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Mosul Dam Full Story: What If The Dam Fails?

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Abstract

Dams are very important infrastructure to any country where they serve for different purposes. Unfortunately, they represent risks to life and property due to their potential to fail and cause catastrophic flooding. Recent studies indicate the possibility of Mosul Dam failure. For this reason different failure models were used to estimate the consequences of such failure. Almost all models applied gave similar results. It is assumed that in case the water level in Mosul Dam reservoir is at its maximum operational level the effected population will reach 6,248,000 (about one million will lose their life) and the inundated area will be 7202 square kilometer. This catastrophe requires prudent emergency evacuation planning to minimize loses.

Keywords: Mosul Dam, Iraq, Dam failure

1 Introduction

Dams are built to get their obvious benefits, which may include among other things: storing irrigation water, power generation and flood control. It is clear that their construction aims at the common good and development of human societies, but this, however, brings with it always the worry of their possible failure. Large dams with sizable impoundments pose real threats judging from the extensive losses of human lives and material properties in case of their failure. Normally, designers and constructors of large dams strive towards making their dams as safe as possible with very low probability of failure. Even with the most stringent measures taken in this respect, we still find that failures of some dams have occurred. It is not intended here to give an inventory of dam failures, dam incidents and type of such cases as the literature is rich with them [1]. The case of the Banqiao Reservoir Dam and other dams failure in Henan Province, China in 1975, may only serve as an example of the possible catastrophes. The disaster killed an estimated 171,000 people and 11 million lost their homes [2]. The simulation of dam breach events and the associated flooding are most important to reduce threats from unexpected flooding caused by dam failure and are often

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required by law and sought by dam owners. In Iraq, such a law does not exist; nevertheless, the Government has a moral obligation toward its people under the international human law in the event of failure of any of the Iraqi Dams. Basic knowledge is needed in the identification of the endangered areas and the calculations of flood wave propagation, which are the basic information required for any rescue plan and for warning system that could be implemented.

In recent studies and reports it was established that Mosul dam is in a state of high relative risk of failure. Problems in the foundations were known to exist since the later years of construction and first impounding in 1986 [3], [4]. A number of hypothetical Mosul dam failure studies and the consequences of the resulting flood wave were carried out by various consultants and researchers only to indicate the colossal magnitude of the catastrophe that would exceed anything known so far in history. In the following, some of these studies are given with suggestions to actions that may be taken to minimize any possible adverse results.

2 The 1984 Swiss consultant Study

In 1984, the Iraqi ministry of Irrigation commissioned the Swiss Consultants Consortium with the task to prepare a dam break and flood wave study. This was completed after performing surveying of the Tigris River course from the dam site and extending 708 Km along the river course downstream to Salman Pak 24 kilometers south of Baghdad. This work was had already been carried out in 1981, and 412 cross sections were obtained and covered the river reach indicated in Figure 1.

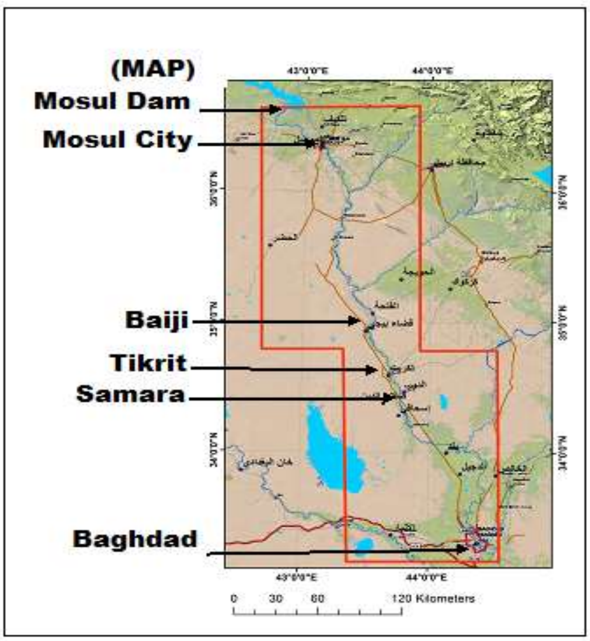

Fig1: Area covered by the Flood Wave Study

Mosul Dam failure was described by the Swiss consultant's own words as by no means probable since the dam had a very defensive design. The report, however, outlined the dimensions of a disaster which could occur if dam maintenance and protection were carelessly neglected, thus underlining the importance of the careful dam safety monitoring. At that time, all seemed to go well with the design and construction of the dam, and nothing was known yet about the problems of gypsum dissolution to be seen later. These were indicated clearly later by the development of seepages, karsts and sinkholes formation and the problems involved during the construction of the deep grout curtain under the main dam. As these problems accumulated the dam break, and the flood wave study acquired considerable new weight, which still holds up to date even with the later studies done on the same subject.

It is not intended here to give the full details of this study which fills three volumes [5, 6, and 7] but just to indicate briefly some of its important aspects and to stress the fact why it had become the basis of all the following studies. The three reports contained full description of the model and its calibration, the hydraulic assumptions made, the possible failure scenarios and the final flood routing along the river course down to 50 kilometers downstream of the Diyala river confluence south of Baghdad.

In this study, the Mathematical model "FLORIS" (Flow in River Systems) was used. It is a one dimensional model; however, by creating a network which enables flow exchange in longitudinal and lateral channels a "quasi" two dimensional simulation is possible. As in similar models the schematization of the river reach under consideration is a first step. The river regime is analyzed; structures and control sections were described with relevant hydraulic equations including tributaries for back water effects, in addition to upstream and downstream conditions. The implicit solution techniques was used in which the Saint-Venant hydro-dynamical equations were applied to sub-reaches of the river by approximation of these equations applied to each sub-reach by finite difference scheme . On a sub-reach Δx the SV equations were approximated by the above implicit finite difference scheme to get a nonlinear system of equations for each time step which can be solved by iterative Newton-Raphson method. Δx can be of variable length and at special points such as river forks, bridges, weirs etc. SV equations were replaced by the appropriate boundary conditions. FLORIS use was not restricted to the river reach downstream but it was also applied to the reservoir itself which was treated as a linear channel (branch) since 40 cross sections were already available.

The mathematical model was calibrated by using major floods data which had been observed in the Tigris River, namely; 1964, 1969 and 1974 floods due to the availability of complete records of the gauging stations on the Tigris and its tributaries and to the fact that these were major recent floods. The objective of the calibration was to show that the model could give good simulation of these flood events for a particular value of Manning "n" which is incorporated in the mathematical model. A value of 0.027 was obtained, but it was also recognized that a higher value should be extrapolated to fit a case of dam break wave due to larger inundated area along the flood plane with more cultivated and inhabited areas causing higher flow resistance. So a value of 0.033 was selected. This choice seems to be in agreement with guidelines given in [8]. In a sensitivity analysis a value of 0.050 increased the wave height by 8% and the peak discharge reduced by 14% as compared to results obtained for "n" value of 0.033, while time of wave travel increased from 3 to 3.6 hours. All figures above relate to Mosul city. Tacking the shorter warning time with higher discharge as criteria the value of 0.033 was adopted in as the more conservative value.

The other important assumption affecting the outcome of the study relates to the breach geometry. For Mosul dam no predominant failure case such as overtopping, military action or failure due to dam stability could be justified, so a breach due to foundation problem was the only reasonable possibility and the initial breach at the base would lead to the complete wash out of the dam. A complete failure should be assumed with different final breach widths assumption and in this case two assumptions were considered plausible, the total channel width of 700 meters was the first, and a width equal twice the dam height i.e. 200 meters was the second. The later assumption was based on a USACE recommendation of bottom gap width which is twice the height of the dam height and a top width of four times the height i.e. 400 meters.

Judging, however, from the size of impoundment in Mosul Dam the width of 700 meter was considered as the more likely one. The breach development was visualized as starting from seepage at the bottom of the dam base due to foundation weakness. This seepage starts initially at a very small rate at some locations in the downstream face which gradually develops into concentrated pipes and result in the erosion of dam materials. These pipes would steadily progress backwards (upstream) until they pass the entire embankment. From published literature the equivalent affected area would be 1/10th the cross sectional area. As flow continuous the width of the weakened zone reaches a width of 94 meters with a height of 50 meters. Above this zone a wedge extends gradually upwards to the crest having side slope 15º to the vertical. The overburden weight in this wedge overcomes the resisting strength of the soil mass and the wedge collapses forming the initial gap. As the reservoir water rushes through this gap the full gap starts developing by eroding the sides and initiating the full flood wave. The full gape extending 700 meters at the base will have side slopes of 0.7 vertical to 1 horizontal resulting in a width of 850 meters at the crest. The total area of the breach will be 77500 m2. Figure (2) explains these stages of breach development.

The time rate of full development of the gap was determined from a study published by Washington state university of Pullman, Washington. This study was conducted for the Oxbow hydroelectric scheme on the Snake River in the states of Idaho and Oregon and it was done on large scale field model and laboratory investigations for materials similar to those used in Mosul Dam. It was established that the rate of lateral erosion of the earth dam progressed at a rate of 1.6 meters/minute. This result indicated that four hours were required for the formation of the 700 m breach in Mosul Dam. In a test for the sensitivity of the results a gap width of 200 meters was also considered following a recommendation of the USACE of adopting a bottom width of twice the height and a top width of four times the bottom width for which a breaching time of two hours would be required.

Table (1) gives summary of the sensitivity test results of breach formation and resulting hydrographs of the initial wave assuming two breach widths, two values of river roughness, and gap formation times of 4 and 5 hours for the these cases. The conclusions that may be drawn from inspection of the results in table (1) are: For the same gap width, the smaller value of Manning “n” gives higher peak discharge and for the case of full gap then the recession limb of the hydrograph will be steeper than the partial case which indicates faster time of travel. This gives full justification for the use of the full gap and smaller roughness scenario in finding the wave characteristics in its progression downstream as the more conservative assumption.

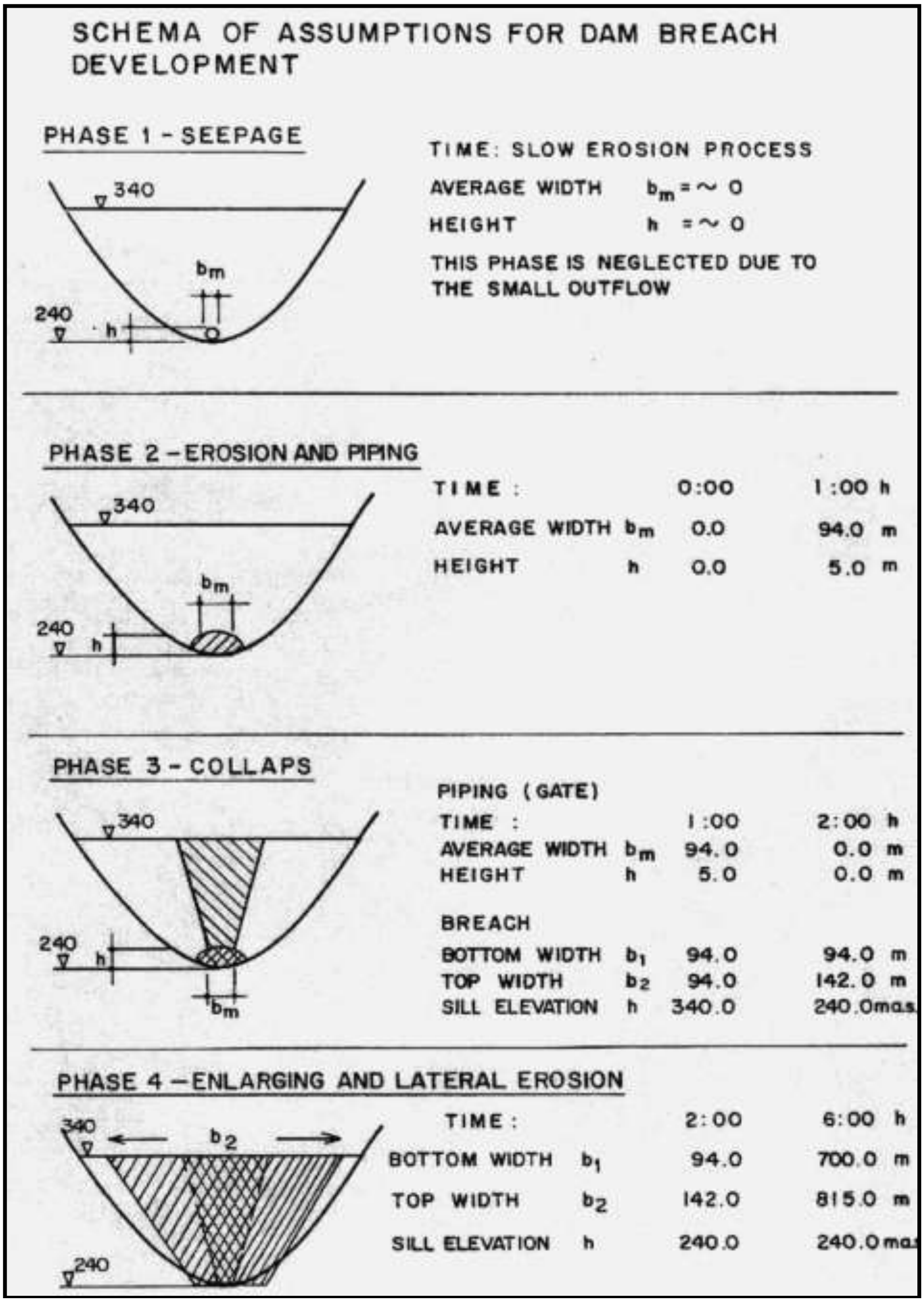

Fig 2: Stages of breach development

In 2004 Black & Veatch (BV) carried out a study on the validity and completeness of the SC flood Dam break and flood wave study [9]. This was done in the context of a contract between WII/BV. JV and the Project Contracting Office of the Iraq Occupation Authority to study the safety condition of Mosul Dam. The report was completed in 2005 [9]. BV used in their work a different modeling procedure by decoupling the derivation of the breach development hydrograph from the wave prorogation downstream. They then used the DAMBRK UK software, a model originally based on DAMBRK which was written by D L Fread and used by the United State Weather Service and which was modified to the UK conditions by Bennie and Partners and the University of Bradford, .Comparing the output with empirical methods results for estimating peak breach flows, they conclude that the treatment of the dam breach adopted by SC in 1984 was sound and did not differ significantly from the treatment which would be adopted if a detailed study, using physically-based dam breach prediction models were to be undertaken in 2004.In Figure (3) the hydrographs obtained in both studies may be seen for comparison.

Using this initial flood wave hydrograph SC continued the routing process along the river channel applying the FLORIS model software again. The progress of the wave downstream did not show uniform decrease of the peak discharge and wave height, but this peak discharge increased markedly over short distance at the narrow sections of the river with corresponding decrease of wave height. This was created due to the formation of negative wave traveling backwards in the river. This case was clearly observed at the Makhul range narrow just upstream of Fatha.

In the confluence of the Tigris with its two tributaries a reverse processes occurred as the wave height increased and the peak discharge decreased which was due to the creation of backwater curve. Table 2 gives the values of wave height and peak discharge at selected locations downstream from the dam site and also the values of arrival time of the wave to these locations. It shows also effect of backwater curves at the confluences of the tributaries and the constriction effect at the Makhul range narrow.

This part of the study was also checked by BV as stated in their report in 2005. At this time more advanced flood wave modeling software were available than in 1984 especially in the presentation of graphical outputs and interfacing with GIS systems to provide inundation mapping. These included as examples ISIS version 2.2 developed by (HR Wallingford and Halcrow UK) and MIKE11 developed by the Danish Hydraulic Institute, but BV accepted the use of FLORIS as they considered the additional output did not add to the accuracy already obtained by SC using FLORIS. As a conclusion BV accepted all the results of the SC study and confirmed that it was done in a highly professional manner, in the calibration of the model by using historical floods, in the choice of Manning "n", the schematization of the river course, and in the representation of tributaries and structures such as Sammara barrage. Based on the findings of this study Luleå technical university produced in 2014 the inundation mapping of four major cities on the river including Baghdad as shown in Figure (4) [10].

Table 1: Development of full breach and partial breach and the resulting flood hydrograph for various values of Manning "n".

case	1	2	3	4	5	6
Manning "n"	0.033	0.050	0.033	0.050	0.033	0.050
Width of Breach(m)	700	700	700	700	200	200
Breaching Time (hr)	4	4	5	5	2	2
Time in Hours (hr)	Q x1000 m^3/sec					
0	1	1	1	1	1	1
1	13	13	13	13	50	50
1.5	80	80	80	80	385	380
2.0	215	210	215	212	425	415
2.5	372	356	335	325	405	390
3.0	474	452	422	404	385	365
3.5	535	499	480	453	375	330
4.0	551	510	509	475	360	310
4.5	538	469	497	460	345	290
5.0	507	469	497	460	330	275
6.0	405	382	435	405	280	260
8.0	271	266	186	278	205	210
10.0	186	192	195	198	180	160
12.0	123	136	130	142	150	80
18.0	37	47	39	49	50	65
24.0	18	2	19	22	20	40

Table 2: Discharge, wave heights and time of arrival at selected points along the course of the river

Location	Distance (km)	Discharge x1000 (m^3/sec)	Wave Height (m)	Time of Arrival(hr)	Remarks
Dam Site	0	551	54	0	
Regulating Dam	9	545	48	1.3	
Eski Mosul	17	481	45	1,6	
Mosul City	69	405	24	4	
Hammam Ali	97	370	18	5	
Upper Zab C.	225	345 310	20	7	Backwater extends 10 km.in the Tigris and 15 km.in the upper Zab. Wave height value is average
Lower Zab C.	330	250 210	25	13.5	Backwater extends 25 km. in the Tigris and 20 km. In the Lower Zab. Wave height value is average
Makhul Range Narrows	361	361 195	30 17	16	The drop in wave height is 13 meters in short distance
Tikrit	422	185	15	22	
Sammara	479	162	10	25	
Balad	516	115	9	28	
Khalis	566	81	6	31	
Tarmiya	597	72	4	33	
Baghdad (North)	638	46	4	38	
Baghdad Center)	653	35	4	44	
Baghdad (South)	674	34	3.5	48	
Diyala C.	685	34	3	>48	
Salman Pak	708	31	3	>48	

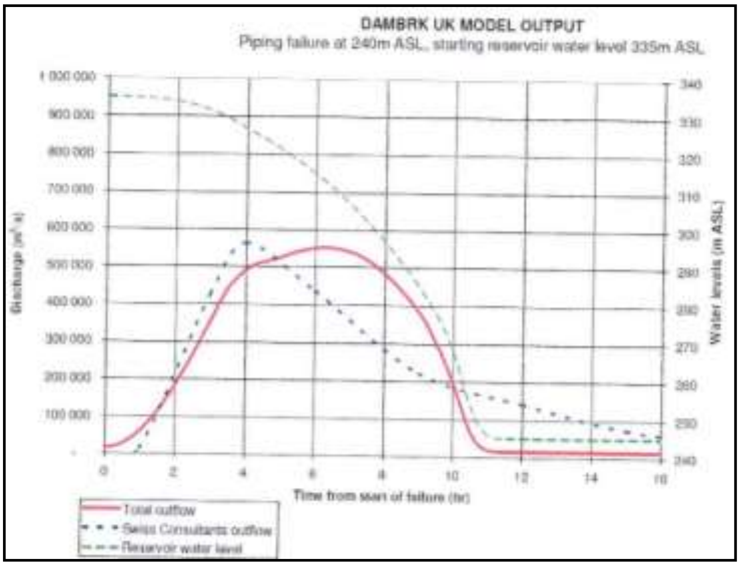

Fig. 3: Dam breaks Hydrographs obtained by FLORIS and DAMBRK UK software [9].

In considering the material damage that may result from the Mosul Dam break flood wave the SC study observed that these would be "too large to be estimated" and BV concurred with this also. But In the estimation of potential loss of life the BV study sites the research carried out by the US Bureau of Reclamation [11] which had concluded that 1.5 hours was the absolute minimum warning time for any effective evacuation of the endangered population and when such time is available the potential loss of life (LOL)= PARx0.0002. PAR is the population at risk.

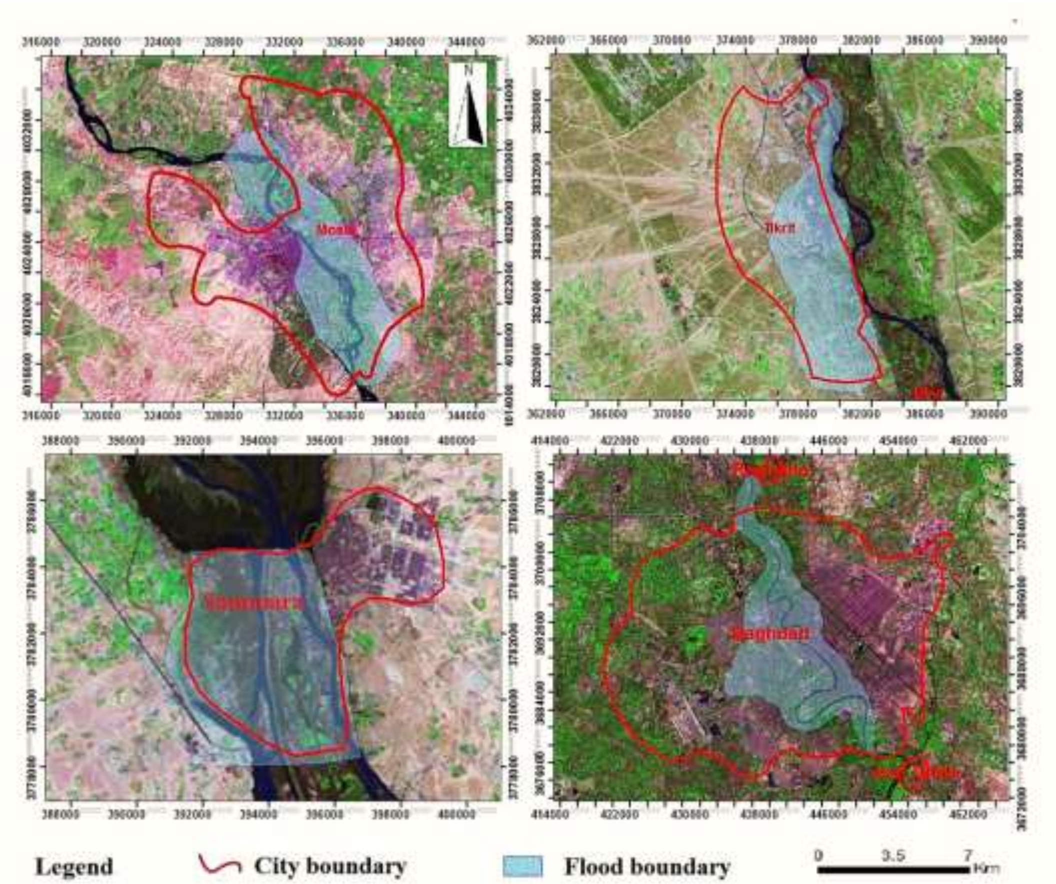

Figure 4: Inundated areas in Mosul, Tikrit, Sammara and Baghdad Cities [10]

If this is to be of any meaning to Mosul city which is the first major city at risk number of conditions have to be satisfied:

- early detection of the initiation of the breach;
- measures to pass that information to decision makers;
- the time taken to corroborate the alert and activate the emergency action plan (EAP) presuming such plan is amiable
- effective implementation of the EAP, including dissemination of the information to the police forces, military, other emergency services, the media and ultimately to the general public; and effective mobilization of transport, emergency shelters, reception centers, medical assistance, catering and so on. For villages above Mosul city where this 1.5 minimum warning time is not available the LOL =PAR0.6 and the same requirements would apply.

But in this context it may be said that the USBR study cited above is based on historical data of dam failures which are far less in magnitude than the case of Mosul Dam hypothetical failure and the resulting flood wave. This wave is more of a tsunami than an actual flood wave and has no precedence in history. Rough indicators from the Japan Earthquake tsunami of March 11, 2011 may be drawn. Statistics showed that the number of confirmed deaths was15, 891 as of April 10, 2015, according to Japan's National Police Agency [12]. Most people died by drowning. More than 2,500 people were also reported missing. Less than an hour after the earthquake, the first of many tsunami waves hit Japan's coastline. The tsunami waves reached run-up heights of up to 39 meters) at Miyako city and traveled inland as far as (10 km) in Sendai. The tsunami flooded an estimated area of approximately 561 square kilometers.

The waves overtopped and destroyed protective tsunami seawalls at several locations. The massive surge destroyed three-story buildings where people had gathered for safety. Although Mosul Dam wave has a different nature the information is given only to say that Mosul Dam could have worse consequences.

3 Other studies

In an effort to quantify the damage that would be inflicted on Mosul city as result of a dam break flood wave, two researches from Mosul University performed in 2009 a flood wave analysis and estimated the inundated area between the dam and the city and within the city itself. [13].The study covered five scenarios for the reservoir water levels when the dam break starts. These were (330, 320, 310, 300, and 290). The simulation model used was SMPDBRK and no mention was given of the plotting tools that were used and the paper claimed that geographic information system was utilized.

The SMPDBRK model being a mean to simulate gradually varied flow along a given river course does not cover the initial flood wave formation. Instead the outflow is derived from weir formula .The initial wave discharge, the dam gap width and the time of formation of this gap would be needed as input to the SMPDBRK model. The authors use five empirical equations derived from historical dam break cases with varying degree of input data accuracy to arrive at these values. The calculated gap widths in this paper showed wide range of variation. For reservoir water level of 290 meters the five equations gave breach width range between 120 meter to 388 meters, and for a reservoir water level of 330 meters the breach width varied between 240 m to 649 meters. Similarly the five equations gave widely ranged results for the time of gap formation, and the results varied for reservoir water level 290 meter between 0.25 hour to 3.55 hours while for reservoir water level 330 meter it varied between one hour to 9.30 hours.

Ignoring their own calculations it seems that the authors adopted some other assumed values of the gap width and time of breach formation and did not mention how these values were arrived at or any justification for them, which sheds a lot of doubt on the accuracy and dependability on the outcome of this study.

The other area of major concern in this study is the selection of the roughness coefficient of the river channel i.e. Manning “n”. The authors stated that they had used a value of n= 0.03 for the river channel to calibrate the model for some recorded discharge flowing in a particular section in the city of Mosul without mentioning whether this was a normal discharge, a historical flood discharge or any other discharge. A value of 0.04 for the bank and 0.1 for the populated area in the city were also selected without mentioning the source or the way these values were derived. Clearly the value of 0.03 for the river channel without the flood plain is too low considering the meandering of the river and type of bed material [14], while a value of 0.04 cannot be justified without actual historical flood data. As the values of the peak discharge, the height of wave and the arrival time are very sensitive to the selected “n” value, then the authors could have at least attempted to use parametric analysis with various values of “n” to examine the range of variation in the outputs and use the more conservative one if the resulting inundation maps were to be used in any rational evacuation plan.

Similar study was done in 2015 by researches from the Iraqi Ministry of Higher Education and Scientific Research [15], and they used the SMPDBK 91 model. Originally the DMBRK model was used in the early eighties by the National Weather Service (NWS) [1516]. It was developed at the Brigham Young University in cooperation with USACE Waterways Experimental Station and it developed later into many versions. It can be said that the SMPDBK 91 is a simplified version of the original DMBRK model. [17].In the Tigris valley characterization the study stated that the digital elevation model DEM was used to construct the river cross sections. The report however did not mention the source of the digital maps from which DEM derived these cross sections. The SMPDBK 91 normally requires the user to estimate some of the parameters related to the breach formation for the initial calculations which include the breach bottom elevation to which the breach cuts and the final width of the breach in addition to the time of breach formation, the user’s manual prescribes default values for these parameters. The performed study however did not show that this was followed and two hypothetical widths of 100 meter and 200 meters were assumed contrary to the fact that this was shown as being unrealistic in the SC and BV studies. Nothing on the time of breach formation was mentioned which adds another question mark on how the initial flood wave hydrograph was defined.

In finding the required value of Manning “n”, SMPDBK 91 considers that the roughness coefficient for out-of bank (flood plain) flows may be estimated to be between 0.04 to 0.05 for cross sections located in an area where the overbank is pastureland or cropland, 0.07 for a moderately wooded area, and 0.10 to 0.15 for a heavily wooded area where the higher value may be used to account for effects caused by significant amount of debris in the downstream valley. For the in-bank roughness coefficient a specific equation is given to derive this value but it should not exceed the value of 0.035. In the case of flood wave where the flow covers an extensive flood plain of variable characteristics the SPMDBK recommends using a weighted roughness value for each elevation of the channel width vs. elevation table rather than the use of a single value of Manning “n” for all levels of flow in the cross section. The study report explained that (Landsat 8) images were used to describe the features of the land along river course through the use of the model (Arc Map), but this was not enough to assign a proper “n” value for each type of terrain, and so the study report assigned some arbitrary values of 0.06 for cropland, 0.08 for forests, 0.05 for water bodies and 0.07 for bare land and no justification was given to this choice. These two facts as in the previous study raise doubts on the output of the study and reduce it into a mere exercise in the mathematical application of the model and cannot be used to describe the aftermath of Mosul Dam failure.

In comparing the results obtained in these two studies for the Mosul city wide range of variation can be observed. For The Ministry of Higher Education study the peak flow of the wave passing Mosul would be 121716 m3/ sec for a gap width of 200 meter and reservoir water level of 319 meters, the maximum wave depth would be 22.7 meters and time of arrival would be 8.9 hours. The results obtained from Mosul University study give values of 207632 m3/sec, 25 meters, and 5.22 hours respectively for initial reservoir water level of 320 meters. For only one meter difference in reservoir water level such differences cannot be justified and only show that there are substantial errors in the assumptions used and the application of the models.

In a recent update on the study of the Mosul Dam flood Wave the Joint Research Centre (JRC) of the European Commission in-house science issued the report of a study which was carried out in April 2016 [18]. The goal was to investigate time-evolution and the characteristics of the flood wave and its effects on the population on the banks of the river Tigris. The study used the (HyFlux2) computer code, developed at the JRC [18] and routinely used for tsunami and storm surge events but originally developed to analyze dam break problems. The report recognized all the previous studies on the subject but in comparison, it provided in addition a complete timescale of the water flow progression, detailed maps of the water depth and extent in the affected cities' areas and focuses on the numbers of population affected by various water depths.

The main scenario analyzed in this study, considered that 26% of the dam was destroyed which was equal to a gap area of 40560 m2 out of the 155000 m2 (Considering that the dam to be 2 km long and 78m high measured from the maximum water level of the lake of 330 meters down to level 252 in the river), and that most of the lake's water is allowed to flow out fast. This scenario resulted in a very high wave of water in Mosul city (in places 25 m high, mean height around 12m) and arriving at the city after 1h 40 min. The capital Baghdad would be reached after about 3.5 days with a max water height of 8m and a mean height of around 2 m. A number of other scenarios involving lower initial levels of the lake were also analyzed, considering levels of 319m (the current one), and 309, 307, 305 and 300.Table (3) gives the values of wave time arrival, time of maximum wave and the maximum height of wave for various scenarios at Mosul, Baije, Tikrit ,Samara and Baghdad It may be seen that the value for the maximum wave height in Mosul in these calculations is in good agreement with the values estimated in the study of Swiss Consultants in 1984 (24m). The time of arrival is also in good agreement: SC gave a value of 4h for a wave of 24m, while this study gives 3 hours for 20m and 6 hours for the maximum of 26m.

Table 3: values of wave time arrival, time of maximum wave and the maximum height of wave for various scenarios.

City	Mosul			Baeji			Tikrit			Sammara			Baghdad		
R.L	**T_1**	**T_2**	**H**	**T_1**	**T_2**	**H**	**T_1**	**T_2**	**H**	**T_1**	**T_2**	**H**	**T_1**	**T_2**	**H**
330	**1.7**	**6.2**	**26.3**	**16,8**	**23.5**	**14.3**	**21.08**	**26.8**	**14.5**	**26.12**	**30.08**	**16.1**	**67.0**	**67.0**	**8**
319	**2.29**	**-**	**22.7**	**18.59**	**-**	**11.8**	**24.07**	**-**	**11.8**	**30.05**	**-**	**13.8**	**76.20**	**-**	**7.6**
309	**2.55**	**-**	**19.2**	**22.54**	**-**	**9.3**	**29.00**	**-**	**9.5**	**36.48**	**-**	**11.1**	**96.40**	**-**	**7.5**
307	**2.54**	**-**	**18.6**	**23.45**	**-**	**8.9**	**30.04**	**-**	**9.1**	**38.12**	**-**	**10.4**	**103.05**	**-**	**7.4**
305	**3.17**	**-**	**17.9**	**24.53**	**-**	**8.3**	**31.19**	**-**	**8.7**	**40.12**	**-**	**9.9**	**111.31**	**-**	**7.3**
300	**3.40**	**-**	**16.0**	**28,32**	**-**	**7.3**	**35.58**	**-**	**7,8**	**46.18**	**-**	**8.3**	**141.33**	**-**	**7.1**

R.L = Reservoir water Level (m.a.s.l.), T_1 = Time of wave arrival (hours)

T_2 = Time of maximum wave height (hours), H = Maximum wave height (meters)

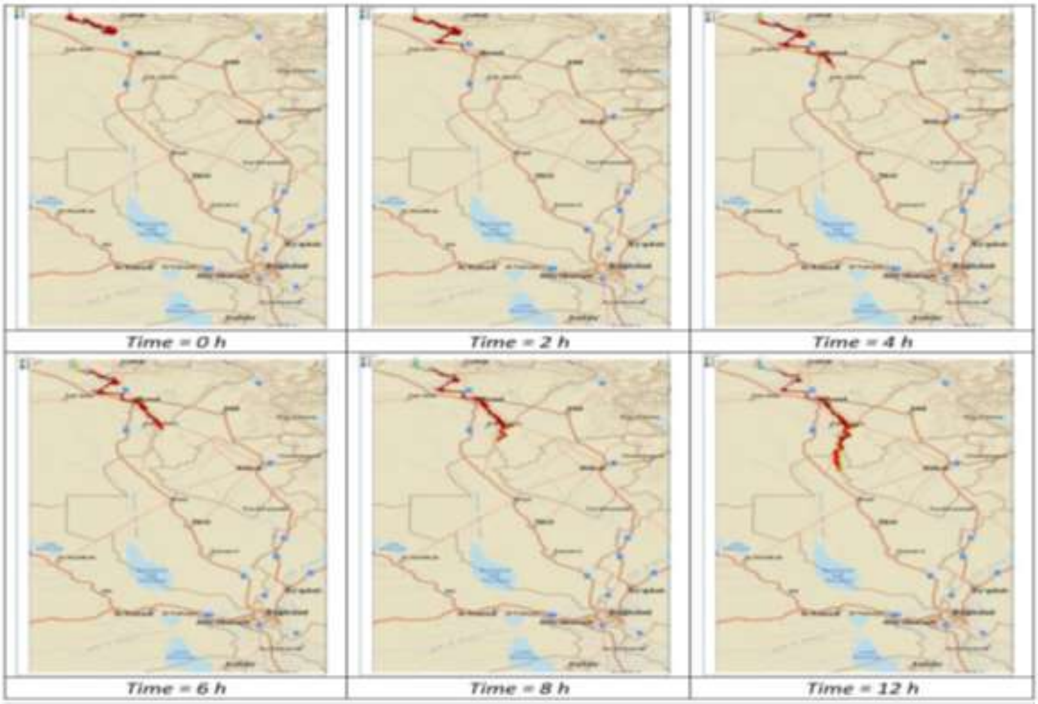

Figure 5: Wave propagation in the River Tigris from hour (0) to Hour (12)

In order to find out the number of affected population the LANDSAT 2014 Global Population Database and the STRM 91 topography layer with a resolution of 1 Km^2 were used. The method was to superimpose various water depths on the LADSAT 2014 Global Population Database and find the number of people affected. These depths used were 0.1m, 0.5m ,2.0m , 5.0m , 10m and 10m and for areas (Table 4).

Table 4: Number of people affected and areas inundated at various water depths of flood water.

Inundation	Population	Area (km^2)
0.1 – 0.5m	948 000	637
0.5 – 2.0m	3 144 000	2 022
2 – 5m	1 626 000	2 482
5 – 10m	260 000	1 150
> 10m	270 000	916
Total	**6 248 000**	**7 202**

From the above table the study shows that total of more than 6 million people (close to one sixth of the country's population) will be affected by floodwaters, with two million of them facing water of more than 2m. Water heights of more than 10m would inundate an area with 270 000 people, most of them in Mosul city and its surroundings, whose lives, houses and infrastructure would risk complete destruction.

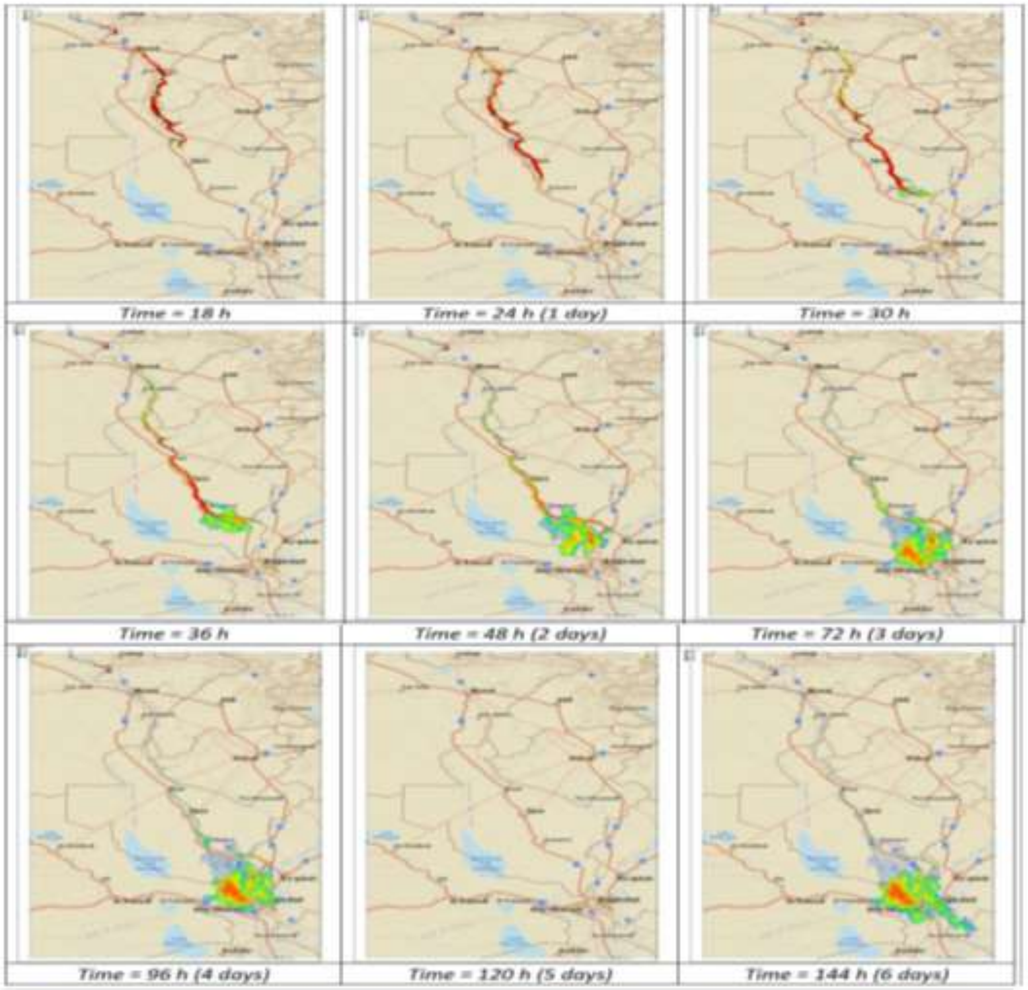

Figure 6: Continuing propagation of wave up to hour (144)

From the data given in this study one can construct the following table to show the affected population and the inundated areas for the different considered reservoir water level. In this table also the number of highest lake area cases will be extended beyond 6 days while all the other cases have been run for 12 days.

Table 5: Population Affected and Area Inundated for Various Initial Reservoir water Levels

Reservoir Water Level (m.a.s.l)	Affected Population	Inundated Area (km^2)	Days
330	6,248,000	7202	6
319	4,263,000	5757	6
309	3,291,000	3672	12
307	3,052,000	3923	12
305	2,921,000	3595	12
300	2,205,000	2791	12

Early in the year of 2016 the office of the Iraqi Prime Minister issued a public statement urging peoples to move 5 kilometers from the river in case of alarm. So this study attempts to calculate the affected population in five cities between 5 kilometers and 10 kilometers from the center of these cities as shown in tables (6,A,B,C,D,E)

Table 6 A: 330 – 6day

Inundation	Mosul	Bayji	Tikrit	Samarra	Baghdad
0.1 – 0.5m	21 000	0	0	0	746 000
0.5 – 2.0m	55 000	300	100	3 000	2 949 000
2 – 5m	41 000	400	2 500	100	1 134 000
5 – 10m	60 000	17 000	14 000	5 500	26 000
> 10m	183 000	2 000	4 000	3 500	0

Table 6B: 319 - 6 days

Inundation	Mosul	Bayji	Tikrit	Samarra	Baghdad
0.1 – 0.5m	27 000	0*	0*	0	803 000
0.5 – 2.0m	12 000	500	0*	0	1 756 000
2 – 5m	51 000	15 000	3 500	1 000	750 000
5 – 10m	66 000	4 500	14 000	10 000	78 000
> 10m	125 000	0*	500	1 000	0*

Table 6C:309 – 12 days

Inundation	Mosul	Bayji	Tikrit	Samarra	Baghdad
0.1 – 0.5m	10 000	0	500	0	571 000
0.5 – 2.0m	22 000	6 000	1 500	1 000	1 434 000
2 – 5m	41 000	11 000	11 000	7 000	476 000
5 – 10m	107 000	2 000	4 000	3 500	78 000
> 10m	38 000	0	0*	0	0

Table 6D: 307- 12 day

Inundation	Mosul	Bayji	Tikrit	Samarra	Baghdad
0.1 – 0.5m	12 000	5 500	0*	0	526 000
0.5 – 2.0m	15 000	5 000	2 000	1 000	1 274 000
2 – 5m	53 000	7 000	13 000	7 000	421 000
5 – 10m	89 000	1 500	2 000	3 500	66 000
> 10m	36 000	0*	0*	0*	0*

Table 6E:300 -12 days

Inundation	Mosul	Bayji	Tikrit	Samarra	Baghdad
0.1 – 0.5m	14 000	500	500	1 000	382 000
0.5 – 2.0m	15 000	9 500	7 000	7 000	850 000
2 – 5m	86 000	3 500	8 000	3 000	229 000
5 – 10m	54 000	0*	500	500	60 000
> 10m	4 000	0*	0*	0*	0*

These tables show that even at the lowest reservoir water level of 300 and even with an inundation between 0.1 and 0.5 meters the affected population in Baghdad in the zone 5-kilometers from the center will exceeds 300,000 people while the maximum affected number of people will be when the inundation depth is between 0.5 – 2.0 meters in the same zone.

From the forgoing this study gives fairly good representation of the flood wave event in case of Mosul Dam break but some limitations do exist and should be remedied in future updates. First is the assumption of the gap bottom level at 252 meter. It was established already that the most probable scenario of failure was due to piping at the bottom of the dam at river section, so a level of 246 meter is more plausible and should be used in any update. Second no mention was given of the inflow to the reservoir at the stat of the dam break and through it. Thirdly sensitivity analysis by varying the percentage of the assumed break area of the total dam area should be made to judge the magnitude of the changes in the outputs due to the uncertainty in predicting the gap area. Finally as mentioned rightly in the study more detailed and updated population data should be obtained and used. As a conclusion this study may be considered as comparable to the SC in its comprehensiveness and end results. This study, however, surpasses all the previous studies even the SC study by estimating the possible number of affected population and giving indications of the amount of material destruction at each level of inundation.

Before closing this section it is worth to mention another study made by an unknown author [19]. In a recent blog on the: http://www.chaldeansonline.org/MosulDamBreachStudy.pdf. Dr. Ghassan Hanna who had worked with the Americans in Mosul in 2011 and who was responsible for following reconstruction projects carried out by them quoted from a lecture on the Mosul Dam flood wave given by an officer in the Iraqi Federal Police in upgrading course given to the force preparedness to deal with emergencies in catastrophic situations. The following maps(Figures 7-14) show the wave progress along the river in Mosul, Makhul Narrows (just a little distance north of Baiji), Tikrit and Samara were. No more maps beyond Sammara were given. Dr. Ghassan thought in his blog that the maps might have been taken from an American study on this event. This may lead to the think that this study was done by the USACE in an effort to check safety situation of the American bases that were located along the river. On each map the time from the wave initiation was recorded.

No comments are offered on this study because of the absence of the author name. All efforts to contact Dr. Ghassan Hanna to get more knowledge proved fruitless. The presentation of this study is given for information only.

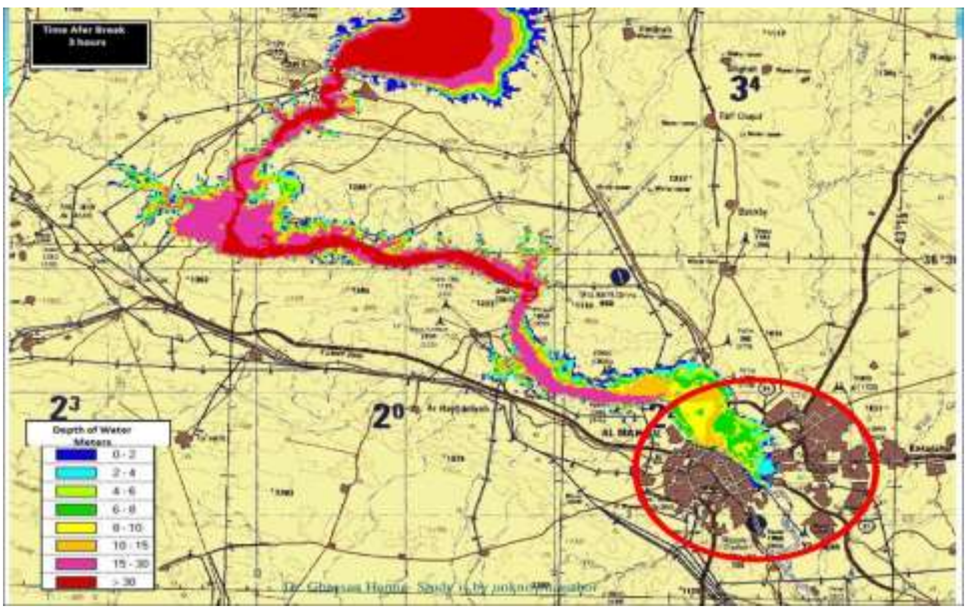

Figure 7: Flood wave at Mosul after 3hours of Dam break and various depths of inundation are explained by the colored legend.

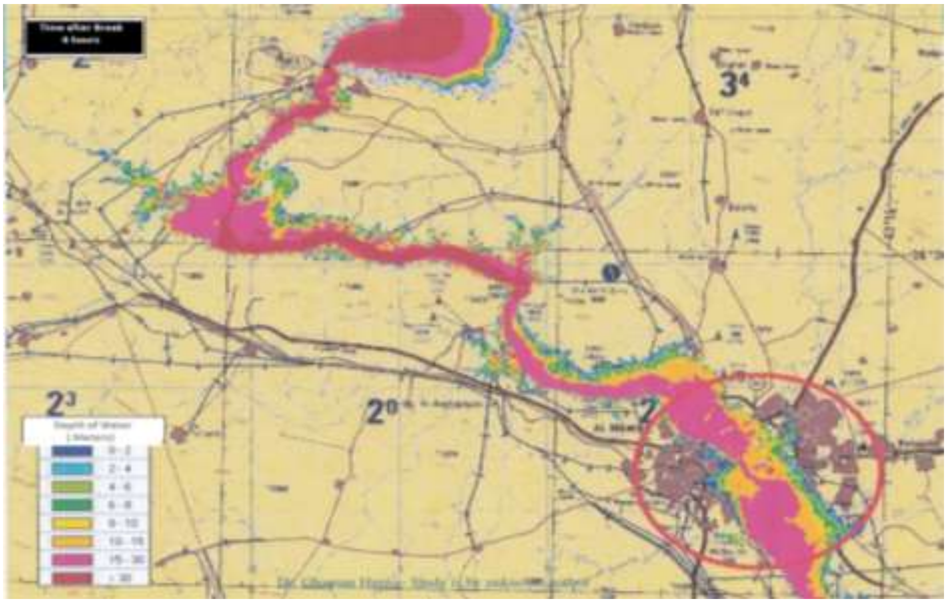

Figure 8: Flood Wave at Mosul after 6 hours of Dam Break

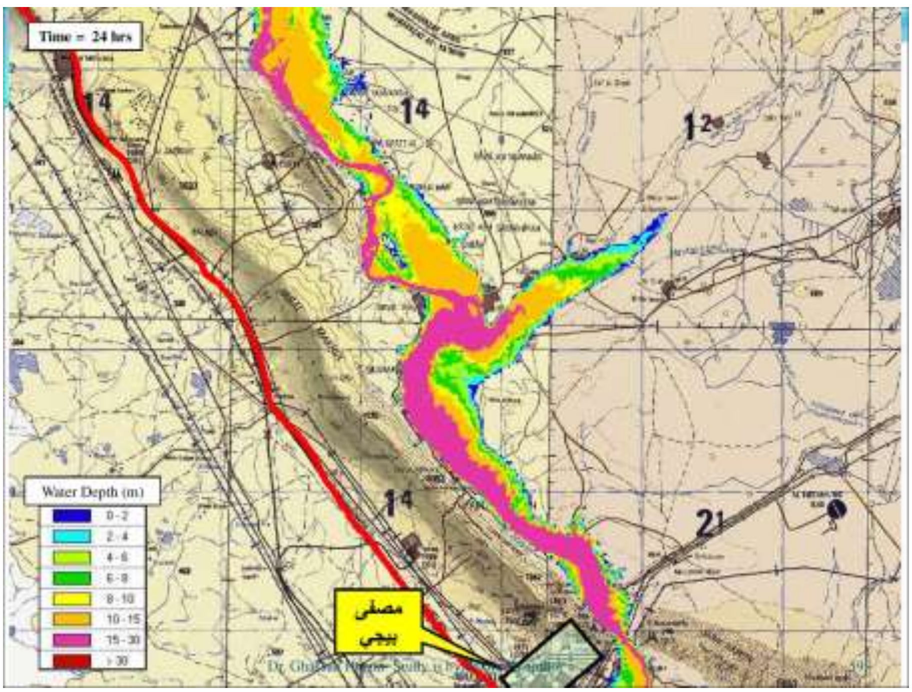

Figure 9: Wave at Makhul (Just North of Baije) after 24 hours of Dam Break

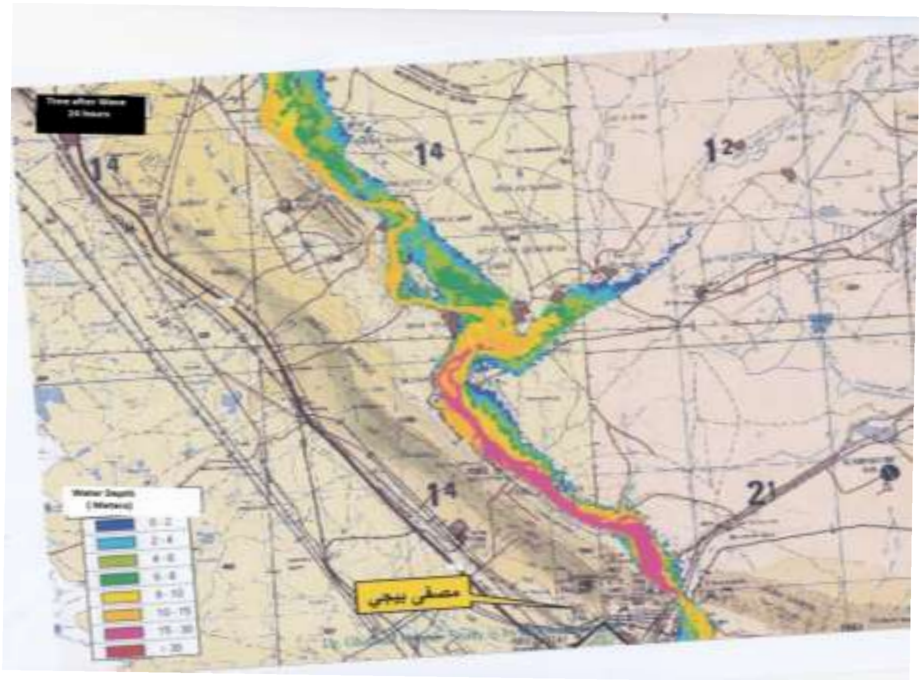

Figure 10: Wave at Makhul (Just North of Baije) after 36 hours of Dam Break

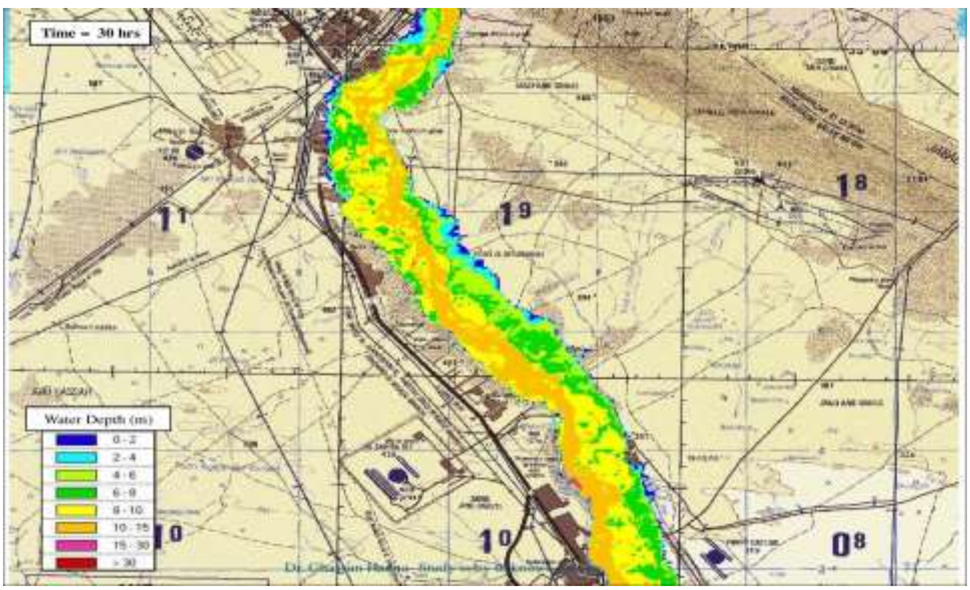

Figure 11: Wave at Tikrit after 24 hours of Dam Break

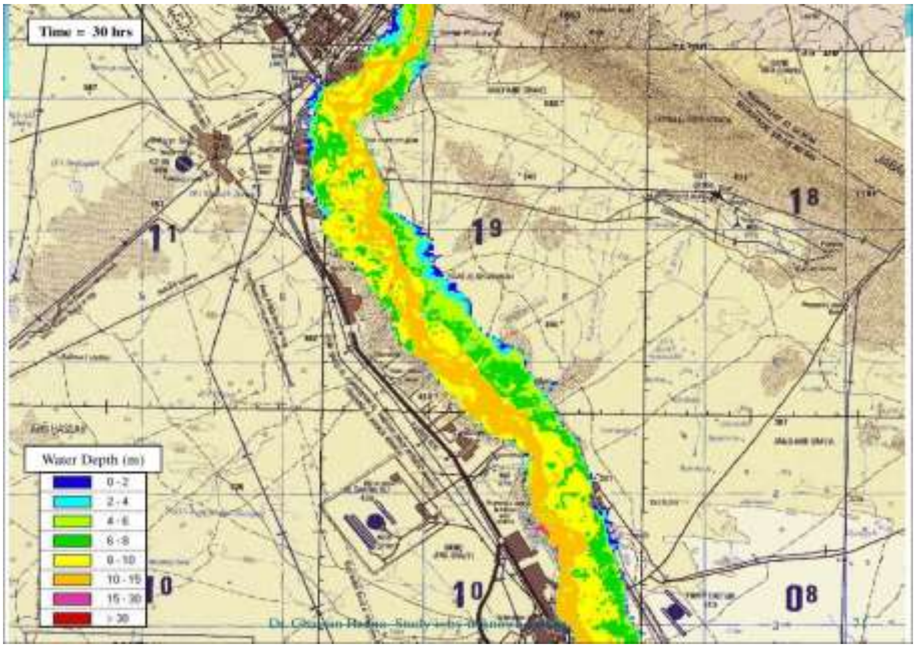

Figure 12: Wave at Tikrit after 30 hours of Dam Break

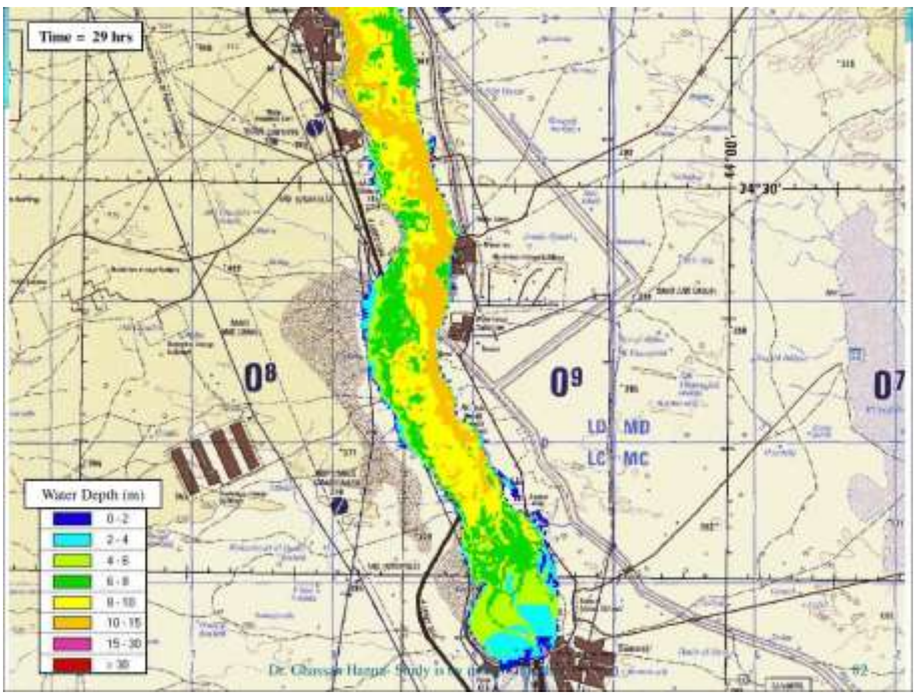

Figure 13: Wave at Sammara after 29 hours of Dam Break

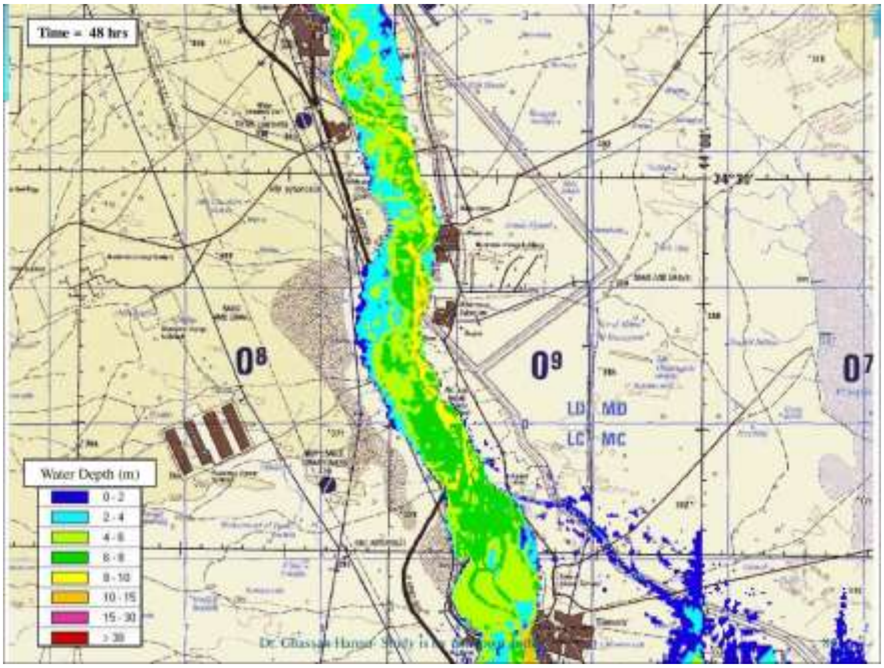

Figure 14: Wave at Sammara after 48 hours of Dam Break.

In summary engineering reports for dam break inundation analysis and downstream hazard classification computation/estimation of a dam break flood is dependent upon numerous characteristics of the dam, the mode of failure and the volume of storage at the time of failure.

Reports that discuss the findings from a Dam Break Inundation Analysis should address the following issues and list the pertinent parameters selected.

DAM BREAK FLOOD

- The reservoir level and assumed inflow at the time of the hypothetical failure,
- The method of estimating/selecting the breaching dimensions and characteristics for the assumed mode of failure,
-The magnitude of the estimated dam break peak discharge at the dam site and the attenuation of the flood peak discharge as it propagate through the downstream valley.

INUNDATION ANALYSIS

- The travel time of the flood wave to various locations in the downstream valley,
- An inundation map depicting the areal extent of flooding,
- Representative channel/valley cross-sections depicting flow depth and typical flow velocities.

DOWNSTREAM HAZARD CLASSIFICATION

- A general description of the valley and level of development downstream of the dam,
- The method used to determine the Downstream Hazard Class.

4 What is to be done next?

In previous writings the Mosul Dam was shown to suffer from existential threats and that there was a very high relative risk of its failure [3][4]. An International workshop which convened in Stockholm during the period 24-25 May 2016 had the objective was to study this case and come up with required solutions. The workshop was organized by Leleaº Technical University and many international dams and geotechnical experts were invited to participate as a Panel of Experts. The final statement issued by the workshop suggested a list of remedial and protective actions which were put up by the Luleå university team and strongly supported and endorsed by the Panel of Experts as recommendations to the Iraqi government for implementation. Preparing an emergency action plan (EAP) was one of these [4].The following paragraph is quoted from this statement to show its importance:

"The LTU team reported that there is no meaningful Emergency Action Plan (EAP) in place functioning in the event of a breach of Mosul Dam. An EAP should be developed and implemented as soon possible to minimize the impacts to the population downstream of Mosul Dam if it fails. The EAP should be consistent with international practices. While an EAP is being developed and finalized, the existing breach assessment should be reevaluated to determine where it needs to be updated especially in the light of new developments and urbanization of the river reach downstream of the dam".

It the light of this recommendation the following actions should be taken:

1. The JRC dam break study being the most up to date and most comprehensive study done so far, so it must be checked for any areas of improvements weather in the assumptions or the updating of population statistics. The outputs of this study shall also define "Rescue Line" in all the threatened zones for each reservoir water level scenario. Contour maps indicating these rescue lines should be prepared and projected on the ground with participation from the government to mark these rescue lines.
2. Evacuation sites must be selected at safe locations and alternative routes leading to them must be established and marked.
3. A National Crisis Management Group should be established (by law) from top officials which should meet at a very short notice from sounding of the alert and shall have full authorizations over all rescue and relief services including those connected to transport, food supplies and .health care services. All civil, military and civil defense authorities shall be represented in the group which shall also have full coordination of all civil local authorities and the police in the affected areas.
4. An advanced alarm system shall be established connecting all population centers and important nodes along the river course to transmit warning alerts to the population and to urge all those who are endangered to move quickly to the previously designated evacuation sites outside the danger zones to reduce human fatalities as much as possible
5. The success of any self-directed evacuation is most likely dependant on effective crises communications in educating and warning at-risk populations ahead of the dam break. This shall comprise of a set of instructions where to go and alternative routes. These warning should be transmitted by all communication facilities and groups and repeated many times ahead of the event so that they acquire credibility within the population.

6. Frequent drills on evacuation and relief activities shall be conducted. This shall include air lifting, relief supplies dropping to isolated areas in addition to all other life medical lifesaving practices.
7. In flat flooded areas from Sammara downwards and especially in Baghdad area stagnate water is expected to last for weeks if not for months This water will be heavily contaminated with mud, sewage water, corpses dead animal and other foreign bodies which pose a great health hazard to the returned people. All efforts to remove as much of all these must be done and all health protection measures should be taken.
8. Stockpiling of materials and equipment required for the aftermath efforts necessary to reestablish a reasonable living environment must be done. These shall include such things as fuel, medical supplies, disinfection materials, sludge and ordinary pumps, portable electric generators and the like. Hubs for such stockpiles shall be located at short distances outside of danger zones for easy and quick access.
9. Cleary the volume of works required is colossal and beyond the capacity of the government so pre-arrangements should be made with governments and specialized international aid and relief agencies and organizations to step in quickly in the event of such crisis.

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