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The Mathematical Model of RCC Dam Break, Bastora Dam as a Case Study

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Abstract

In this study, the simulation of the hypothetical failure of Bastora dam and prediction of the resultingflood wave are performed. Bastora dam is a roller compacted concrete (RCC) dam, it is located North East of Iraq about 30 km from Erbil city. Five different cases of breach width are investigated for the analysis of dam break simulations (0.2, 0.3, 0.35, 0.4, and 0.5) times of the dam crest length to determine the peak outflow. To predict the flood wave, the hydrologic technique involves the level pool routing method is used to compute the reservoir outflow hydrograph. Routing the breach outflow hydrograph downstream the dam is achieved by using the U.S. Army Corps of Engineers computer program (HEC - RAS 3.1.3) which is based on the complete one dimensional Saint-Venant equations for unsteady flow. The maximum water levels and maximum discharges at (11) sections of the river downstream the dam are determined for the case of Bastora dam failure due to over-stressing. The rescue level is also determined.

الخلاصة

تمت في هذه الدراسة محاكاة الفشل الافتراضي لسد باستورا والتنبوء بموجة الفيضان الناتجة عنه. إن سد باستورا يعتبر من السدود الكونكريتية المرصوصة بالحدل ويقع في شمال شرق العراق على مسافة (30) كم من مدينة أربيل. عند محاكاة الانهيار بحثت خمس حالات لعرض خرق السد وهي (0.5,0.4,0.35,0.3,0.2) من طول قمة السد لإيجاد أعظم تصريف خارج من السد. وللتنبوء بموجة الفيضان استعملت طريقة استتباع الحوض المستوي (التقنية الهيدرولوجية) لحساب منحني التدفق من الخزان. وتم استتباع منحني التدفق أسفل السد باستخدام البرنامج الحاسوبي لفيلق المهندسين العسكريين الأميركي (HEC-RAS) الذي يستند على معادلات (Saint-Venant) ذات البعد الواحد للجريان غير المستقر. وتوصلت هذه الدراسة إلى أعظم منسوب للماء وأعظم تصريف في (11) مقطع من النهر أسفل سد باستورا في حالة فشله نتيجة الإجهاد المفرط. وتم كذلك تحديد مستوى الإنقاذ.

1. Introduction

Dams provide society with essential benefits such as water supply, flood control, recreation, hydropower, and irrigation. However, catastrophic flooding occurs when a dam breaks. Usually, the magnitude of the flow greatly exceeds all other floods. Early warning is very important and necessary for saving lives during a dam break event. Evaluating the safety of existing dams or for planning new ones is necessary to determine the extent of damage and the amount of warning time if a dam breaks.

Roller compacted concrete (RCC) is a no-slump consistency material which is transported, placed and compacted by the same equipments as used in the construction of earth and rockfill dams. The design of RCC gravity dams is similar to conventional concrete gravity dams. The differences lie in the construction methods, and concrete mix design **[1]**.

Failure of concrete gravity dams are often more catastrophic, because they have less obvious symptoms prior to failure, collapse may be very rapid, with little or no advance warning **[2]**. A study of the different dam failures indicates that concrete gravity dams breach by sudden collapse, overturning, or sliding away of the dam due to inadequate design, earthquakes, enemy attack, and over-stressing **[3]**. In this study, failure due to over-stressing will be adopted to determine the breach outflow hydrograph of Bastora dam.

To predict the flood wave resulting from the hypothetical failure of Bastora dam, the hydrologic model technique involves the level pool routing method is used to compute the reservoir outflow hydrograph. Routing the breach outflow hydrograph downstream the dam will be achieved by using the computer program HEC - RAS the U.S. Army Corps of Engineers River Analysis System. This software is based on four-point implicit finite difference solution of the one dimensional unsteady flow equations of Saint-Venant.

2. Governing Equations

The one dimensional saint-Venant equations based on the conservation of mass and momentum are written in form with no lateral inflow as **[4]**:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(Q^2/A\right)}{\partial x}+gA\left(\frac{\partial z}{\partial x}+S_f\right)=0$$

where:
Q = discharge, (L^3T^{-1})
A = cross - sectional area of flow, (L^2)
z = water surface elevation, (L)
x = distance along the channel, (L)
t = time, (T)
g = gravity - acceleration constant, (LT^{-2})
S_f = friction slope, defined as

$$S_f=\frac{n^2Q^2}{A^2R^{4/3}}$$

in which:
n = Manning's roughness coefficient
R = hydraulic radius, (L)

3. Reservoir Outflow Hydrograph

The determination of the reservoir outflow hydrograph can be divided into two tasks **[5]**:

1. Simulating the dam breach.
2. Routing the reservoir outflow hydrograph through the breached and outlet structures.

Estimation of the dam break flood hydrograph depends on size, shape, and time of the breach formation, which are called dam breach parameters. The breach characteristics that are needed to simulate the dam breach are: i) initial and final breach width; ii) shape of the breach; iii) time duration of breach development, and iv) reservoir water level at time of start of breach.
As per **the U.S. Federal Energy Regulatory Commission (FERC) Guidelines (1988) [6]**, in the case of concrete gravity dams, the breach width should be taken 0.2-0.5 times the crest length of the dam. The breach development time should be about 0.2 hour. The breach side slope is taken as zero. The breach depth can be taken corresponding to the average foundation level of the dam. The breach shape develops in time from initiation to its ultimate configuration. The simplest development rate is linear; that is, the breach dimensions grow at a uniform rate **[7]**. The outflow through the breach at any instant is calculated using a formula for concrete gravity dam.

3.1 Bastora Dam Break Simulation

Table (1) Dimensions of Bastora Dam

Dam type	RCC Dam
Dam crest length	577.3 m
Dam crest level	897.5 m asl
Dam height	87.5 m
Maximum reservoir level	892.5 m asl
Storage at spillway level	218 MCM
Spillway sill level	892.5 m asl

Five different cases of breach width are investigated for the analysis of dam break simulations (0.2, 0.3, 0.35, 0.4, and 0.5) times of the dam crest length to determine the peak outflow. In all these five cases, the initial breach elevation is taken corresponding to the top of the dam (EL. 897.5 m asl). The final bottom elevation of the breach is taken as (EL. 810.0 m asl) corresponding to the average foundation level of the dam at the location of the breach. The growth of the breach will proceed quickly vertically down at a rate of 7.3 m / minute until the breach reaches its final elevation and horizontally towards the dam sides at the same rate until the dam destroyed completely except the dam parts that lie above the reservoir water surface elevation. This rate is obtained by dividing the dam height (87.5 m) by the breach development time (12 minutes). The breach parameters for the five cases of failure and discharge through the breach are shown in Table (2) and the outflow hydrograph from various breach width are shown in Fig.(1). Based on the results shown in Table (2), the breach parameters corresponding to case 5 are adopted for the inundation studies because it represents the worst case. The breach formation is assumed to consist of two phases

Table (2) The Breach Parameters

Case No.	**Breach width(w) (m)**	**Breach Elevation (m)**		**Max. Discharge through The Breach (m^3/s)**
		Initial	**Final**	
1	115.46	897.50	810.00	116218.90
2	173.19	897.50	810.00	120890.47
3	202.06	897.50	810.00	124243.07
4	230.92	897.50	810.00	128171.92
5	288.65	897.50	810.00	138023.92

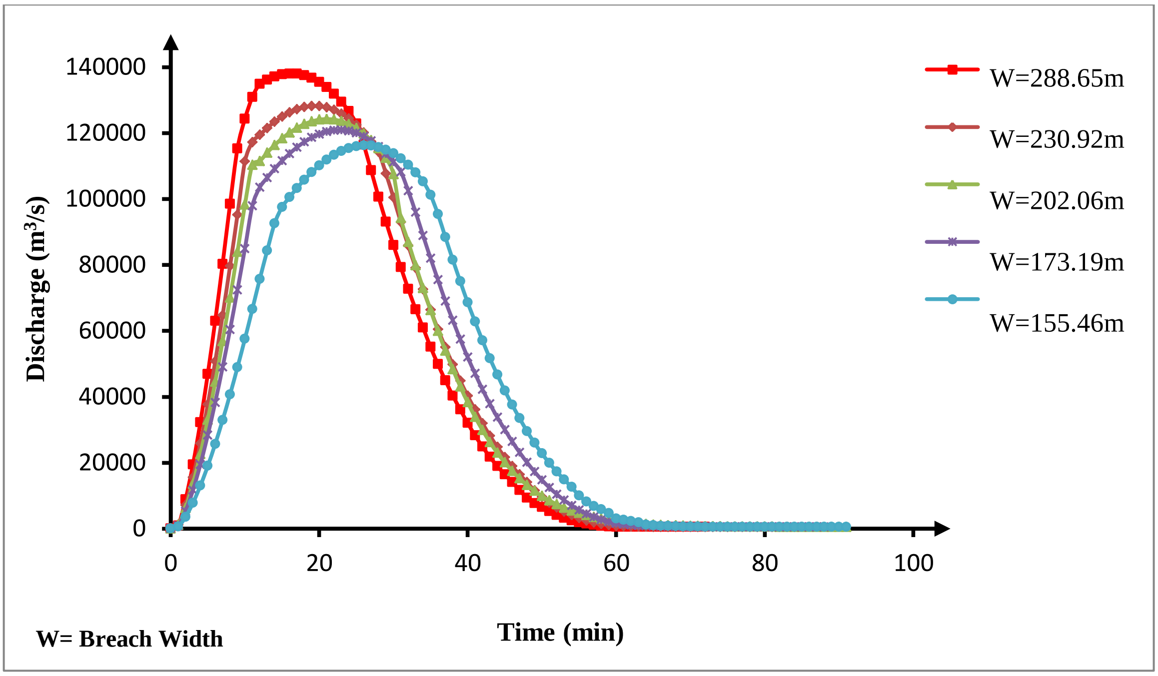

Fig. (1) The Outflow Hydrographs for Various Breach Width

The sketch of case (5) is presented in Fig. (2).

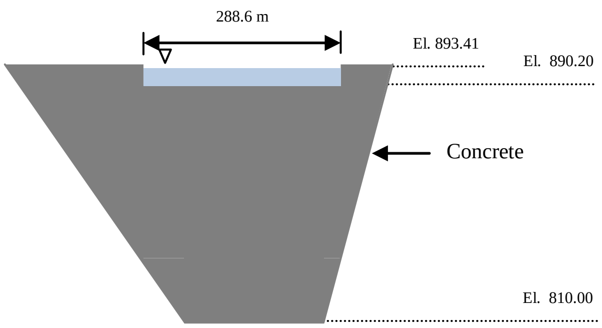

Fig. (2a) First Stage of Phase (1)

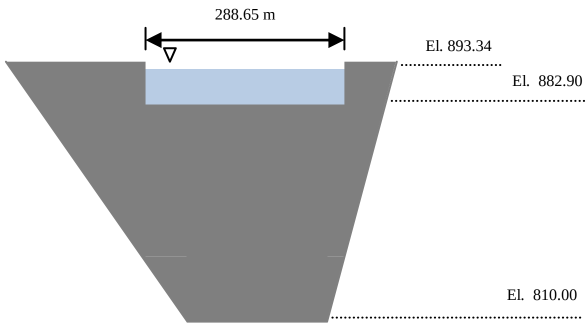

Fig. (2b) Second Stage of Phase (1)

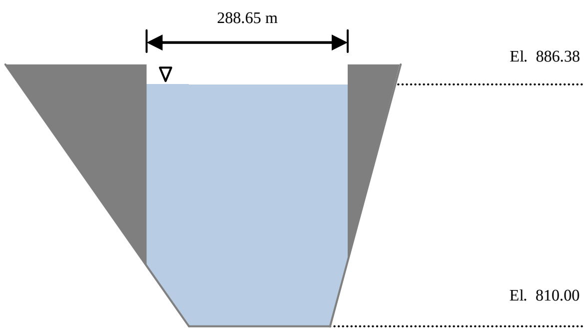

Fig. (2c) End Stage of Phase (1)

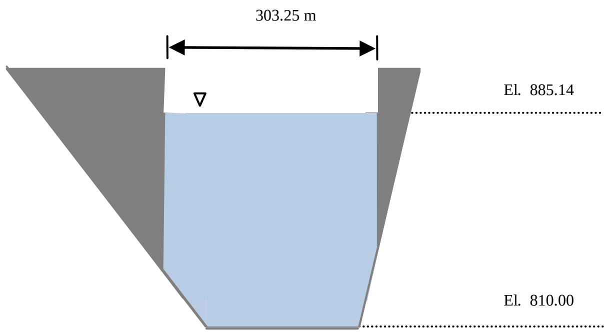

Fig. (2d) First Stage of Phase (2)

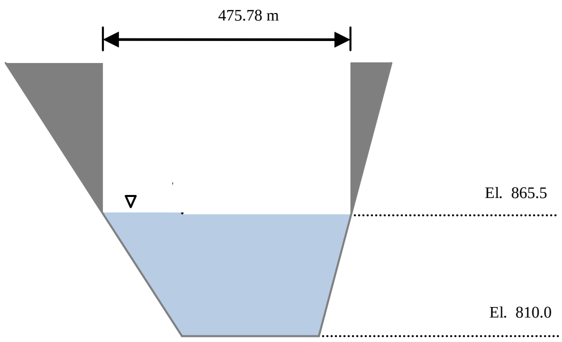

Fig. (2e) End Stage of Phase

3.2 Reservoir Outflow Hydrograph Routing

The reservoir routing system is analyzed by using the level pool routing method in which storage is a nonlinear function of discharge. This method existents in reference **[8]**. The reservoir flood routing process requires determination of the following:

3.2.1 Bastora Reservoir Storage - Elevation Relationship

The relationship between storage and elevation is very important in the dam break study, the equation that represents this relationship was **[9]**:

$$Volume = 9.669 * 10^{-5}\left[El. - 801.5\right]^{3.243}$$

where:

El. = reservoir water surface elevation (m asl)
Volume = volume of the reservoir (MCM) at elevation (El.)

3.2.2 The Outflow from the Reservoir for the Initial Conditions

The maximum mean monthly outflow from Bastora reservoir was (21.6 m^3/s) which occurred on December **[9]**, 1976**.** This flow was assumed to be the initial inflow and outflow from Bastora reservoir.

3.2.3 The Initial Elevation of the Reservoir Water Surface before the Failure

Bastora reservoir is assumed to be full to its maximum live storage capacity. This corresponds to spillway sill level of (892.5 m asl).

3.2.4 The Inflow to Bastora Reservoir

The flood hydrograph of return period 1000 years was selected as the inflow to Bastora reservoir since it represents the maximum instantaneous inflow hydrograph, as shown in Table (4) **[10]**.

Table (4) Flood hydrographs for (1000 years) Return Periods in (CMS) at Bastora Dam

Time (hr)	Inflow (CMS)	Time (hr)	Inflow (CMS)
0	0.0	7	97.4
1	120.9	8	43.8
2	510.0	9	18.5
3	680.6	10	7.4
4	567.0	11	2.9
5	364.9	12	0.0
6	199.4		

3.2.5 Modeling Outlet Works, Spillway and Breach Flows

In this study it is assumed that at the onset of failure the irrigation and power tunnels are locked for any reason; therefore, their flows need not to be modeled.
The reservoir water surface elevation was assumed to be at elevation (892.5m asl) at the onset of failure which is at the spillway sill level; therefore, the spillway flows do not need to be modeled.
The breach (weir) is defined by its sill elevation and width, both given as a function of time. Breach outflow is calculated according to the formula for concrete gravity dam **[11]**.

$$Q_d = 0.9 * b * h_d^{1.5}$$

where:
Q_d = the discharge at the dam site (m^3/s)
h_d = breach head (m) - defined as depth of water at time of breaching
b = breach width (m)

4. Breach Outflow Hydrograph

The computed reservoir outflow hydrograph from Bastora dam is shown in Fig. (3), the figure shows that after about 16 minutes from the dam failure, the peak breach outflow (138023.92 m^3/s) and after about 99 minutes from the dam failure, the whole volume of the reservoir will going out to the river reach, and that indicates the reservoir was depleted at the end of simulation time.

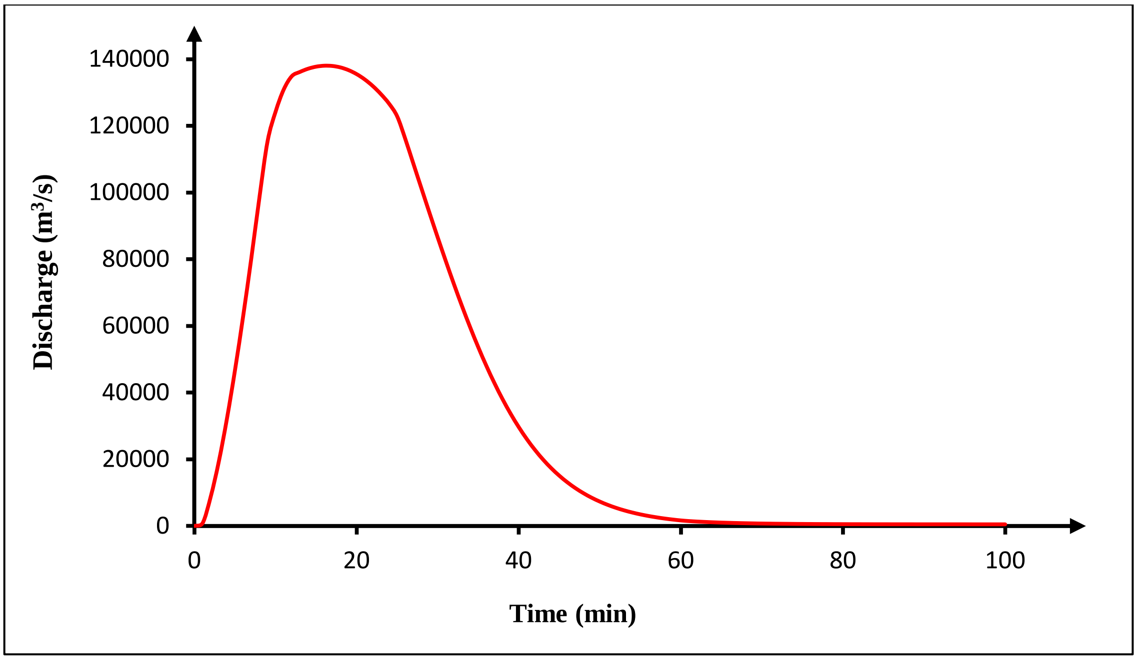

Fig. (3) Reservoir Outflow Hydrograph

5. Routing the Reservoir Outflow Hydrograph downstream Bastora Dam

The (HEC-RAS) computer program was used to route the outflow hydrograph downstream Bastora dam. The basic data requirements for performing the one dimensional flow calculations within HEC-RAS are classified as **[12]**:

5.1 Geometric Data: For dam break study of Bastora dam the river length of (14 km) downstream the dam site, has been represented in the HEC-RAS model by cross sections located at average distance about (1000m -1750 m).

5.2 Hydraulic Data: Unsteady flow model requires, at minimum two forms of hydraulic data energy loss coefficients, and unsteady flow data **[12]**.

5.2.1 Energy Loss Coefficient

In this study, the loss coefficient is utilized by the numerical model to evaluate energy losses:

5.2.1.1 Manning's Coefficient: The value of Manning's roughness coefficient of Bastora river is (0.0255) and it is assumed to remain constant with time and distance **[9].**

5.2.2 Unsteady Flow Data

5.2.2.1. Boundary Conditions: Boundary conditions must be established at all of the open ends of the river system being modeled, also they can be established at internal locations within the river system where the Saint-Venant equations are not applicable, such as spillway, waterfalls, highway embankment, and so on**.** In this study the flowing boundary conditions are used in the numerical model:

a. Upstream Boundary Condition: The reservoir outflow hydrograph shown in Fig. (3) is used to define the upstream boundary condition.

b. Downstream Boundary Condition: The downstream boundary condition used in numerical model is a rating curve at the last section of the routed reach worked out using Manning's equation is given in Table (5).

Table (5) Bastora River Rating Curve at the Last Cross Section

Discharge (m^3/s)	Stage (m asl)	Discharge (m^3/s)	Stage (m asl)
0.00	482.4	7867.30	490.5
7.90	483.3	10317.56	491.4
79.92	484.2	13040.94	492.3
293.08	485.1	16029.72	493.2
705.92	486.0	19277.86	494.1
1369.11	486.9	22780.63	495.0
2328.55	487.8	26534.27	495.9
3830.36	488.7	30535.83	496.8
5700.34	489.6	34782.96	497.7

5.2.2.2. Initial Condition: The maximum mean monthly outflow from Bastora reservoir was (21.6 m^3/s) which occurred on December, 1976 **[9]**. This flow was assumed to be the initial inflow and outflow from Bastora reservoir.

6. Results and Discussion

The computed peak discharges, the maximum water levels, and their time of occurrence at the downstream locations along Bastora river are listed in Table (6). The computed outflow hydrograph for (11) cross section downstream Bastora dam are shown in Fig. (4). The computed peak discharges along Bastora river for (11) cross section are shown in Fig. (5). The computed peak elevations are shown in Fig. (6). Rescue level is an elevation, which is considered safe from flooding. It is usually taken 1 to 4 meters above the maximum calculated water levels, rounded to the next full meter **[13]**. The initial water surface elevation, peak elevation and the rescue levels for (11) sections downstream Bastora dam are shown in Table (7) and Fig (7). The rescue level is taken 2 meter above the maximum calculated water levels, rounded to the next full meter.

From the dam break simulation the peak outflow from the breach is (138023.92 m^3/s) when the breach width is (288.65 m) which corresponds to (0.5) of the dam crest length, this discharge decreases non linearly at the other cross sections until reaches to (103945.0 m^3/s) at the last cross section while the maximum elevation decreases from 593.92 m asl. at the first cross section to 508.96 m asl. at the last cross section of the study reach.

Table (6) Peak Discharges, Water Levels and Time of Occurrence

Section No.	Peak Discharge (m^3/s)	Time of Occurrence (min)	Peak Elevation (m asl.)	Time of Occurrence (min)
1	138023.9	16	593.92	18
2	135916.1	18	591.86	22
3	126939.6	22	576.62	26
4	123507.0	26	576.01	26
5	122401.5	26	561.48	28
6	121650.9	28	548.70	28
7	120092.7	28	538.71	30
8	117398.7	30	528.54	34
9	113848.9	32	516.92	36
10	110360.9	32	508.99	38
11	103945.0	36	508.96	38

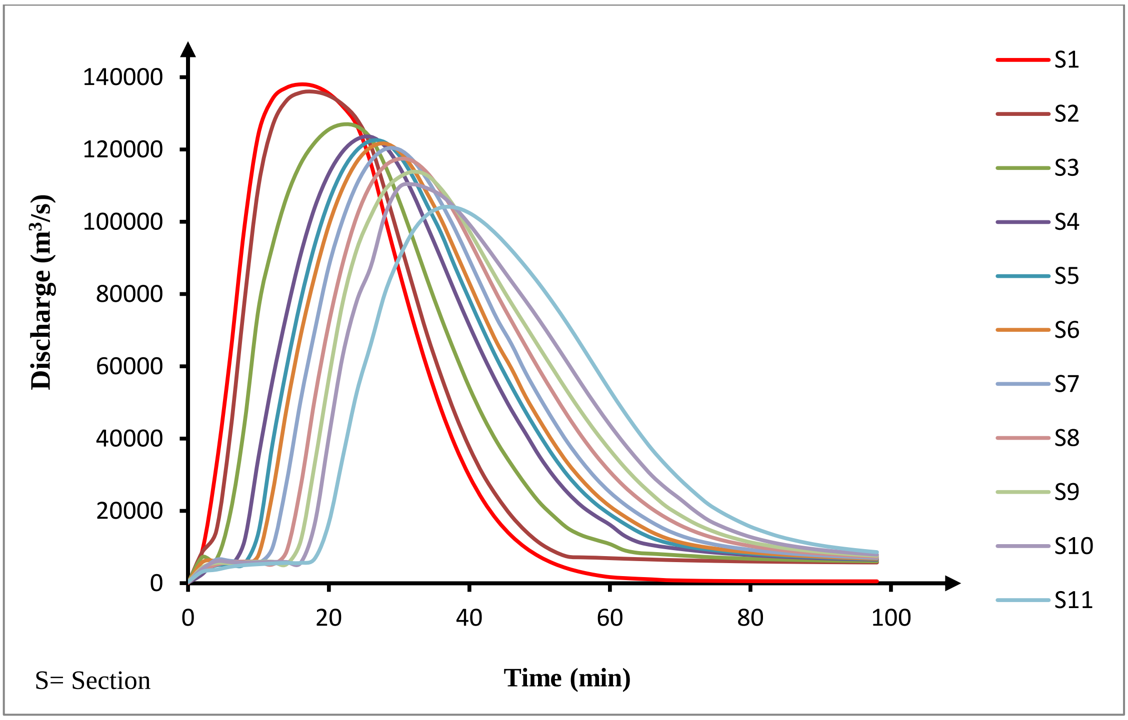

Fig. (4) Outflow Hydrograph for (11) Cross Section Downstream Bastora Dam

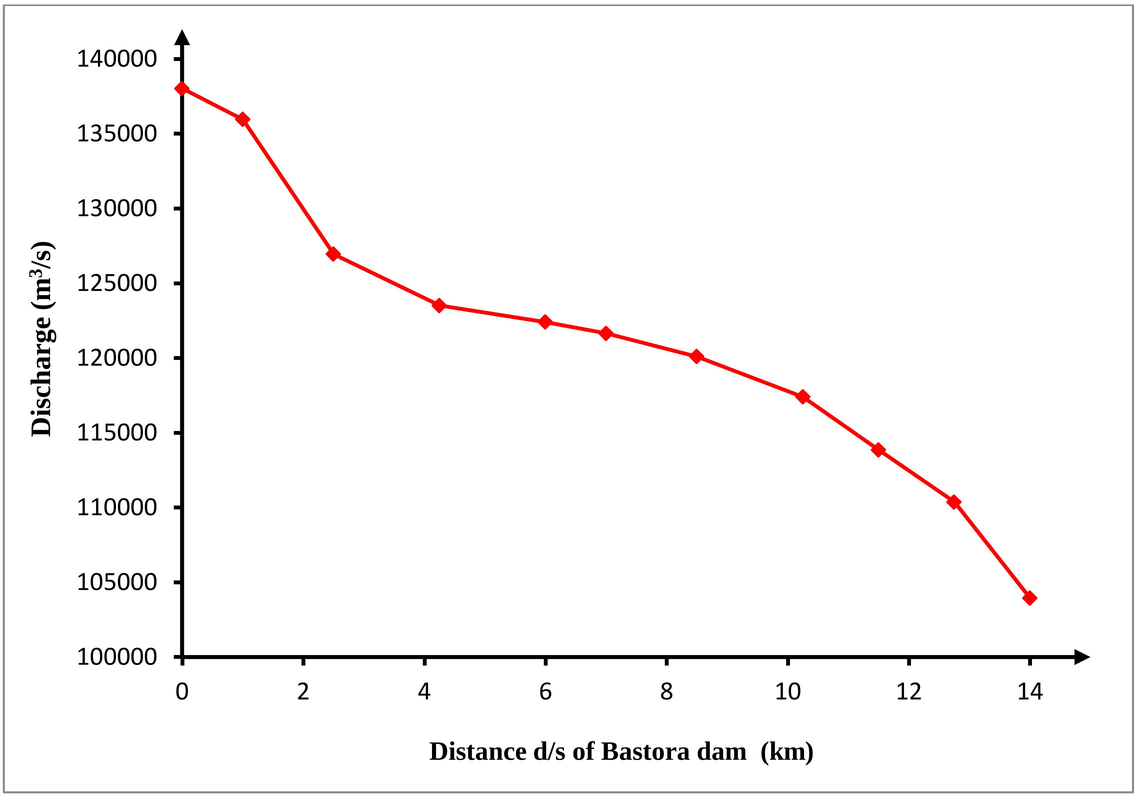

Fig. (5) Peak Discharge Profile

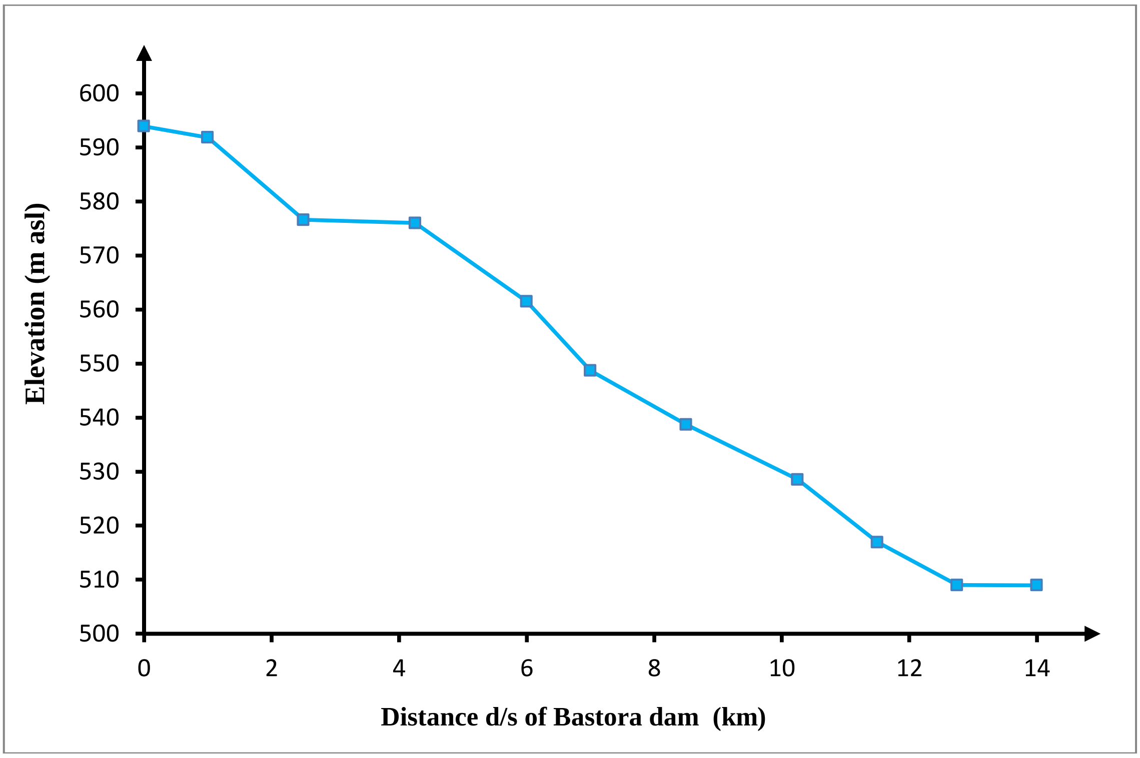

Fig. (6) Peak Elevation Profile

Table (7) Initial Water Surface Elevation, Peak Elevation and The Rescue Levels Downstream Bastora Dam

Section No.	Initial Water Surface Elevation (m asl)	Peak Elevation (m asl)	Rescue Level (m asl.)
1	586.72	593.92	596.00
2	576.33	591.86	594.00
3	565.64	576.62	579.00
4	555.66	576.01	579.00
5	545.27	561.48	564.00
6	534.45	548.70	551.00
7	524.71	538.71	541.00
8	514.20	528.54	531.00
9	503.83	516.92	519.00
10	493.48	508.99	511.00
11	483.47	508.96	511.00

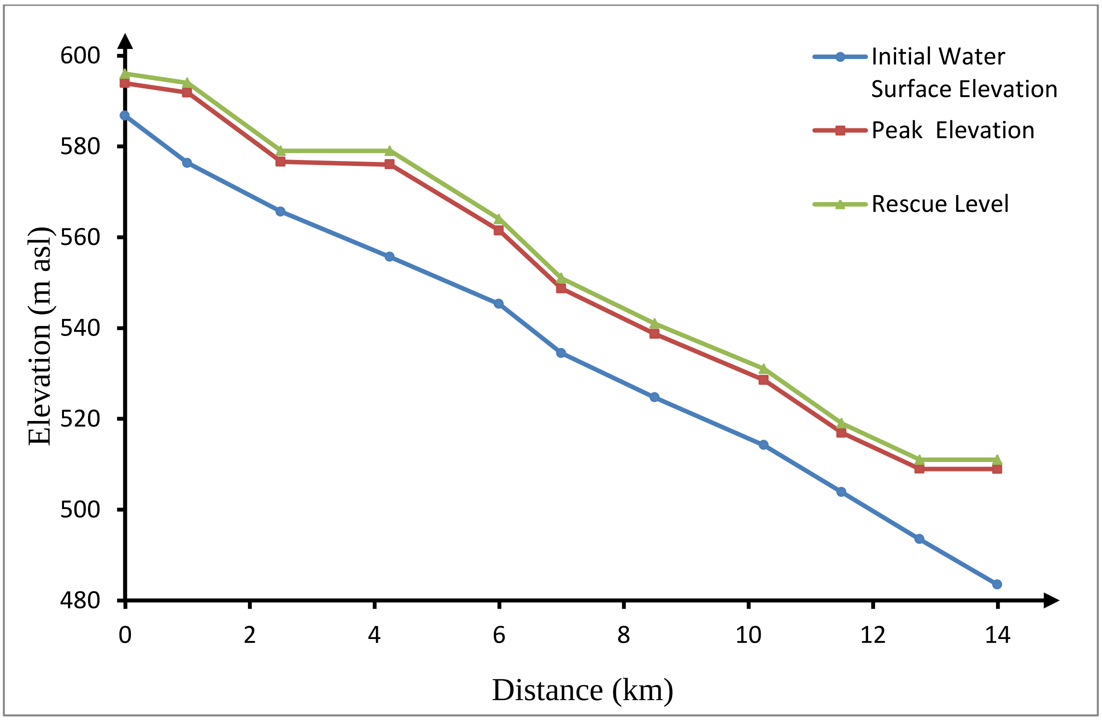

Fig. (7) Initial Water Surface Elevation, Peak Elevation and The Rescue Levels Downstream Bastora Dam

7. Recommendations

From the dynamic routing, the last cross section floods after (36 min); therefore, peoples must evacuate from this area before that time when the dam breaks; and the rescue level ranged from (596 m asl) at the first cross section to (511 m asl) at the last cross section. This may be used as a rescue boundary to evacuate peoples from the areas which are threatened by the flood wave.
This study recommends that the rescue level may be taken into consideration when planning to construct any building downstream Bastora dam.

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