friction coefficient, and τ_s is the surface wind stress [2].

The stability of calculations in the HEC-RAS software is influenced by the chosen grid dimensions. In this study, a grid size of 20 meters proved to be adequately effective for calculations, given the relatively flat and expansive nature of the floodplains under examination. For the analyzed flood area with grid dimensions of (20×20) meters, a calculation grid comprising a total of 25,563 cells was generated. To establish the calculation timeframe, careful attention was given to the stability condition, specifically the Courant number. This dimensionless parameter, integral to fluid dynamics simulations, plays a crucial role in ensuring stability. To define the time for the calculation, the stability condition according to Courant number:

$$C_r = \frac{V \cdot \Delta t}{\Delta x} \leq 1.0 \tag{16}$$

where C_r is the Courant number, V is the flood wave velocity, Δt is the time step and Δx is the grid cell size.

In addition to ensuring the stability of the numerical model, defining precise initial and boundary conditions, along with Manning's roughness coefficient, is crucial. The initial boundary condition for the dam breach was established using a hydrograph. For the downstream boundary condition, a uniform flow regime was assumed, incorporating a bottom slope value of 0.0012 m/m. The values for Manning's roughness coefficient were determined based on land cover, resulting in coefficients of 0.028, 0.030, and 0.035 for the mean river channel, forested areas, and settlement zones, respectively. These values were selected in accordance with the existing literature [21-24].

3. Results and Discussion

3.1. Result Breach Parameters Estimations

Based on the available data and the formulated Equations 9 and 10 for estimating breach parameters, a comparison was made between the results obtained and those obtained by Froehlich (2008) [6]. The following figure illustrates the calculated medium width of the breach, while Figure 9 depicts the breach formation time.

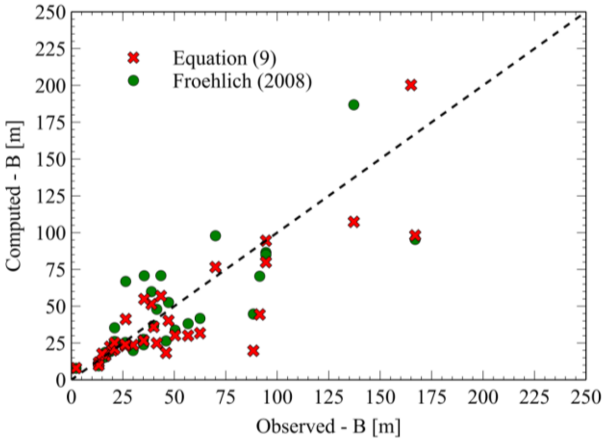

Figure 8. Results comparison between average breach width computed by the derived equation Froehlich (2008) [6] and the Equation 9

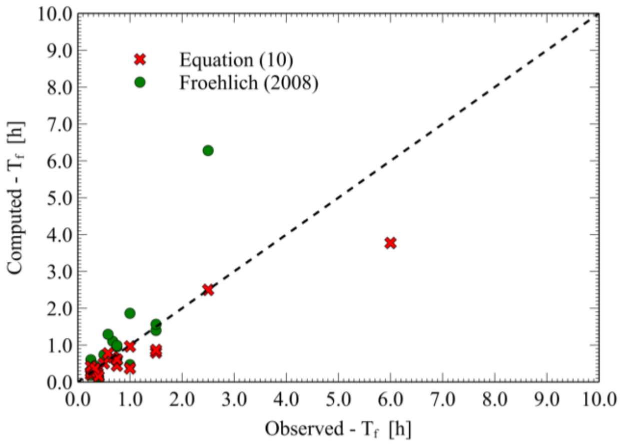

Figure 9. Results comparison between breach formation time computed by the derived equation Froehlich (2008) [6] and the Equation 10

The obtained results are assessed using the mean relative error (ε), coefficient of determination (R^2), and correlation coefficient (r). The results are presented in Table 3.

Table 3. Summary of results

Breach parameter	Average breach width – B_{ave} [m]		Breach formation time – T_f [h]	
Method	Froehlich (2008) [6]	Equation 9	Froehlich (2008) [6]	Equation 10
ε [-]	0.3860	0.3166	0.6005	0.2774
R^2	0.6982	0.7361	0.9694	0.9441
r [-]	0.8356	0.8580	0.9846	0.9716

As evident from the presented results, the Equation 9 formulated for calculating the breach width demonstrates slightly improved results when compared to the results obtained by the Froehlich (2008) Equation [6]. The summarized outcomes exhibit superior performance across all employed agreement indicators, as indicated in Table 3. Regarding the breach formation time, the results favor the Froehlich (2008) Equation [6] over the formulated Equation 10. Equation 10, however, exhibits a lower mean relative error compared to the Froehlich (2008) Equation [6].

3.2. Results Flood Hydrograph

To visualize the results of the output hydrographs, RAS Mapper was used. The output hydrographs are displayed directly on the dam profile during the dam failure simulation. Breach parameters, determined both from literature equations and equations obtained through the regression model in this study, were employed in simulating the Medjedja dam breach, utilizing different breach progression curves. The shape of the output hydrograph varies based on breach parameters and the chosen progression curves, highlighting the significant influence of these factors on the resulting hydrograph. The various forms of output hydrographs for different breach parameters and progression curves are presented in the following Figures 10 and 11.

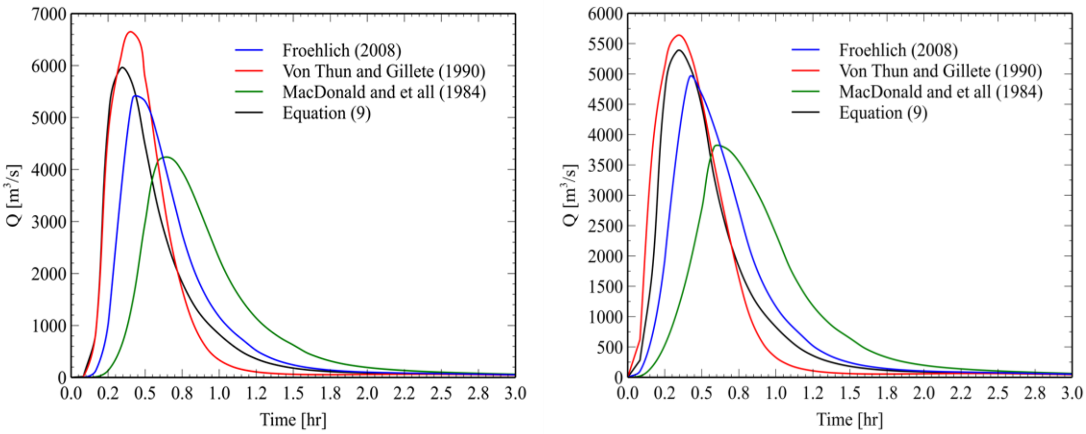

Figure 10. Hydrograph on dam profiles for a sinusoidal (left) and linear (right) breach progression curve

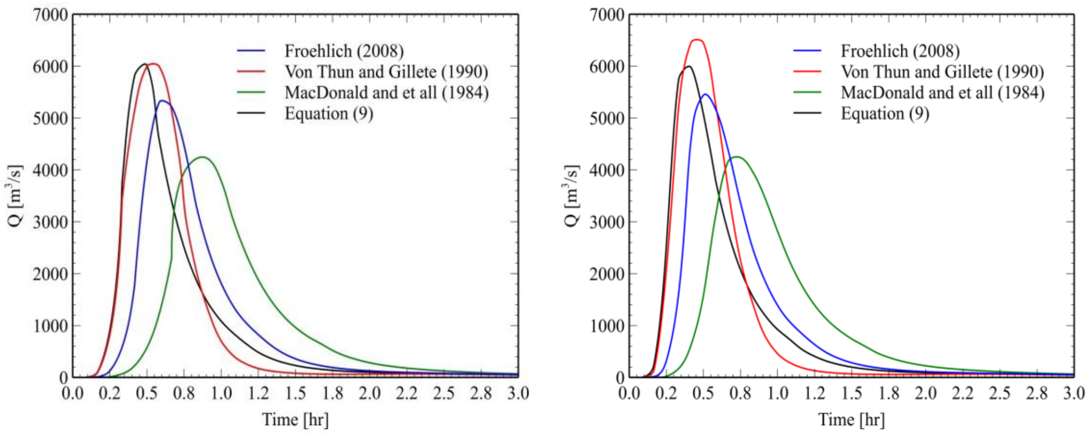

Figure 11. Hydrograph on dam profiles for square polynomial (left) and present study (right) breach progression curve

When examining the shapes of the output hydrographs, it can be observed that, for all breach progression curves, the breach parameters obtained by the regression model exhibit the best alignment with the output hydrograph compared to the VonThun & Gillette (1990) [11] breach parameters. Additionally, this approach yields a higher value for the maximum flow. The Froehlich (2008) [6] equation results in a smaller form of the output hydrograph compared to the breach parameters obtained by the regression model, and significantly smaller when compared to MacDonald & Langride-Menopolis (1984) [12], for all types of breach progression curves.

The maximum flow for breach progression curves is obtained based on VonThun and Gillette (1990) [11], concurrently resulting in the smallest temporal base of the hydrograph. Conversely, the minimum flow value is obtained for MacDonald & Langride-Menopolis (1984) [12], which yields the largest temporal base of the hydrograph. When comparing only the duration of the temporal base according to Froehlich (2008) [6], VonThun & Gillette (1990) [11], and the regression model, the hydrograph base lasts up to 2.0 hours, while for MacDonald & Langride-Menopolis (1984) [12], it extends to 3.0 hours. Notably, the time of occurrence of the maximum flow, according to Froehlich (2008) [6], VonThun & Gillette (1990) [11], and the derived regression model, falls between 0.40 – 0.60 hours for all types of breach progression curves, while for MacDonald & Langride-Menopolis (1984) [12], it occurs around 0.80 hours.

For a better representation of the maximum flow values, the box plot in Figure 12 illustrates the results according to the breach progression curves used.

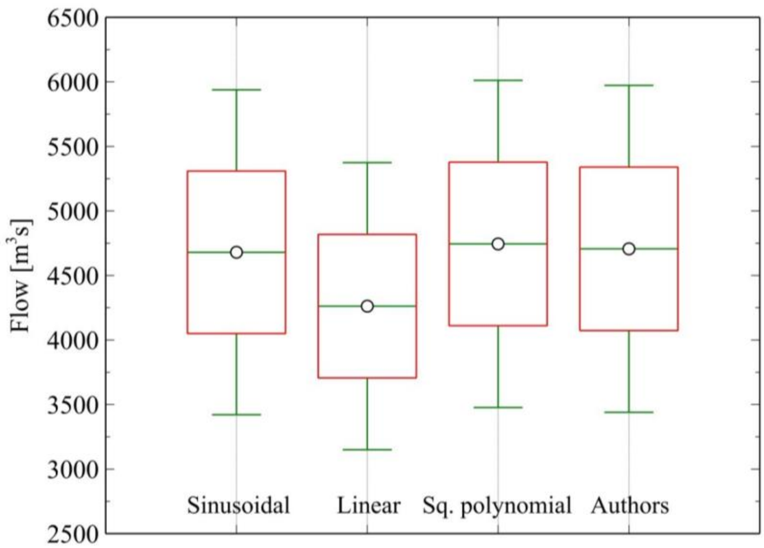

Figure 12. Box plot maximum flows by the breach progression curve

3.3. Results of Inundation Maps

Based on the previously presented results for various average breach widths and different breach progression curves, the flood wave propagation downstream of the Medjedja dam was simulated. The analyzed area covered a length of approximately 3.50 km, with varying values of inundation maps obtained. The following table shows the results of the resulting inundation maps (Table 4).

Table 4. The value of inundation maps in km^2

Method	Sinusoidal	Linear	Square polynomial	Present study
Froehlich (2008) [6]	4.439	4.355	4.443	4.443
Von Thun & Gillette (1990) [11]	4.687	4.534	4.634	4.688
MacDonald & Langridge-Menopolis (1984) [12]	4.227	4.141	4.244	4.232
Equations 9 and 10	4.501	4.439	4.517	4.506

According to the values presented in Table 4, the largest flooded area values are obtained in the case of Von Thun & Gillette (1990) [11] for all types of breach progression curve shapes, as expected, since this scenario corresponds to the largest flood wave volume or maximum flow value. The smallest inundation values occur in the case of MacDonald & Langride-Menopolis (1984) [12]. It's interesting to note that Froehlich (2008) [6] and the derived regression model provide similar values for the downstream flooded area from the Medjedja dam. What is noteworthy is that in the case of a linear model of the breach progression curve, the minimum flow value is obtained, corresponding to the smallest flooded area, while the highest values are obtained for the square polynomial breach progression curve.

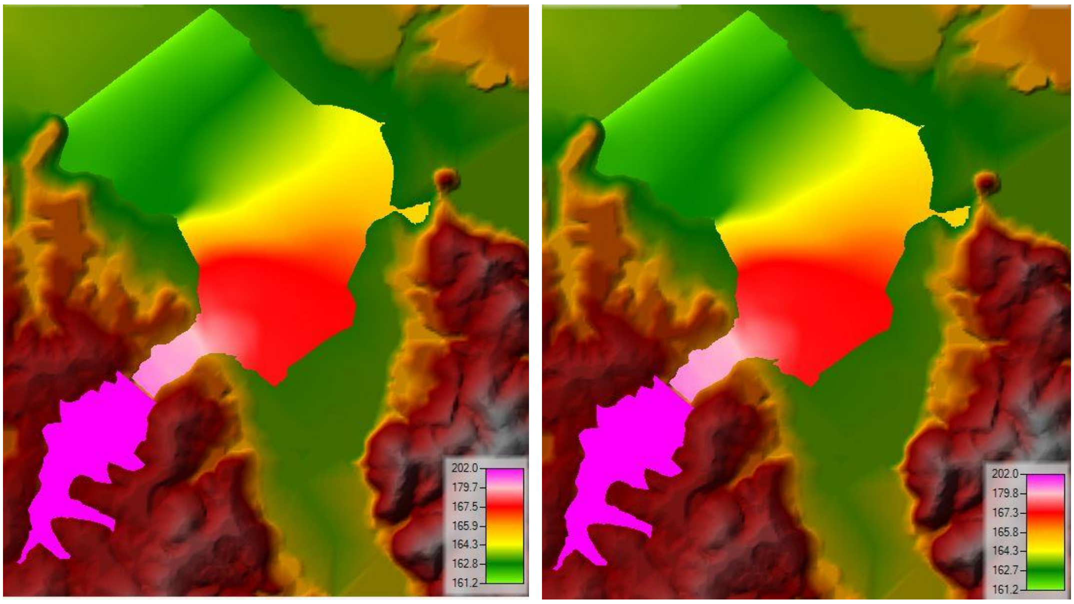

Figure 13. Distribution of water surface elevation for sinusoidal (left) and linear (right) breach progression curve

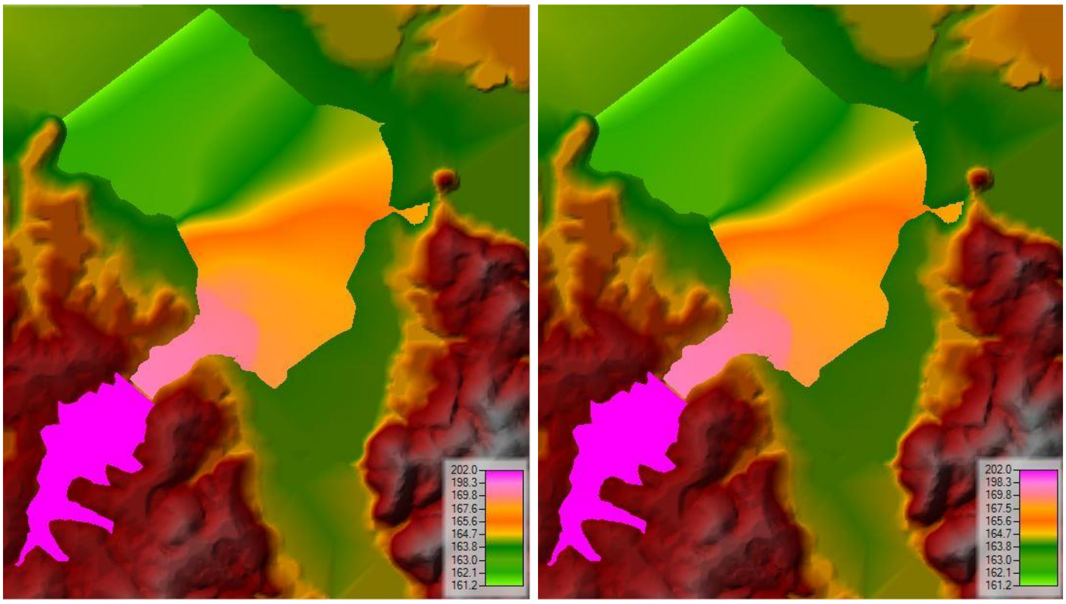

Figure 14. Distribution of water surface elevation for square polynomial (left) and present study (right) breach progression curve

4. Conclusion

The benefits of constructing dams are manifold, but their failure poses significant risks for both people and the environment. The mechanism of dam failure is highly complex and not yet fully understood, relying on assumptions and empirical equations derived from global dam failure data. Numerous researchers have contributed to this field, proposing various equations for calculating breach parameters. This research introduces equations for estimating breach parameters using data from the failures of homogeneous earth-fill dams worldwide, specifically in cases of overtopping, employing a regression model. In addition to the equations for calculating breach parameters, the impact of different breach progression curves on the outcomes, such as the output hydrograph and inundation maps, was examined. To assess the proposed breach parameter equations, the dam failure simulation of the Medjedja dam in Bosnia and Herzegovina was carried out using the 2D HEC-RAS program. The results demonstrate the influence of the breach progression curve on the shape of the output hydrograph and the maximum flow value for various breach parameter values. This study emphasizes the importance of careful consideration of the method used for calculating breach parameters in dam failure simulations to align with realistic conditions. The research findings provide a solid foundation for future investigations into dam failure simulations, especially in assessing the impact for different types of earth-fill dams using various breach progression curves. Thoughtful selection of all necessary input data can enhance the level of safety and enable timely warnings to the population, preparing them for potential evacuation.

5. Declarations

5.1. Author Contributions

Conceptualization, P.P. and M.U.; methodology, P.P.; software, P.P.; validation, M.U. and R.V.; formal analysis, R.V.; investigation, P.P.; resources, M.U.; data curation, M.U.; writing—original draft preparation, P.P.; writing—review and editing, M.U.; visualization, P.P.; supervision, R.V.; project administration, R.V.; funding acquisition, M.U. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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