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LITANI RIVER BASIN MANAGEMENT SUPPORT PROGRAM

DAM BREAK MODELING FOR QARAOUN DAM
VOLUME 1 – MAIN REPORT

JANUARY 2012
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ACRONYMS

HEC-RAS	Hydrologic Engineering Center - River Analysis System (river flow model)
LRA	Litani River Authority
LRBMS	Litani River Basin Management Support
PFMA	Potential Failure Mode Analysis
USAID	United States Agency for International Development

EXECUTIVE SUMMARY

This report considers the modeling of a potential dam break from the Qarauon Dam in the Litani River Basin using an unsteady HEC-RAS model. Topographic data for the Litani River Basin was obtained from contours lines digitized from maps and converted to a 5m x 5m cell-size Digital Elevation Model (DEM) representing the Litani River Basin. The Qaraoun Dam is located at a narrow point at the southern end of Bekaa plain at an elevation of 800m above sea level. The concrete faced rockfill dam has a maximum capacity of 220 million m^3.

The Litani River Basin downstream of the Qaraoun Dam is very steep, dropping 800m in approximately 90 km distance to the mouth of the river at the Mediterranean Sea. The river flows through several deep and winding canyon sections interspersed with wide, flat reaches over this interval making the dam break modeling problem challenging as many cross-sections must be used in the model (1-5 m spacing between sections), along with a short time step (5 seconds).

A Potential Failure Mode Analysis (PFMA) of the Qaraoun Dam identified the main potential failure modes as due to seismic loading and flood overtopping. Overtopping and breaching after seismic activity is the most probable and worst mode of potential failure of the Qaraoun Dam (consideration of a river flood, even exceptional, would not add much to the peak flood generated by the dam breaching and reservoir emptying). It is the failure mode described and modeled in this report. The unsteady hydraulics of the dam breach due to this failure mode was modeled using U.S. Army Corps of Engineers HEC-RAS software. The breach formation time used in the model is 1.5 hours, as calculated using the U.S. Bureau of Reclamation recommended procedure.

The model results show a peak flow of 67,528 m^3/s at the dam and 37,738 m^3/s at the sea outlet. The flood wave generated by the breach is initially 40 m high and does not abate significantly until the reaching the coastal valley where it decreases to 10-15m. The lag time between the peak flow at the dam and at the mouth of the river is 115 minutes; the flood wave travels 85.4 km in 115 minutes or 44.6 km/hr. Sensitivity analysis was performed on the time of the dam breach and the width of the formed breach, showing that the model results are sensitive to the breach formation time, but not to the width of the breach formation.

Maximum stage, flow and time of peak flow for selected Litani River stations below Qaraoun Dam.

Cross-section (distance in km from sea outlet)	Initial Rise Time *	Peak Time *	End Time *	Peak Flow	Flood Height
	hr:min	hr:min	hr:min	m3/sec	m
85.7 (dam)	0:00	1:25	3:20	67500	37.0
81.6 (Sohmor)	0:25	1:35	4:10	48700	42.6
75.5 (Yohmor)	0:40	1:35	5:00	48300	28.6
66.3 (Berghoz)	0:55	1:45	6:25	47400	39.0
60.6 (Blat)	1:05	1:50	7:35	46800	41.1
52.3 (Khardale)	1:15	2:05	7:45	45400	29.3
44.3 (bend to the west)	1:30	2:15	11:00	43800	52.8
32.1 (Kfar Syr)	1:55	2:35	12:00	41900	37.6
7.3 (coastal valley, upstream of Khasmiye)	2:35	3:05	13:00	39200	16.3
Sea outlet	2:50	3:20	13:15	37700	10.8

* Time from time of breach initiation

These results will be mapped in a GIS to indicate the extend of potential inundation of the surrounding areas, and will help in the development of an Emergency Management Plan for the lower basin. The model should also be updated if downstream dams are built in the future, as envisioned, in Khardale and Kfar Syr.

ملخص تنفيذي

يتناول هذا التقرير نموذجًا لانهيار محتملٍ لسدّ القرعون في حوض نهر الليطاني بالاستناد إلى نموذج نظام تحليل الأنهار لمركز الهندسة الهيدروليكية HEC-RAS الذي يمكنه التفاعل مع الأوضاع المتقلبة. وتمّ تجميع بيانات حوض نهر الليطاني الطوبوغرافية من خطوط الكفاف المرقّمنة المستقاة من خرائط والمحوّلة إلى خلايا رقمية بقياس ٥ أمتار*٥ أمتار، وهي تُمثّل على نظام الارتفاعات الرّقمي Digital Elevation Model (DEM) حوضَ نهر الليطاني. يقع سد القرعون في نقطة ضيقة من الطّرف الجنوبي من سهل البقاع على ارتفاع ٨٠٠ متر عن سطح البحر. ولا تتعدّى السعة التخزينية لهذا السدّ الركامي ذي الواجهة الخرسانية ٢٢٤ مليونَ مترٍ مكعّب.

يُعَدّ مجرى النّهر شديد الانحدار إذ تتدفّق المياه من ارتفاع ٨٠٠ متر عن سطح البحر مسافةَ ٩٠ كيلومترًا تقريبًا لتصل إلى مصبّ النّهر في البحر الأبيض المتوسط. ويجري النّهر عبر عددٍ كبير من الأخاديد الضيّقة والمتعرّجة تتخلّلها مسطّحات واسعة وكبيرة على امتداد هذه المسافة، ما يشكّل تحديًا مهمًا لمشكلة إعداد نموذجٍ لانهيار السدّ لأنّه يستوجب استخدام الكثير من المقاطع العرضية (تفصل بينها فسحة تتراوح بين متر و٥ أمتار) ناهيك عن خطوة زمنية قصيرة (٥ ثوانٍ).

أشار تحليل نمط الإنهيار المحتمل لسدّ القرعون (Potential Failure Mode Analysis (PFMA إلى أنّ أنماط الإنهيار المحتمل الأساسية تُعزى إلى النّشاط الزلزالي وإلى الفياضانات المؤدّية إلى ارتفاع المياه. وفي الواقع، يعتبر ارتفاع المياه في السّد وحدوث فجوات في جوانبه النمطين الأكثر شيوعًا والأسوأ لانهيارٍ محتملٍ لسدّ القرعون (وإن وضِع في الحسبان احتمال فيضان النّهر، مهما كان استثنائيًا، فإنّ تصريفه سيكون أقلّ من ذروة الفيضان الناتجة عن الفجوات في السّد وإفراغ الخزان). يصف إذًا هذا

التّقرير نمط الانهيار ويضع نموذجًا له. وتمّت الاستعانة ببرنامج HEC–RAS الخاصّ بفيلق المهندسين في الجيش الأمريكي U.S. Army Corps of Engineers بغية نمذجة التقلبات الهيدروليكية لحدوث فجوات بسبب نمط الانهيار المحتمل. وفي النّموذج هذا، بلغت مّدة حدوث الفجوة ساعة ونصف، وقد احتُسبت بما يتوافق مع اجراءات ينصح بها مكتب الاستصلاح الأمريكي U.S.Bureau of Reclamation.

تظهر نتائجُ دراسةِ النّموذج ذروةَ فيضانٍ يبلغ تدفّقها ٦٧٥٢٨ مترًا مكعبًا في الثانية على مستوى السّد وينخفض تدفّقها إلى ٣٧٧٣٨ متراً مكعباً في الثانية عند المنفذ إلى البحر. ويبلغ ارتفاع موجة الفيضان التي تولّدها الفجوة ٤٠ مترًا في البداية ولا تنحسر بشكل ملحوظ إلاّ عندما تصل إلى المناطق السّاحلية حيث تنخفض إلى ما بين ١٠ أمتار و١٥مترًا. ويصل الفارق الزمني بين ذروة الفيضان على مستوى السدّ وعند مصبّ النهر إلى ١١٥ دقيقةً إذ إنّ موجة الفيضان تنتقل مسافة ٨٥,٤ كلم في ١١٥ دقيقة أو ٤٤,٦ كلم في السّاعة. وتمّ إجراء تحاليل الحساسية على وقت حدوث الفجوة في السّد وعلى حجمها، فأظهرت نتائج النّموذج أنّه يتأثّر بوقت حدوث الفجوة لا بحجمها.

مرحلة ذروة الفيضان القصوى وتدفقها وتوقيتها في محطات نهر الليطاني المختارة أسفل سد القرعون

قطاع عرضي (المسافة بالكيلومتر من المنفذ إلى البحر)	وقت ارتفاع الموجة الأولي*	وقت الذروة*	وقت انتهاء الموجة*	ذروة الفيضان	ارتفاع الموجة
	الدقيقة:الساعة	الدقيقة:الساعة	الدقيقة:الساعة	متر^3/الثانية	متر
7.58 (السّد)	0:00	5:: .	3:: 0	08.00	3850
7550 (سحمر)	0:25	1:35	4:10	48700	42.6
8.5. (يحمر)	0:40	1:35	5:00	48300	28.6
0053 (برغز)	0:55	1:45	6:25	47400	39.0
0050 (ب. ط)	1:05	1:50	7:35	46800	41.1
53: (الخردلي)	1:15	2:05	7:45	45400	29.3
53.. (الانخراف نحو الغرب)	1:30	2:15	11:00	43800	52.8
5:55 (كفرصير)	1:55	2:35	12:00	41900	37.6
853 (المناطق الساحلية)	2:35	3:05	13:00	39200	16.3

على القاسمية)					
المنفذ إلى البحر	2:50	3:20	13:15	37700	5057

*الوقت منذ بدء الفجوة الأساسية في السدّ

سيتم وضع هذه النتائج على خرائط بواسطة برنامج نظم المعلومات الجغرافية GIS بغية تحديد المناطق المحيطة التي من المحتمل أن تغمرها المياه ما سيساهم في تطوير خطة طوارىء للحوض السفلي لنهر الليطاني. ولا بدّ من تحديث النّموذج هذا في حال بناء سدود عند المصبّ في المستقبل في الخردلة وكفرصير كما هو متوقّع.

1. INTRODUCTION

1.1. THE LITANI RIVER BASIN MANAGEMENT SUPPORT PROGRAM (LRBMS)

The USAID funded project Litani River Basin Management Support (LRBMS) Program is undertaken in Lebanon to support the Litani River Authority (LRA) to improve water resources management. This Task Order is to set the ground for improved, more efficient and sustainable basin management in the Litani River Basin through provision of technical support to the LRA and implementation of limited small-scale infrastructure activities.

To achieve the LRBMS program objectives, the Consultant undertakes tasks under the components:

1) Building calacity of the LRA towards Integrated River Basin Management
2) Long term water monitoring of the Litani River
3) Integrated Irrigation management with two sub-components:
    a. Participatory agriculture extension program: implementation under a Pilot area: West Bekka Irrigation Management Project
    b. Machghara Plain Irrgiation Plan
4) Risk Management in two sub-components
    a. Qaraoun Dam Monitoring System
    b. Litani River Flood Management Model

1.2. MAIN PURPOSE OF THIS REPORT

The purpose of this report is to look at the issue of modeling a potential dam break from the Qarauon Dam in the Litani River Basin using an unsteady US Army Corps of Engineers HEC-RAS model. The Litani River drains the central and south Bekaa Valley, and the Qarauon dam is located at the southern end of the valley. Downstream the river flows through a narrow valley, a canyon in some places dropping 800 m to sea over some 70 km.

The main task of this report is the issue of modeling a potential dam break from the Qaraoun Dam using an unsteady U.S. Army Corps of Engineers HEC-RAS (USACE, 2010) model for the dam and the downstream river to the sea.

2. LITANI RIVER BASIN

2.1. INTRODUCTION

The Litani River Basin is the largest in Lebanon at 2,088 km^2, running 118 km north to south, 32 km east to west at its widest point, and 6 km at its narrowest. It covers four administrative regions (Mohafazats): Al Bekaa, Al Nabatiye, Jabal Lubnan (Mount Lebanon) and the South one (Al Janoub) (MENBO, 2007). The river rises in the northern Bekka Valley, occupies the Central and South Bekaa Valley between Mount Lebanon to the west and the Anti-Lebanon mountain range to the east and runs southward to Beaufort Castle where it turns westward to the Mediterranean Sea (Amery, 1993). A geographic bounding box is 34°1'2" N, 36°23'31" E in the lower left corner and 33°11'24" N, 35°13'19" E in the upper right corner.

The annual precipitation in the Litani River Basin averages 750 mm/year and ranges between 300 mm/year inland and 1300-1400 mm/year over the mountains (MENBO, 2007). The average flow for the basin is approximately 580 million m^3 per year for the period 1947-1971, 27% occurring in the summer (May-October) and 73% during the winter (November-April) (Soffer, 1994). Flow records of the Litani River Authority (LRA) show the annual flow of the Litani River at the point where it enters the Qaraoun Reservoir to be 339 million m^3 (LRBMS, 2011).

Floods created by heavy winter precipitation are common occurrences in the valley and their impacts have been increasing recently. In February 2003 one of the largest floods was experienced in the basin with an estimated return period of about 70 years or 1.4 % probability of exceedance in any year (LRBMS 2011a). This flood occurred after approximately 10 consecutive days of heavy rainfall in combination with snowmelt. Limited flow data exists in the Litani River Basin (only daily discharge values with unknown accuracy and limited duration) and some historical flooding information has been collected from accounts of witnesses.

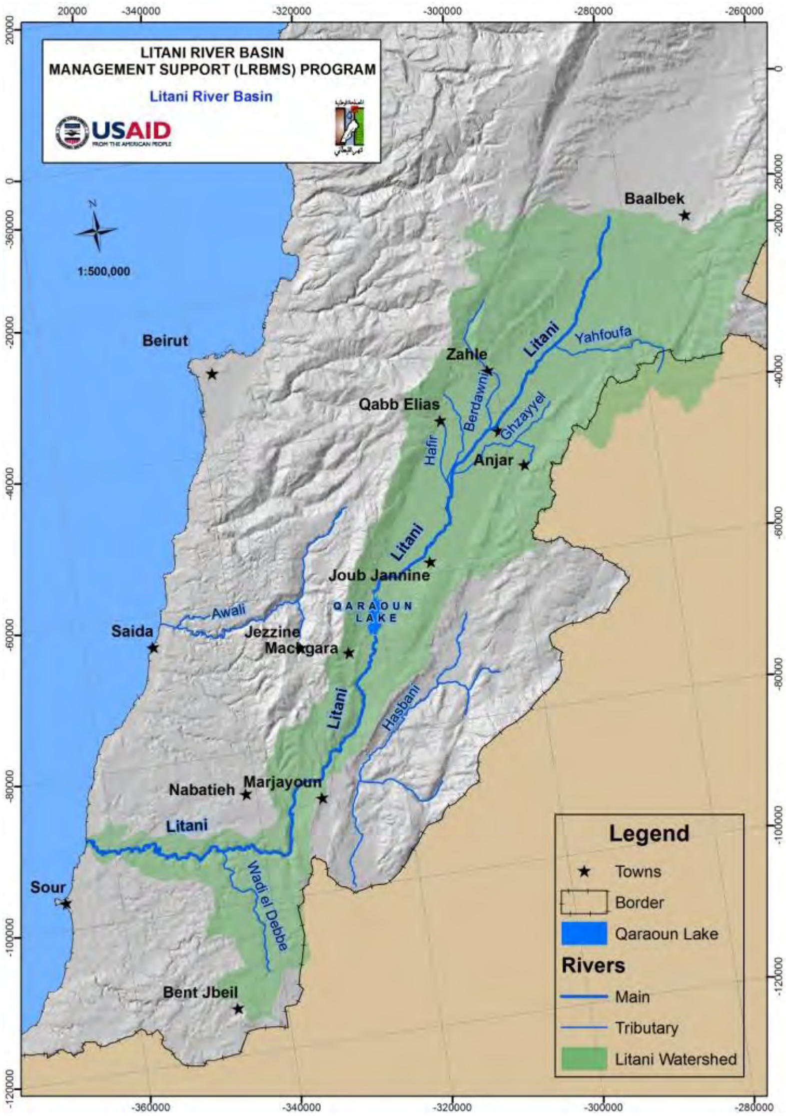


Figure 1. Litani River Basin.

Table 1. Average Monthly Litani River Flows at Qaraoun Dam inflow (1962-2010).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Year**
MCM	50.9	74.7	72.1	50.6	23.1	7.5	2.8	2.5	3.7	7.7	13.5	29.9	339.0
m3/s	19.4	28.4	27.4	19.2	8.8	2.9	1.0	0.9	1.4	2.9	5.2	11.4	10.8

Source: LRBMS (2011a, Table 1)

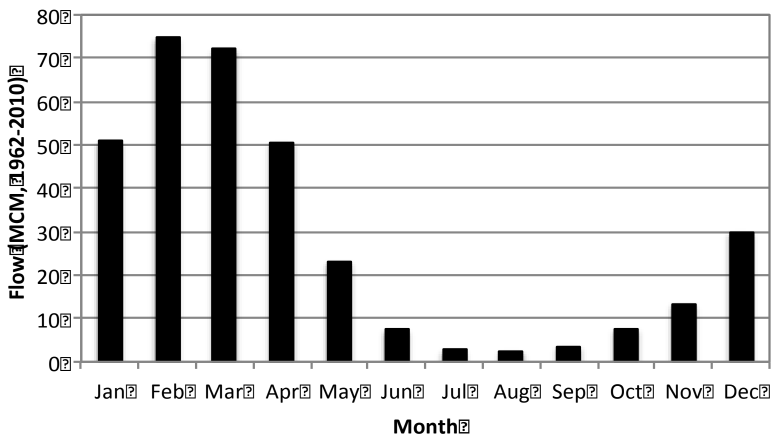


Figure 2. Average monthly Litani River flows at Qaraoun Dam inflow. Source: LRBMS (2011a, Table 1)

2.2. TOPOGRAPHIC DATA

Topographic data for the Litani River Basin was obtained from Lebanese Army 1:20,000 Topographic Maps (LRBMS, 2011b). These maps were scanned and georeferenced according to the local coordinate system in Lebanon (Double Stereographic Projection). The contours lines from the maps were digitized on 10-meter intervals and the contours were converted to a 5m x 5m cell-size raster file (Digital Elevation Model or DEM) representing the Litani River Basin. The final DEM is shown in Figure 3 along with an outline of the lake behind the Qaraoun Dam and the Litani River from the lake to the sea. The elevation change from the dam to the sea is shown in Figure 4.

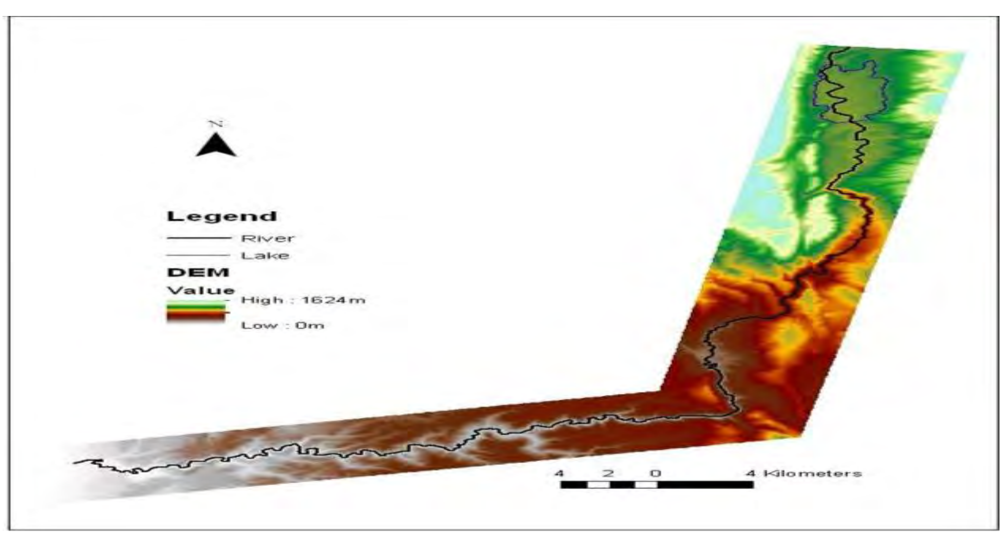


Figure 3. Digital Elevation Model (DEM) of the Litani River Basin below Qaraoun Dam. Source: LRBMS (2011b)

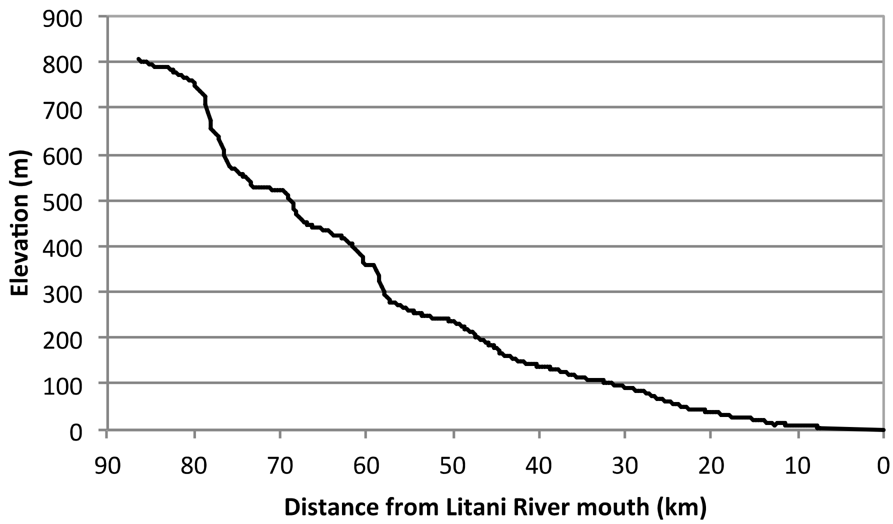


Figure 4. Litani River Basin elevation profile from Qaraoun Dam (on the left of the figure) to the Mediterranean Sea (on the right in the figure)

2.3. QARAOUN DAM

2.3.1. BASIC CHARACTERISTICS OF THE DAM

The Qaraoun Dam (33°34'11.63" N 35°41'51.18" E) is located at a narrow point at the southern end of Bekaa plain at an elevation of 800m above sea level (Figures 5 and 6). The catchment area above the dam is 1,600 km^2. The dam has a maximum capacity of 220 million m^3 (at water level elevation of 858m above mean sea level (amsl)) and an effective storage (live storage) of 160 million m^3. The dam has a length of 1090m and is a concrete faced rockfill dam with the principal characteristics as summarized in Table 2 (LRBMS, 2010). The height of the dam is 61 m, and it is 162m wide at the base and 5m at the top. The full lake covers an area of 12.3 km^2. The dam is multipurpose, including: hydropower generation, irrigation and domestic water supply. The maximum flood elevation for the spillway is 862m where the area of the lake is 12.6 km2. The average water level for power generation is 835m with the minimum level operational level is 827m. Plan and center cross-section views of the dam are shown in Figure 7 and 8.

Figure 5. Qaraoun Dam in Bekaa Valley, Lebanon. (Source: Draft RBM Plan, LRBMS, 2011)

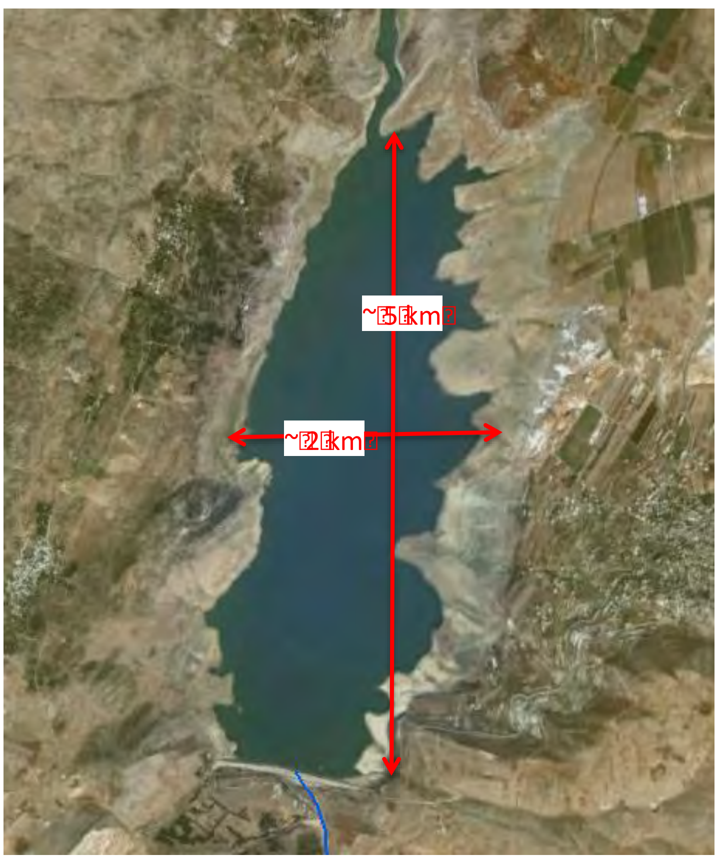


Figure 6. Qaraoun Dam and reservoir. Source: Google Earth (accessed 18 December 2011)

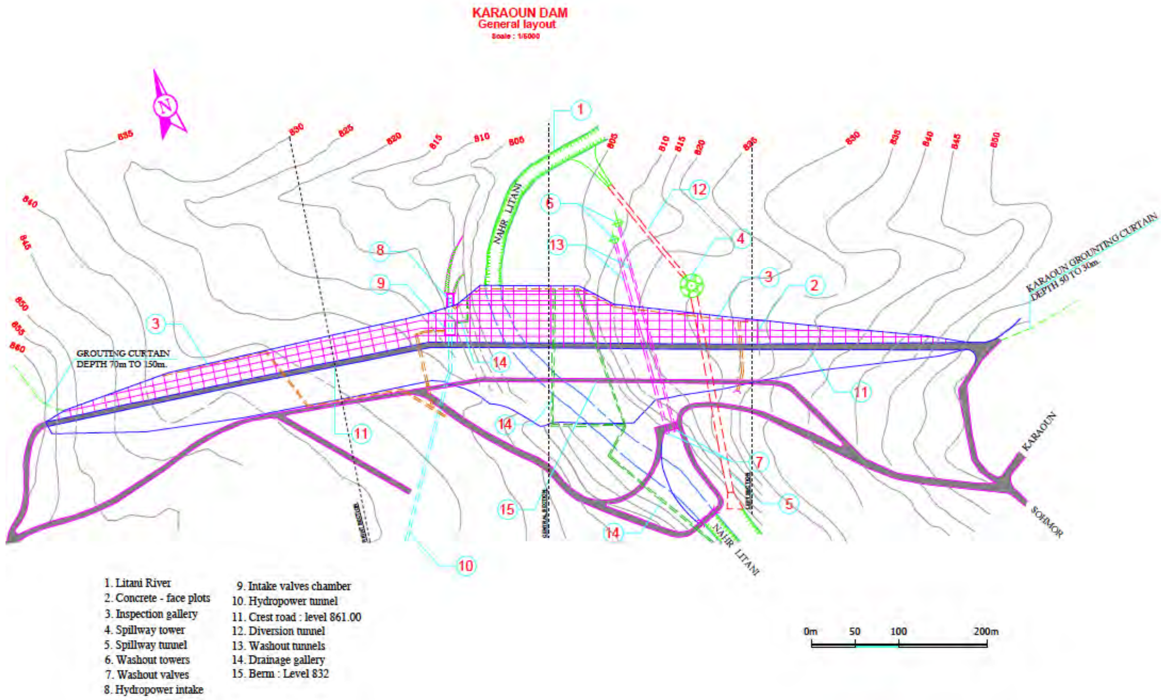


Figure 7. Qaraoun Dam plan view. Source: LRBMS Program, personal communication (2011)

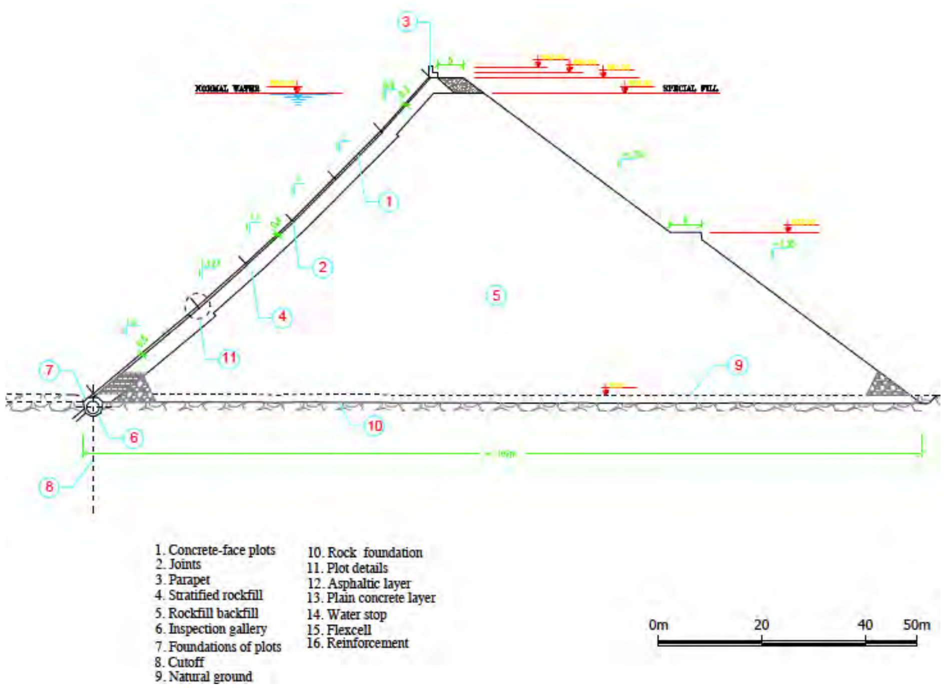


Figure 8. Qaraoun Dam main section view. Source: LRBMS Program, personal communication (2011)

Table 2. Quaraoun Dam Charactistics. Source: LRBMS (2011)

Item	Description
Length	1,100m
Height	60m
Elevation of the top of the spillway	858m
Elevation of the highest water for spillway flow	860.5m
Elevation of the crest of the dam	861m
Slope of the embankment – downstream	1.35H:1.0V
Slope of the embankment – upstream	1.2 to 1.0H:1.0V
Thickness of the reinforced concrete facing	50cm at bottom to 30cm at top
Dam reservoir capacity (at elevation 858m)	220 million m3
Area of the reservoir (at elevation 858m)	1,200 ha
Nominal capacity of the spillway	600m3/s
Drains capacity below elevation 858m	140m3/s

2.3.2. POTENTIAL FAILURE MODE ANALYSIS

A Potential Failure Mode Analysis (PFMA) was performed for the Qaraoun Dam in 2010 to identify potential failure modes under static loading, normal operating water level, flood water level, and earthquake conditions (LRBMS, 2010). The PFMA results indicate that the Qaraoun Dam and appurtenant structures have functioned satisfactorily to date with no major safety concerns. While the risk of failure is very low, the most probable failure modes are seismic loading and flood overtopping.

- **Seismic loading failure:**
  The dam is located in an earthquake-prone zone where high intensity earthquakes are considered probable. The Qaraoun Dam is considered to be susceptible to damage and potential catastrophic failure under high earthquake loading. Deformations result in freeboard loss to such a degree that the crest is lower than the reservoir, causing a breach by overtopping erosion of the rockfill structure. Such a breach would enlarge through progressive erosion and collapse of the crest of the dam resulting in a catastrophic loss of the reservoir. This breach could form whether or not there is flow through the rockfill (piping) as the result of damage to the concrete facing.

- **Flood overtopping failure:**
  An extreme flood occurrence causing the dam to be overtopped has significant potential to cause a rapid breach of the dam if overtopping is significant. Flow over an embankment dam (earth or rockfill) usually leads to erosion of material on the downstream slope and failure of the dam. Overtopping of Qaraoun Dam could result in movement of the material on the downstream slope

of the dam with progressively more material dislodged causing collapse of the concrete face panels resulting in higher flows over the dam until total collapse occurs.

2.3.3. DAM FAILURE SCENARIOS

Three types of failure scenarios for the Qaraoun Dam could be considered, as follows.

- **Seismic loading failure:**
  An earthquake weakens the dam, which fails when the reservoir is full with a breach opening from the top and reaching a width equal to 1-2 H (H = dam height of 60m) with slopes 1/1 and a failure time of about 1 hour. Breaching parameters are calculated according to the US Bureau of Reclamation standard of practice as described in Froelich (1995a, b) and Wahl (2004). Initial conditions are minimal river flow, say 1 to 5 m^3/s. Upstream flow conditions are the flow generated automatically by HEC-RAS based on the breach starting at a given time, 1 hour after the start of simulation and developing as mentioned above. Downstream boundary condition is the river outlet into the sea.

- **Flood overtopping failure:**
  The reservoir is full and a large flood comes. The spillway for Qaraoun Dam is uncontrolled (i.e. it operates automatically when water level reaches the overflow) and is sized for very large flood discharges (i.e. 10,000-yr return period flood), so the overtopping risk is almost nil. This risk could become of consideration only in the case of:

- **Ancillary failure:**
  Spillway and bottom gate are blocked/non-operational during a very large flood that overtops the dam causing failure. This scenario would have actually have the same consequences as the seismic failure: breaching would be similar while the addition of a large flood (hundreds of m3/s) is negligible considering the flood generated by the reservoir emptying (tens of thousands of m3/s).

For this report, the primary mode of potential failure of the Qaraoun Dam is considered to be breaching and overtopping due either to seismic activity or flooding.

3. DAM BREAK MODELING

3.1. INTRODUCTION

Dam break modeling requires the solution of an unsteady (rapidly time varying) river flow hydraulics problem. Many early dam-break investigations assumed that the breach or opening formed in a failing dam encompassed the entire dam and occurred instantaneously. While this assumption may be nearly appropriate for concrete arch dams, it is not valid for earthen dams or concrete gravity dams. Because earthen dams generally do not fail completely nor instantaneously, dam break models allow for the investigation of partial failures occurring over a finite interval of time (Fread et al., 1991). The U.S. Army Corps of Engineers HEC-RAS software (USACE, 2010) includes the capability to model the unsteady hydraulics of an embankment dam breach due to several failure mode options. Using HEC-RAS for the routing modeling of dam failures is the current standard procedure in the US, and notably for US Army Corps of Engineers and US Bureau of Reclamation.

The primary input variables of importance in the dam break analysis are (Wahl, 1998):

1) Reservoir volume when breaching commences (m^3). This is often taken as the full reservoir volume for overtopping failure cases;
2) Reservoir water surface elevation when breaching commences (m). This is often taken as the top of the dam for overtopping failure cases;
3) Breach depth (*h*) – the vertical extent of the breach, measured from the dam crest to the invert of the breach (m). This is often taken as the elevation of the river channel at the upstream base of the dam. The bottom of a fully formed breach usually is the dam foundation, which is more resistant to erosion than the embankment material. However, the height might be limited by the volume of water in the reservoir at the time of failure, or by the presence of a layer of erosion-resistant material located in the embankment (Froehlich 2008).
4) Breach width (*B*) – the final width of the breach (m). The breach width and rate of formation have an impact on the peak flowrate and the inundation level downstream from the dam.
5) Breach initiation time – the time from the first flow over or through the dam that will initiate warning, evacuation, or heightened awareness of the potential for dam failure. The breach initiation time ends when breach formation starts.

6) Breach formation time (t) - the time required for the breach formation (hours). The breach formation time is the duration of time between the first breaching of the upstream face of a dam until the breach is fully formed. For overtopping failures the beginning of breach formation is after the downstream face of the dam has eroded away and the resulting crevasse has progressed back across the width of the dam crest to reach the upstream face;

3.2. ESTIMATING DAM BREACH PARAMETERS

3.2.1. MAXIMUM BREACH DISCHARGE

Several researchers have compiled data on the failure of rock-filled embankment dams (Froehlich 1995; Wahl 2004; Froehlich 2008). Wahl (2004) compared the uncertainty of several breach parameter prediction formulas, including the aforementioned equations. The Froehlich equations were found to have the smallest uncertainty and are currently considered as standard procedures.

Using data from numerous embankment dam failures, Froehlich (1995) related the peak outflow in a dam breach to a power function of both the breaching head and outflow volume

$$Q_{max} = 0.607KV^{0.295}\ h^{1.24} \qquad (1)$$

where

Q_{max} is the peak flow (m^3/sec),

h is the height of the dam breach (m),

V is the reservoir volume (m3),

K is an overtopping multiplier (1.4 for overtopping failure, 1.0 for piping failure).

The maximum volume of Qaraoun Dam is about 220 million m^3. Eq. 1 can be used to compute the hypothetical maximum outflow from Qaraoun Dam as

$$Q_{max} = 0.607(1.4)(220\text{x}10^6)^{0.295}\ (60)^{1.24} = 39{,}377\ m^3/sec \qquad (2)$$

3.2.2. BREACH DEVELOPMENT TIME

The expression developed for the breaching time (t, hr) is (Froehlich 1995)

$$t = 0.00254V^{0.53}\ h^{-0.9} \qquad (3)$$

In the case of Qaraoun Dam, the breaching time is approximated as

$$t = 0.00254(220\text{x}10^6)^{0.53}(60)^{-0.9} = 1.68 \text{ hr} \qquad (4)$$

3.2.3. BREACH WIDTH

An expression for the breach width (B, m) was also developed (Froehlich 1995)

$$B = 0.1803 V^{0.32} h^{0.19} \quad (5)$$

In the case of Qaraoun Dam, the final breaching width can be approximated as

$$B = 0.1803(220x10^{6})^{0.32}(60)^{0.19} = 183.4 \text{ m} \quad (6)$$

3.3. REPRESENTATION OF LITANI RIVER AND QARAOUN DAM IN HEC-RAS

3.3.1. LITANI RIVER

The Litani River Basin downstream of the Qaraoun Dam is very steep, dropping 800m in the approximately 90 km distance to the mouth of the river at the Mediterranean Sea. The river flows through several deep and winding canyon sections interspersed with wide, flat reaches over this interval. These aspects of the river make the dam break modeling problem challenging as it is difficult to determine the appropriate number and placement of cross-sections for the model as well as the best model time step for the simulations.

The final DEM is shown in Figure 3 along with an outline of the lake behind the Qaraoun Dam and the Litani River from the lake to the sea. Initial river cross-sections for the HEC-RAS model were generated using this DEM. The initial set of river cross-sections are shown in Figure 9.

The stability of the HEC-RAS model is function of the distance between the cross sections and the time step used in the simulation. The minimum value allowed by HEC-RAS is one second. A five second time step was used for the Litani model to achieve stability of the calculations. Other, larger time steps were tested, but not found to result in stable calculations.

New cross-sections with a shorter distance between them were interpolated between the initial sections at locations where the HEC-RAS solution became unstable. First, all of the initial river cross-sections were interpolated to 10 m and then further interpolation to 5 m was carried out. Finally, some reaches of the river had to be interpolated to 1 m distance between cross-sections in order to achieve a stable solution.

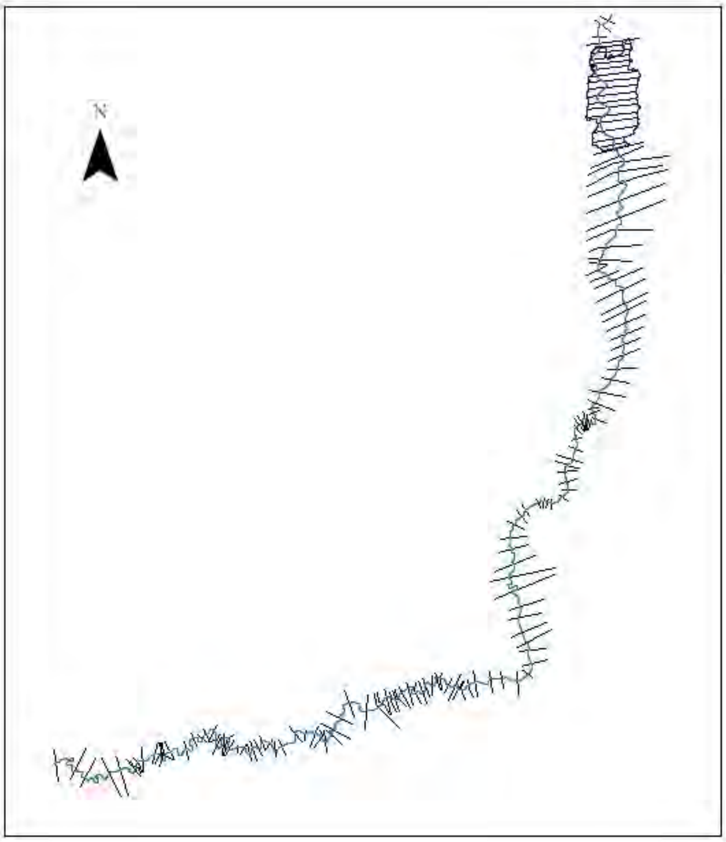


Figure 9. Initial cross-sections for Litani River HEC-RAS model.

The roughness of the terrain due to ground materials and vegetation is represented in the HEC-RAS calculations by the Manning roughness coefficient. The roughness coefficient was considered homogeneous for the entire Litani River model with a value of 0.05. According to Chow (1959) this value is recommended for mountain streams.

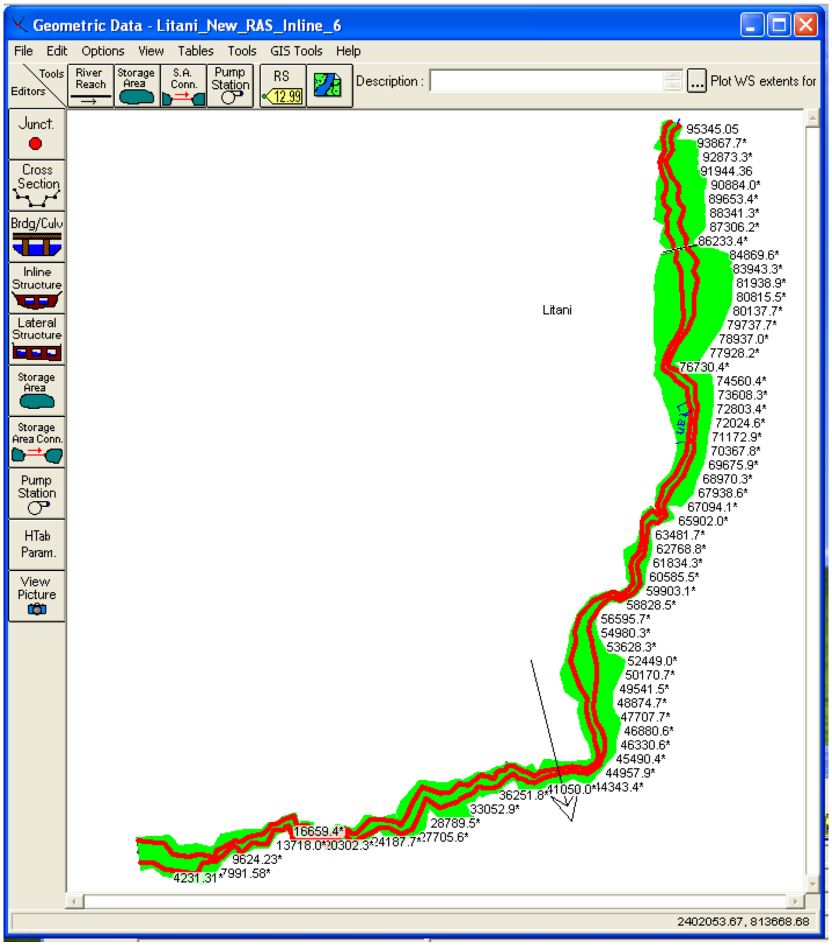


Figure 10. Interpolated cross sections for Litnai River dam breach model.

3.3.2. QARAOUN DAM BREACH DATA

HEC-RAS allows the modeling of the breach process by entering key data and assumptions regarding the dam, the reservoir and the breach most probable characteristics, as shown in Table 3 and Figure 10. The breach formation time for an embankment dam with the same characteristics as Qaraoun Dam was estimated to be 1.67 hours (Froehlich equations, para 3.2). The breach formation time used in the model was initially set to 4.5 hours and then decreased systematically to 1.5 hours to test stability of the model. The breach is produced by overtopping, since this is the most probable case (LRBMS, 2010). The bottom width of the breach is 140 m, representing the river channel width at the bottom of the dam (see Figure 11). In order to have a stable model, the river was considered wet at the beginning of the simulation with an initial flow of 1 m^3/sec.

Table 3. HEC-RAS Dam Breach Plan for Qaraoun Dam on Litani River

Item	Value
River station of Dam	85705.98 m (upstream from the sea)
Pilot Flow	1 m3/sec
Upstream Embankment slope	1.35:1
Downstream Embankment slope	1:1
Center station	752 m
Final Bottom Width	140 m
Final Bottom Elevation	804 m
Left side slope	1:1
Right side slope	1:1
Full formation time	4.5 then 1.5 hr
Failure mode	Overtopping
Trigger Failure	Set Time
Start time	0100

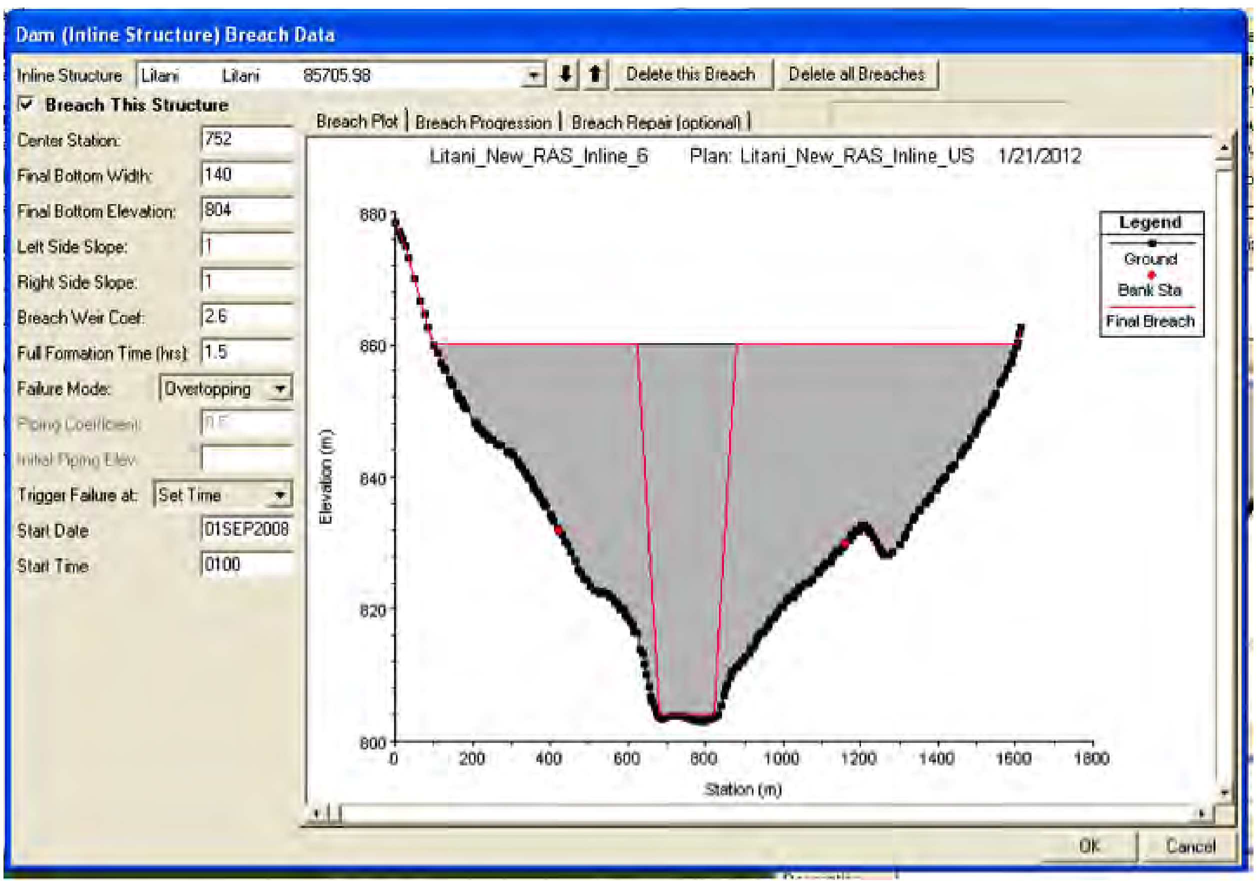


Figure 11. Qaraoun Dam breach model data.

3.4. HEC-RAS UNSTEADY FLOW ANALYSIS PARAMETERS

To model the dam breach process in HEC-RAS, an unsteady flow calculation is performed. A simulation period of 23 hours was used with the dam breach initiated one hour after the start of the simulation. The Qaraoun Dam is modeled as an "inline structure" in the HEC-RAS model. The dimensions of the dam are known from the plan (Fig. 7) and section (Fig. 8) illustrations and the data in Table 2. The data needed to represent the dam breach in HEC-RAS are shown in Table 3 and Figure 11.

Boundary condition and initial condition data must be entered for the unsteady analysis. Boundary conditions at the upstream river reach above the dam was entered as a constant flow rate of 1 m^3/sec. The downstream boundary condition at the sea was as a normal depth boundary condition with a water surface slope of 0.001 m/m. Also, the initial flow in the basin at the start of the simulation period was set to a1 m^3/sec in each section. A number of computational parameters have to be set in order to achieve a stable simulation when modeling a dam break flood. These parameters are shown in Figures 13 and 14.

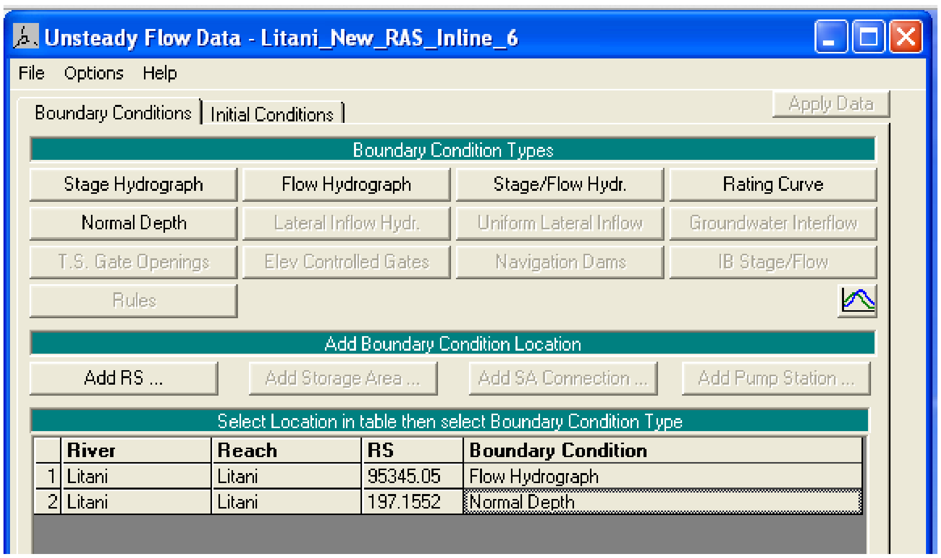


Figure 12. Boundary and initial condition data for Qaraoun Dam breach model.

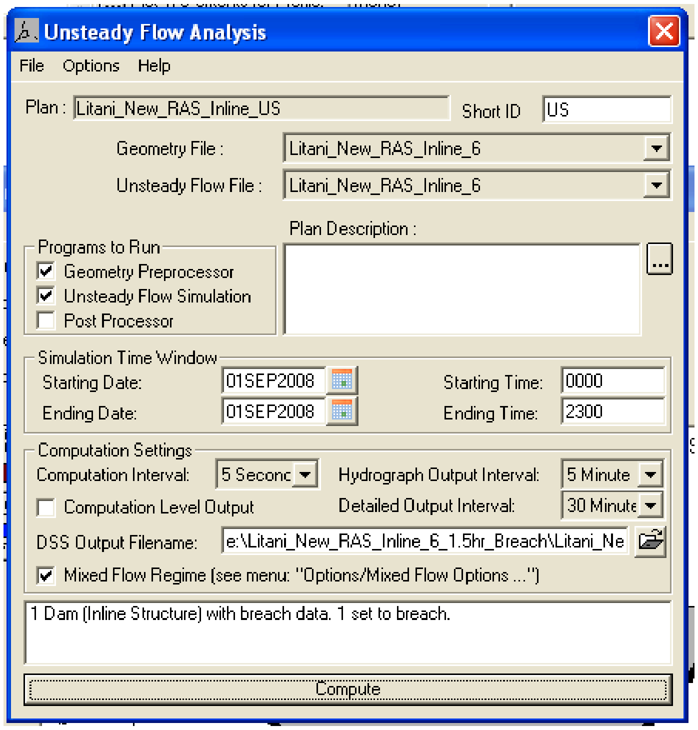


Figure 13. Unsteady flow simulation parameters for Qaraoun Dam breach model.

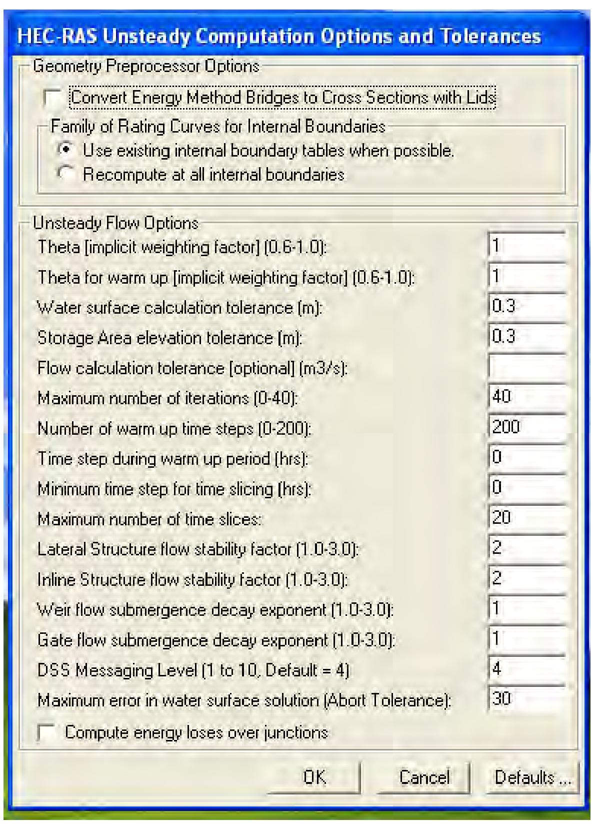


Figure 14. Computational parameters set for the Qaraoun Dam breach model.

4. RESULTS

4.1. DAM BREACH TIME OF 1.5 HOURS

The time for the dam to breach is 1.5 hours, the peak of the outflow from the dam occurs 1 hour and 25 minutes after the beginning of the breaching process. The maximum flow rate from the dam is 67,528 m^3/sec. This value is higher than the previous estimate (from Froehlich equations) of 39, 000 m3/s. This can be explained by the fact that Qaraoun Dam is a rockfill dam, thinner and with a steeper upstream facing than earthfill dams used to develop Froehlich equations.

Figure 15 shows the location of selected stations on the Litani River below Qaraoun Dam where HEC-RAS model results are reported. Table 4 lists these sections along with the main results: initial stage (water elevation) in the river before the dam breach; the maximum stage of the river during the flood; the height of the flood wave passing the section; and the time of the peak of the flood. The flood wave is about 40 m high and does not attenuate much till reaching the coastal valley. The peak flow abates progressively from initially 67,500 m3/s to 37,700 m3/s at the sea outlet.

Figures 16 - 25 show the water elevation, flow rate and cross-section for the cross sections listed in Table 4. From this it is possible to determine that the lag time between the peak flow below the dam at river station 85614 and the peak flow at the downstream cross section 197 at the mouth of the river is 115 minutes. Hence, the dam breach wave would travel the 85 km in slightly less than 2 hours (115 minutes) that is at a pace of 44.6 km/hr.

Table 4. Maximum stage, flow and time of peak flow for selected Litani River stations below Qaraoun Dam.

Cross-section	Initial Rise Time *	Peak Time *	End Time *	Peak Flow	Initial Stage	Peak Stage	Flood Height
	hr:min	hr:min	hr:min	m3/sec	m	m	m
85705.98 (dam)	0:00	1:25	3:20	67528.2	802.2	839.2	37.0
85614 (below dam)	0:00	1:25	3:20	67304.3	802.2	839.2	37.0
81599 (Sohmor)	0:25	1:35	4:10	48679.7	777.9	820.5	42.6
75550 (Yohmor)	0:40	1:35	5:00	48340.2	583.5	612.2	28.6
66319 (Berghoz)	0:55	1:45	6:25	47397.7	449.2	488.2	39.0
60616 (Blat)	1:05	1:50	7:35	46830.0	390.3	431.5	41.1
52329 (Mazraat)	1:15	2:05	7:45	45428.0	245.5	274.8	29.3
44333 (corner)	1:30	2:15	11:00	43839.0	168.9	221.7	52.8
32066 (Marnaba)	1:55	2:35	12:00	41880.2	107.3	144.9	37.6
7278 (Idaide)	2:35	3:05	13:00	39215.1	5.6	21.8	16.3
197 (mouth)	2:50	3:20	13:15	37738.3	2.6	13.4	10.8

* Time from time of breach initiation

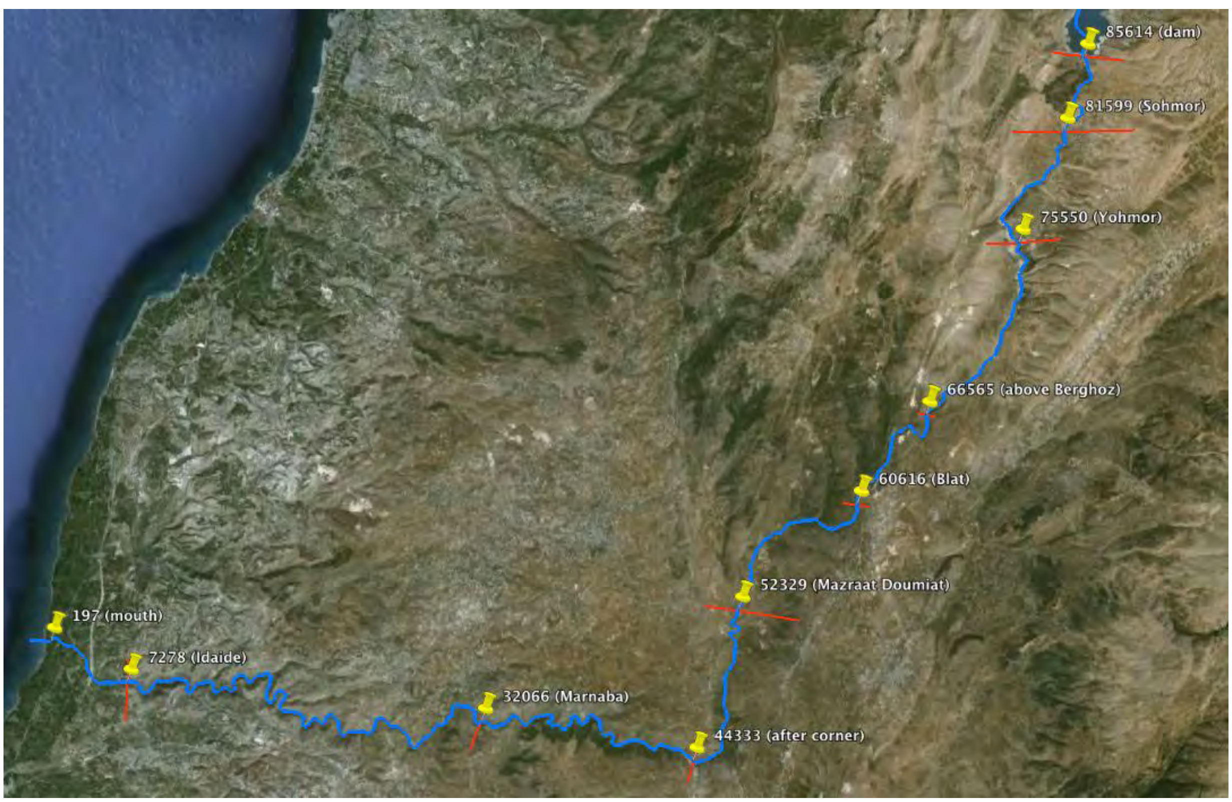
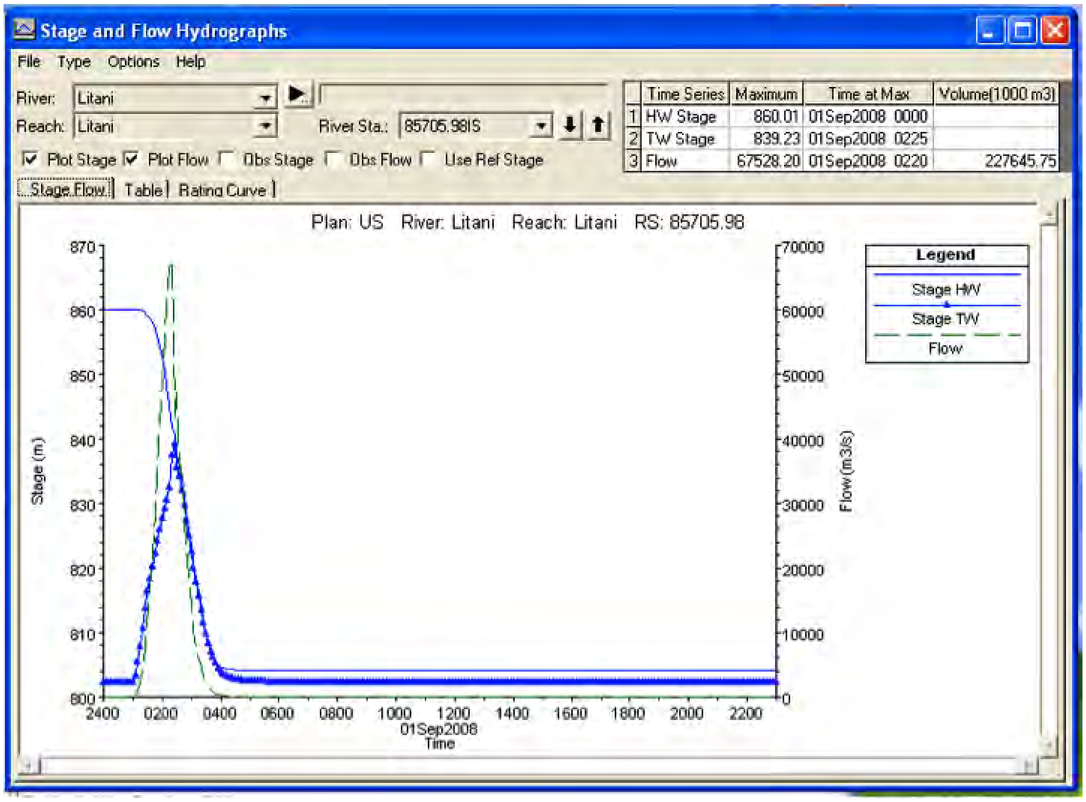
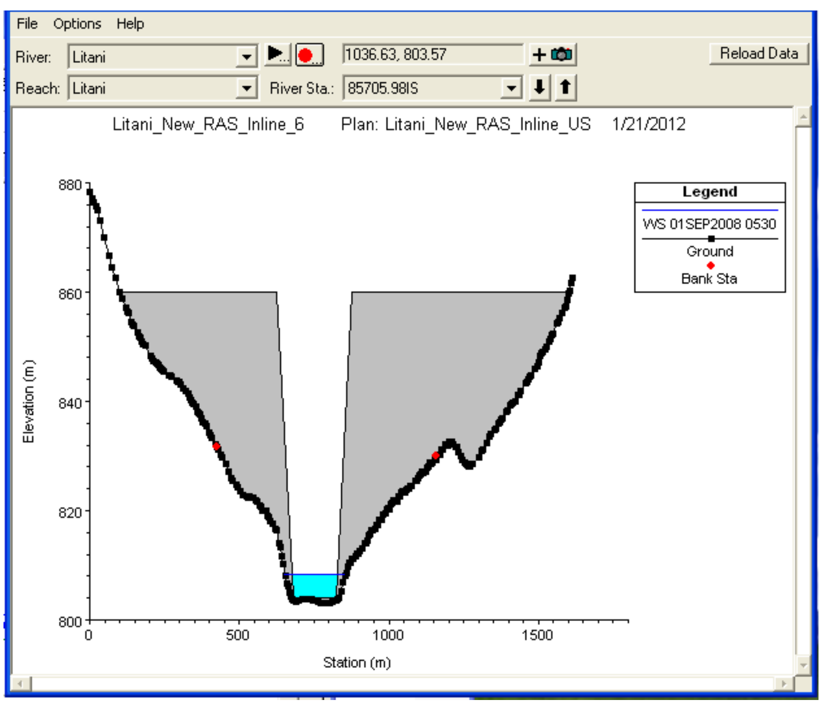


Figure 15. Selected Litani River stations below Qaraoun Dam



(a) Hydrograph at Dam,



(b) Cross Section at Dam

Figure 16. Qaraoun Dam break simulation results. (a) Hydrograph at Dam, (b) Cross Section at Dam

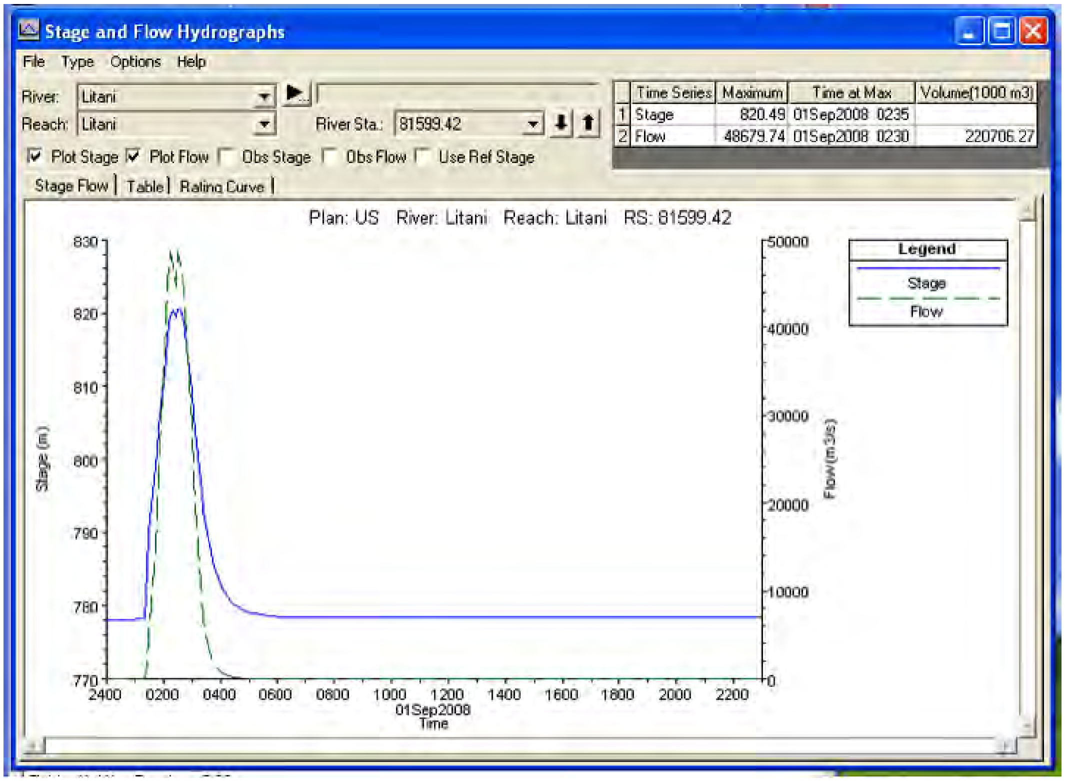


Figure 17. Qaraoun Dam break simulation results. Hydrograph at station 81599 (Sohmor).

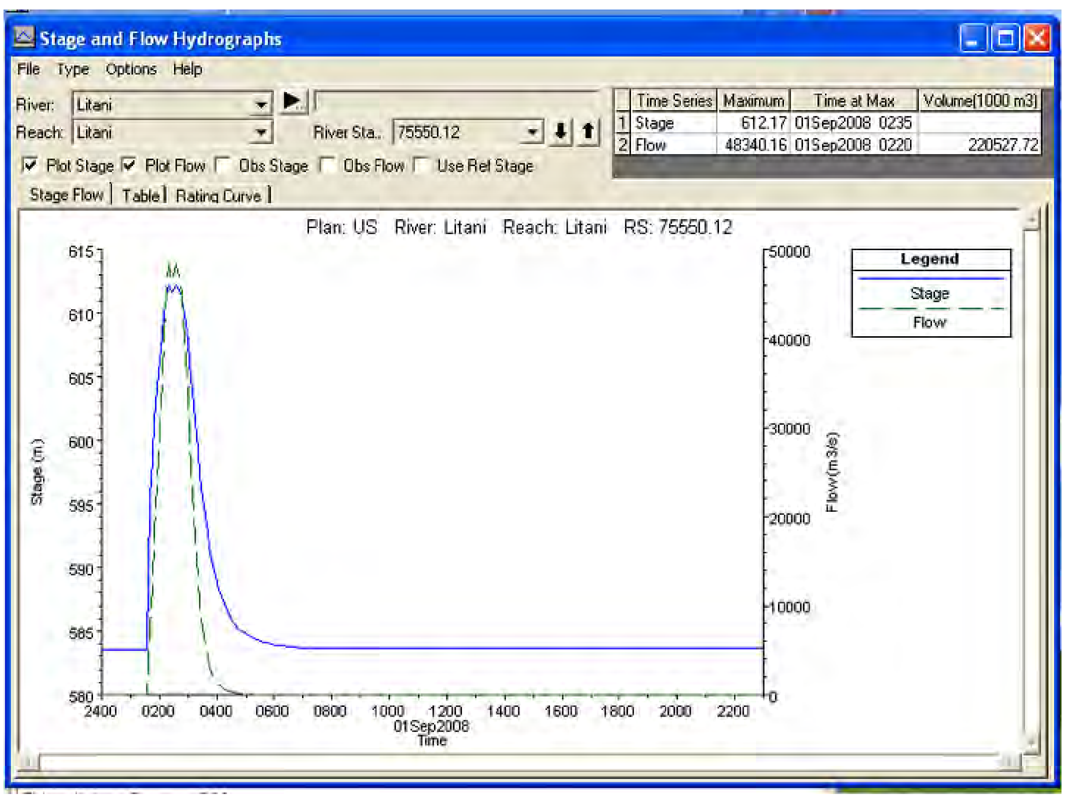


Figure 18. Qaraoun Dam break simulation results. Hydrograph at station 75550 (Yohmor).

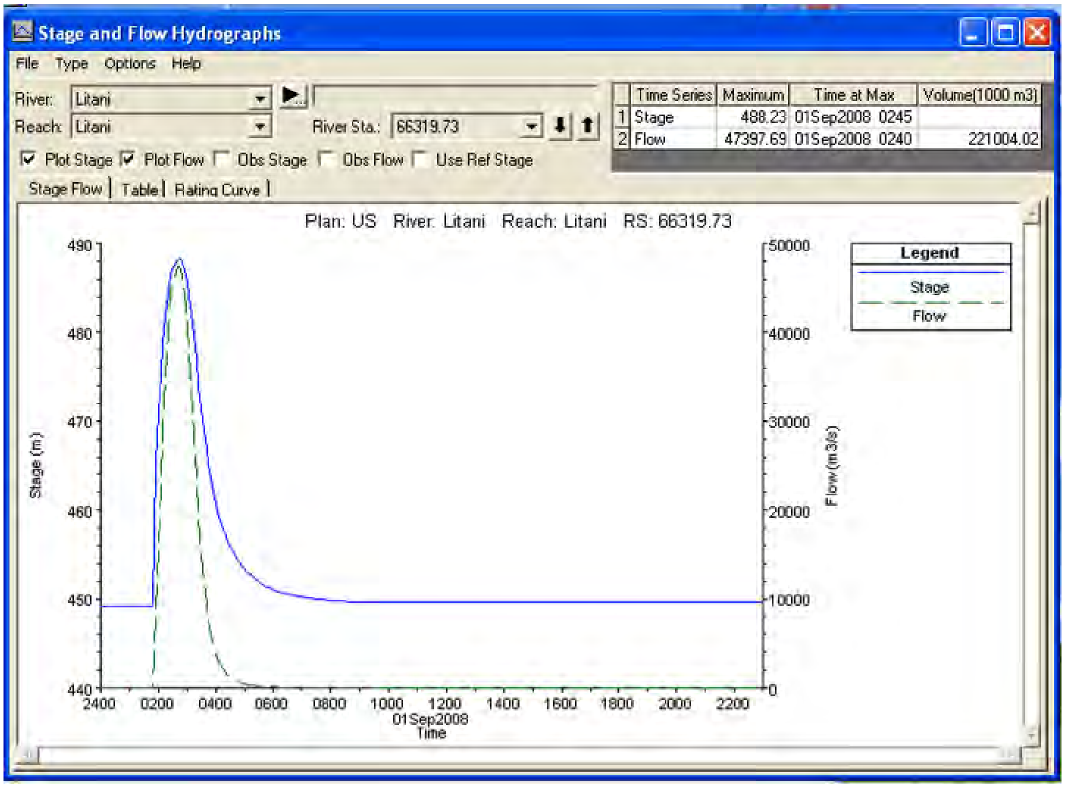


Figure 19. Qaraoun Dam break simulation results. Hydrograph at station 66319 (Berghoz).

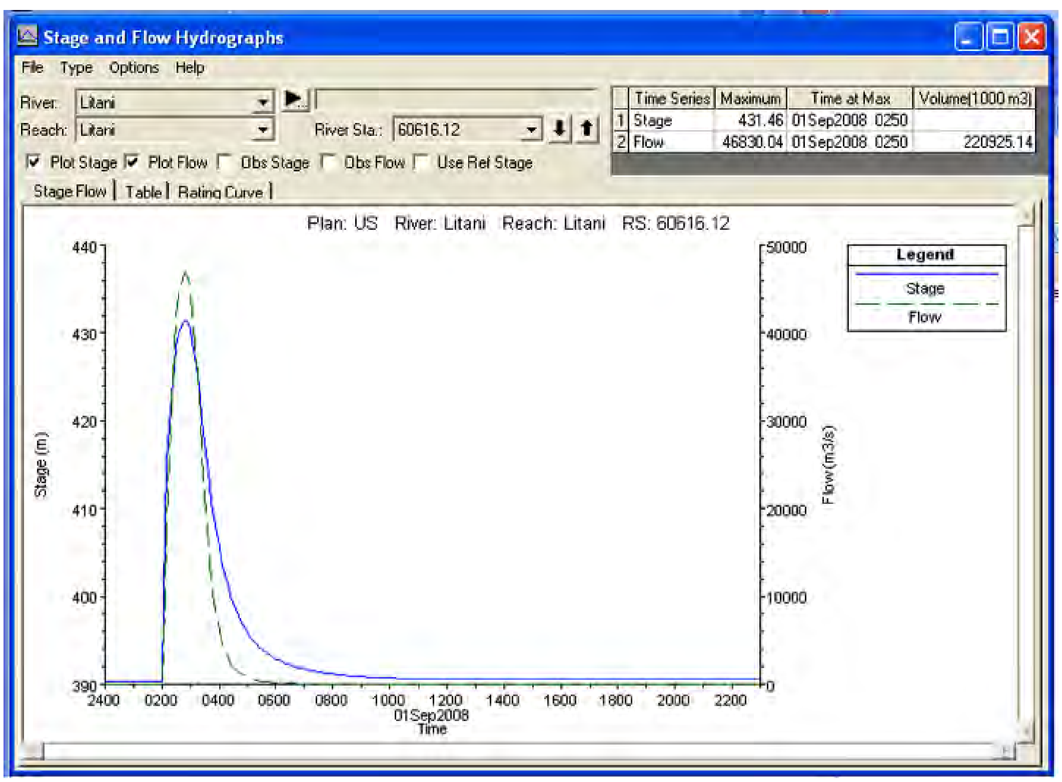


Figure 20. Qaraoun Dam break simulation results. Hydrograph at station 60616 (Blat).

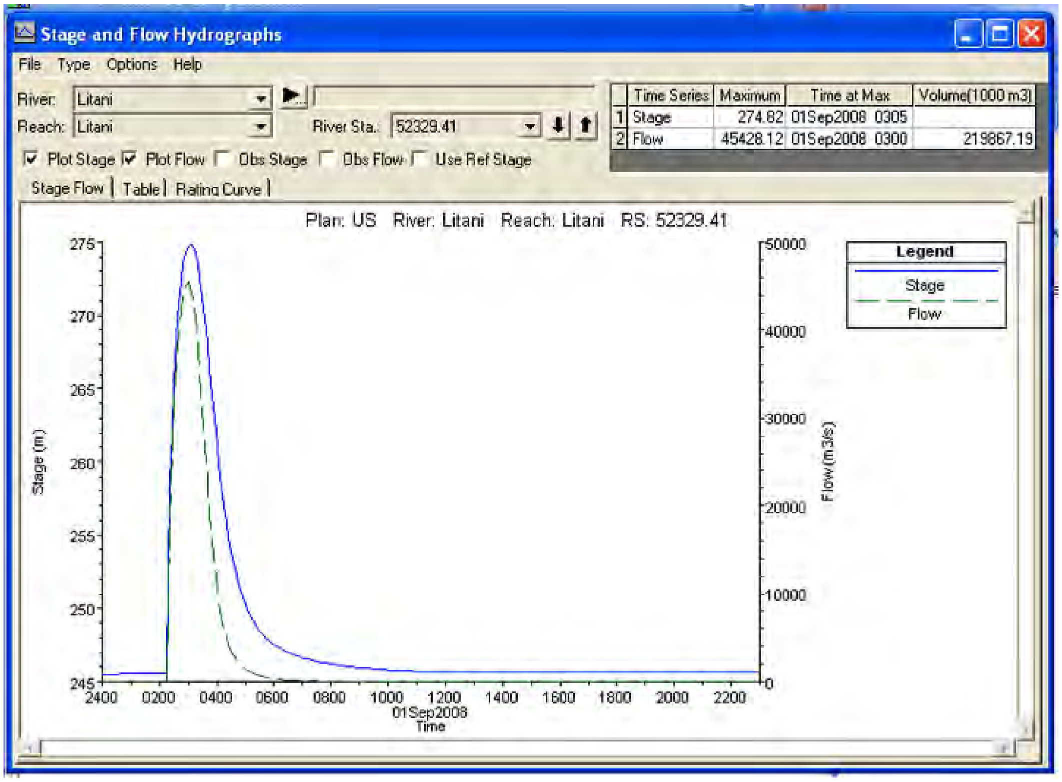


Figure 21. Qaraoun Dam break simulation results at station 52329 (Mazraat Doumiat).

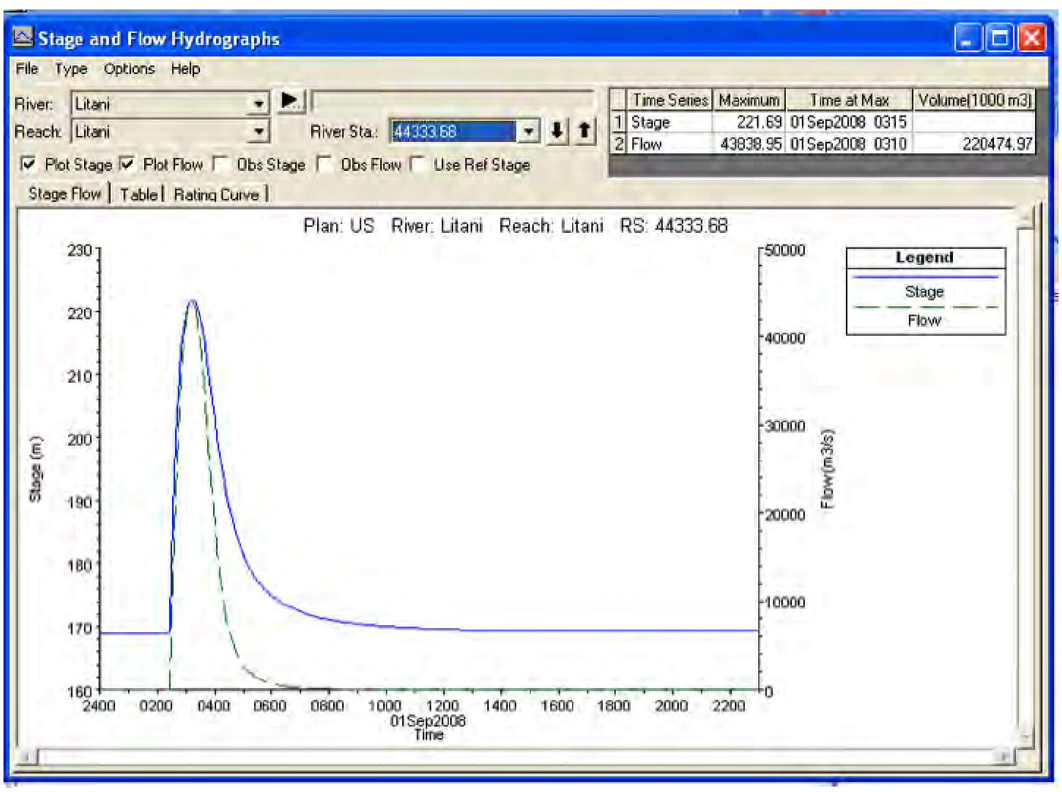


Figure 22. Qaraoun Dam break simulation results. Hydrograph at station 44333 (corner).

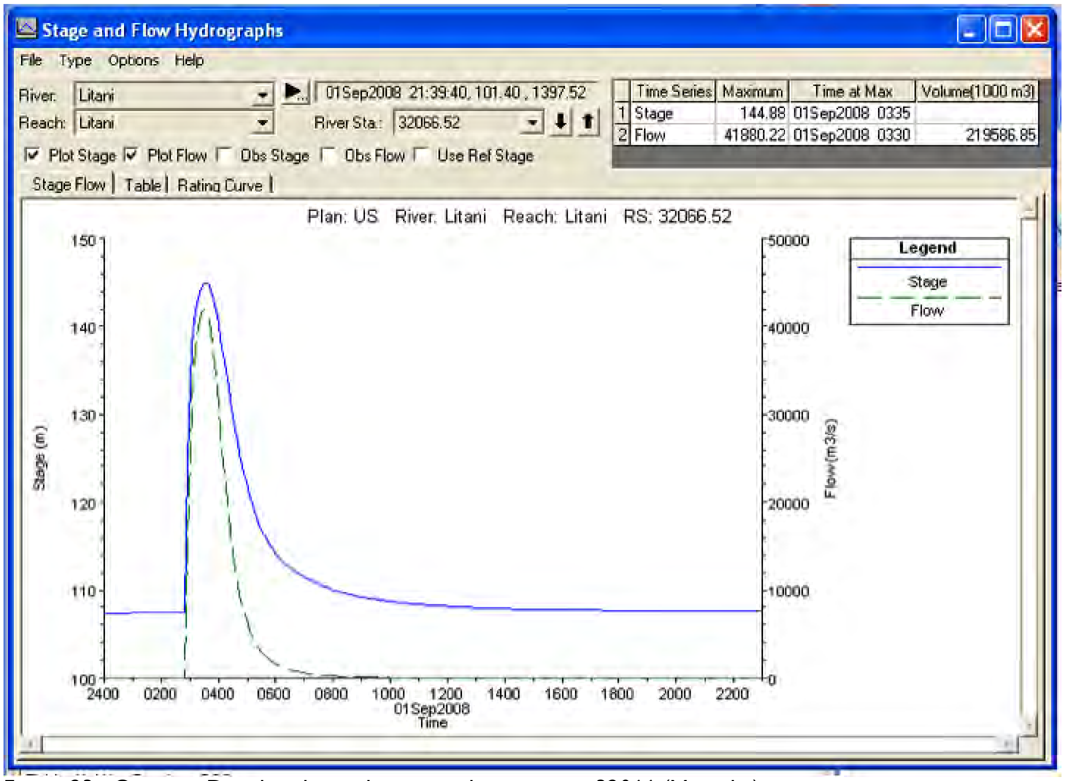


Figure 23. Qaraoun Dam break simulation results at station 32066 (Marnaba).

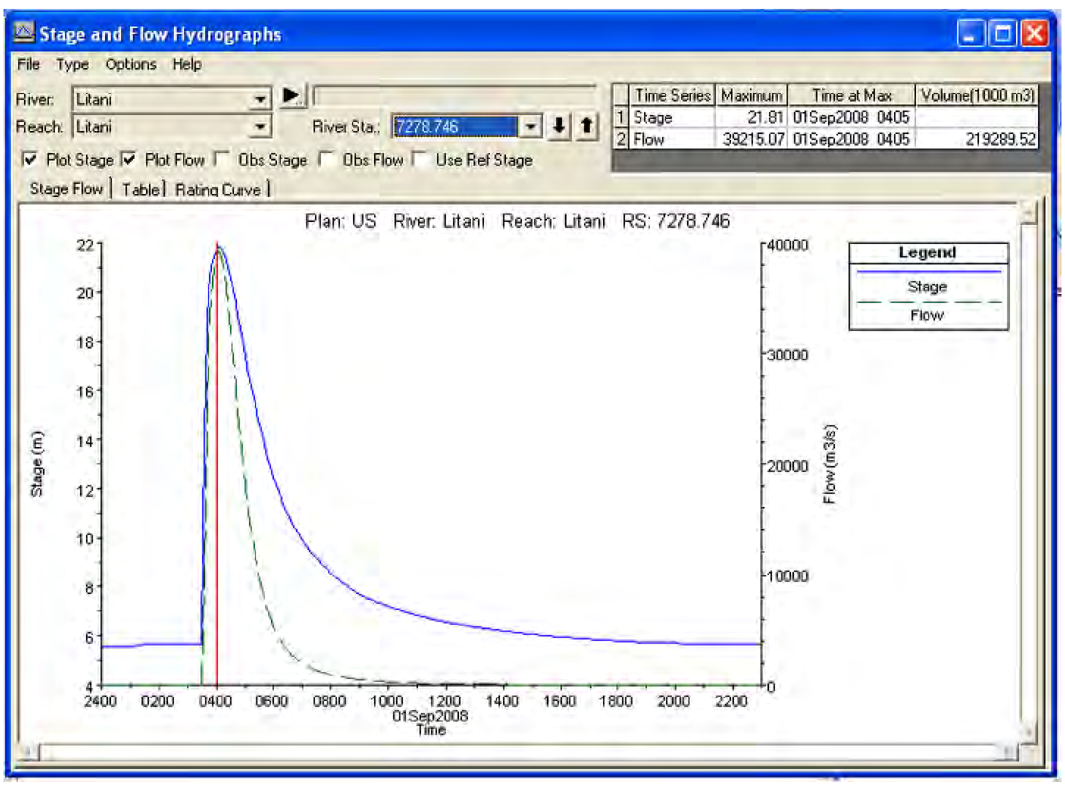


Figure 24. Qaraoun Dam break simulation results. Hydrograph at station 7278 (Idaide).

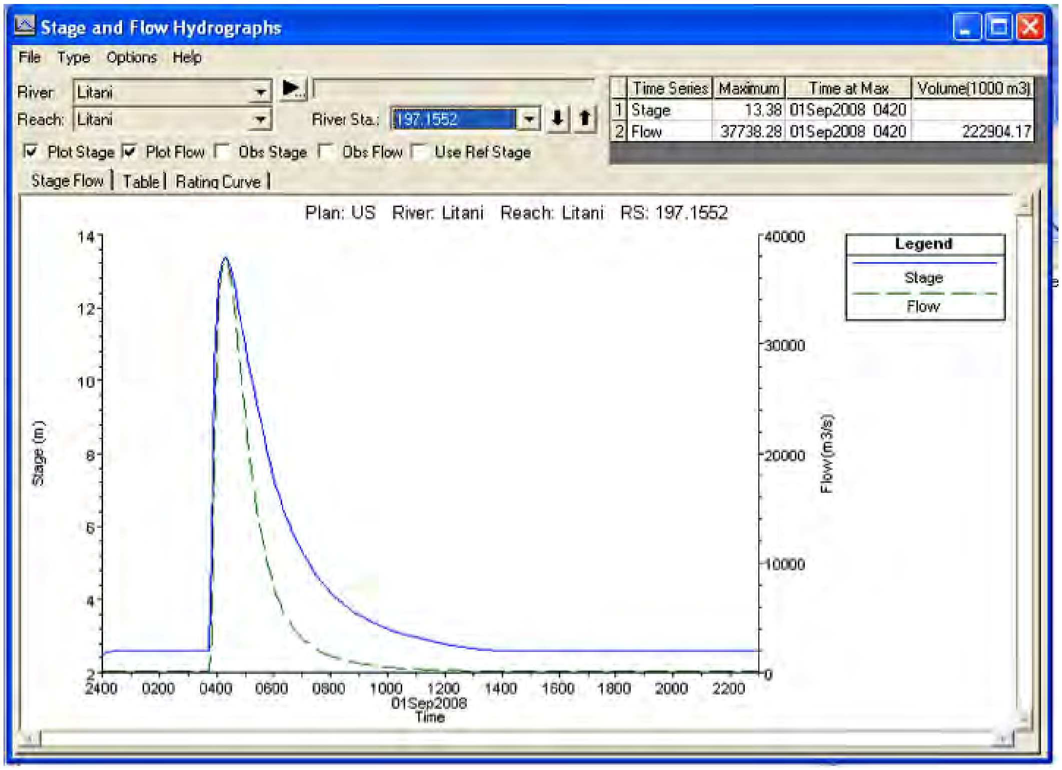


Figure 25. Qaraoun Dam break simulation results. Hydrograph at station 197 (mouth).

4.2. SENSITIVITY ANALYSIS OF DAM BREACH TIME

Table 5 lists the results for a breaching time of 2 hours. For various stations along the river below the dam the table lists the height of the flood wave passing the section; the time of the peak of the flood, and the peak follow of the flood. The flood wave is between 10m and 42m in height, except for the section just downstream of the corner in the river where the height increases to almost 52m. These results are almost the same as the results for a 1.5-hour breaching time.

Table 5. Maximum stage, flow and time of peak flow for selected Litani River stations below Qaraoun Dam with a 2.0 hour breach formation time.

Station	Height of Flood Wave (m)	Time to Peak (hr:min)	Peak flow (m3/s)
85614 (below dam)	31.92	1:50	55136.6
81599 (Sohmor)	42.48	1:50	48200.2
75550 (Yohmor)	28.46	1:55	47711.3
66319 (Berghoz)	38.60	2:00	46743.2
60616 (Blat)	40.57	2:10	45823.0
52329 (Mazraat Doumiat)	28.91	2:25	44271.6
44333 (corner)	51.96	2:30	42793.5
32066 (Marnaba)	37.17	2:50	40916.8
7278 (Idaide)	16.15	3:20	38460.7
197 (mouth)	10.68	3:35	37170.8

Table 6 shows the results for a breaching time of 4.5 hours. For various stations along the river below the dam the table lists the height of the flood wave passing the section; the time of the peak of the flood, and the peak follow of the flood. The flood wave is between 10m and 30m in height, except for the section just downstream of the corner in the river where the height increases to almost 40m. These results show a flood of lower magnitude than for a 1.5-hour breaching time.

Table 6. Maximum stage, flow and time of peak flow for selected Litani River stations below Qaraoun Dam with a 4.5 hour breach formation time.

Station	Height of Flood Wave (m)	Time to Peak (hr:min)	Peak flow (m3/s)
85614 (below dam)	21.3	3:15	27455
81599 (Sohmor)	29.2	3:20	27237
75550 (Yohmor)	22.0	3:20	27220
66319 (Berghoz)	29.2	3:30	27112
60616 (Blat)	30.2	3:40	27044
52329 (Mazraat Doumiat)	22.3	3:55	26874
44333 (corner)	39.4	4:05	26680
32066 (Marnaba)	29.6	4:20	26419
7278 (Idaide)	13.7	4:50	25927
197 (mouth)	8.9	5:05	25687

4.3. SENSITIVITY ANALYSIS OF BREACH SIDE SLOPES

In the results reported above the side slope of the breach formed in the dam is specified as 1:1 (see Table 4). The time for the dam to breach is 1 hours and 30 minutes, the peak of the outflow from the dam occurs 1 hour and 25 minutes after the beginning of the breaching process. The maximum flow rate from the dam is 27,458 m^3/sec. In order to understand the impact of the breach slope on the resulting flood characteristics, several different breach slopes were simulated, from 1:1 hours to 4:1. The results for 1:1 slope are shown in Section 4.1 (Table 4).

Table 7 lists the results for a breach slope of 2:1. These results are almost the same as the results for a 1.5-hour breaching time, indicating slopes beyond the 1:1 do not have much impact on the flood formation, since the flow from the breach occurs before the water has a chance to further widen the breach beyond the 1:1 slope.

Table 7. Maximum stage, flow and time of peak flow for selected Litani River stations below Qaraoun Dam with a 1.5 hour breach formation time and side slopes of 2:1 instead of 1:1.

Station	Height of Flood Wave (m)	Time to Peak (hr:min)	Peak flow (m3/s)
85614 (below dam)	39.0	1:20	68748.3
81599 (Sohmor)	39.0	1:20	68784.9
75550 (Yohmor)	42.8	1:30	49447.0
66319 (Berghoz)	28.6	1:30	48269.0
60616 (Blat)	39.1	1:40	47472.3
52329 (Mazraat Doumiat)	41.2	1:45	46940.5
44333 (corner)	29.3	2:00	45494.2
32066 (Marnaba)	52.8	2:10	44012.6
7278 (Idaide)	37.6	2:30	41913.0
197 (mouth)	16.3	3:05	39228.8
	10.8	3:15	37825.0

5. RECOMMENDATIONS

The work described in this report includes the development and application of a dam break model fro the Qaraoun Dam on the Litani River in Lebanon. This dam is in a seismically active zone and is at some risk of failure due to an earthquake. The dam break modeling simulates the resulting development of a flood wave and its propagation downstream to the Mediterranean Sea in the case of a breach. The results have shown the magnitude and timing of the flood wave at selected locations downstream of the dam.

Several recommendations are provided here for follow-on work that could be completed related to the dam safety. Some additional analysis is recommended using the developed dam break model.

There are one or two stream flow gauges in the Litani basin below the Qaraoun Dam that could be used for model calibration under normal flow conditions. If these flow and river stage records were made available, the model calculations could be compared to these measured values and used to adjust some of the model parameters to try to get a better calibration.

GIS mapping of the areas inundated by the dam break flood should be undertaken using the HEC-GeoRAS software. The resulting inundated areas can be mapped in Google Earth for easy interpretation by local communities and responsible officials.

The dam break model results could be used in the preparation of an Emergency Management Plan developed for protecting downstream communities in the event of a dam break and subsequent flood.

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U.S. Agency for International Development
1300 Pennsylvania Avenue, NW
Washington, DC 20523
Tel: (202) 712-0000
Fax: (202) 216-3524
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