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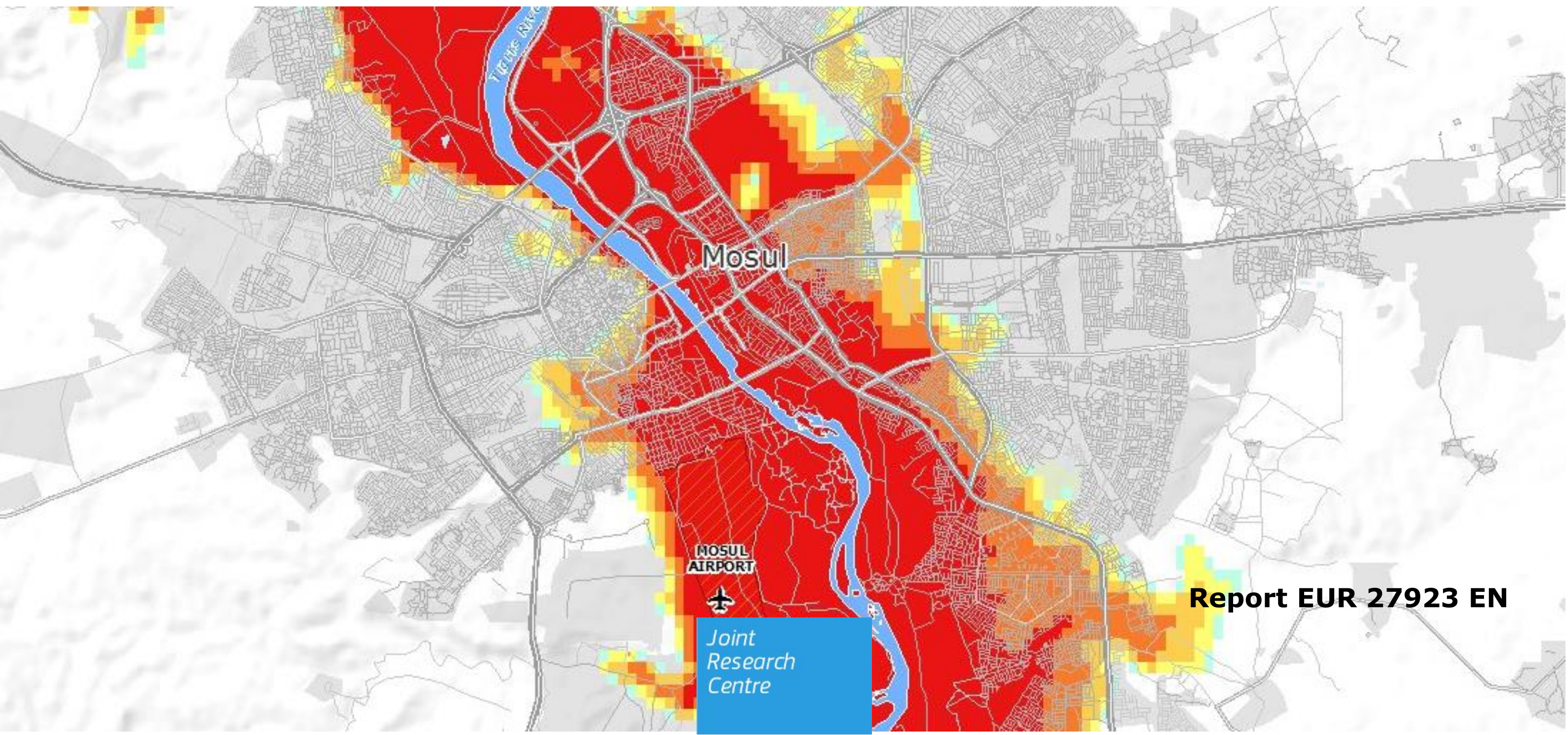
# Impact of flood by a possible failure of the Mosul dam

*Hydrodynamic Simulations*

Alessandro Annunziato, Ioannis Andredakis, Pamela Probst

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# Impact of flood by a possible failure of the Mosul Dam

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## Executive Summary

The dam of Mosul on the Tigris river in northern Iraq is the largest in the country and holds around 11 $km^3$ of water. Built on water permeable rock, the inherent instability of the Mosul dam has been known since it was built and this was mitigated by continuous grouting. In recent years adequate maintenance has not taken place, leading to concerns about the safety of the dam. In 2003 the government decided to lower the maximum water level from 330 to 319 metres. During the recent conflict, maintenance has again been disrupted and signs at the dam have triggered renewed concerns, highlighted in the Schnabel report. As a result, the government of Iraq have contracted the Italian engineering company Trevi to undertake remedial work on the dam. This work is scheduled to start later in the Spring of 2016.

In late February 2016 the Iraqi government advised the residents of Mosul to move at least 5 km away from the river in case of breach. A UN mission of UNDAC experts left for Iraq in early April to assess the situation, supported by an associated expert from the European Union Civil Protection Mechanism.

A number of studies have been devoted to the possible effects of a failure of the dam. In this study we perform a number of medium-resolution (180m) dynamic hydraulic simulations starting from various constant percentages of destruction of the dam and allowing the corresponding quantity of water (supposing the lake to be at its highest level) to flow downslope for periods of 6 and 12 days. Compared to previous studies we provide in addition a complete timescale of the water flow progression, detailed maps of the water depth and extent in the affected cities' areas and focus more on the numbers of population affected by various water depths.

The main scenario analysed in this study, where the dam is 26% destroyed, the level of the lake is at its maximum value of 330m, and most of the lake's water is allowed to flow out fast, results in a very high wave of water (in places 25m high, mean height around 12m) arriving at Mosul city after **1h40min**. The capital Baghdad is reached after about 3.5 days with a max water height of 8m and a mean of around 2m.

The simulations suggest that in the above scenario a 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.

A number of other scenarios involving lower initial levels of the lake are also analysed, considering levels of 319m (the current one), and 315, 309, 307, 305 and 300m. Significant reductions in the affected populations and later arrival times are seen for lower initial lake levels. The differences are quite prominent in Mosul as well as in Baghdad, where we also provide detailed maps of the inundation in the various cases. The scenario of part of the flood wave being diverted to lake Tharthar by an existing channel near Samarra is also examined in detail.

These results are a first-order approximation, favouring speed of calculation over detail for a rapid assessment; it is planned to refine them later using higher resolution ground elevation data (that take much longer to run) and more detailed, time-dependent scenarios of dam failure.

# 1. Introduction

## 1.1 Basic dam information

The dam of Mosul was constructed between 1981 and 1986 in northern Iraq. It dams the river Tigris, forming an artificial lake that holds 11.1 $km^3$ of water at full capacity and its primary function is to control water flow in the Tigris river. It is located 40km NW of the city of Mosul and its primary function is to supply electricity to the city's 1.7 million inhabitants. It is the largest dam in Iraq, measuring 2km in length and 113m in height. It is an earth-fill embankment-type dam with a clay core.

**Figure 1:** The dam of Mosul (Google Earth, 2010)

## 1.2 Dam instability

Concerns about the dam's stability and safety began already during construction: because the dam is built on a foundation of gypsum, anhydrite and limestone, i.e. water-soluble minerals, water can seep under the dam and compromise its stability, posing the risk of catastrophic failure (Al-Ansari et al 2015 and references therein – Ref. 1). To avoid this, continuous maintenance has taken place since the dam's opening, in the form of *grouting*: new leaks are plugged by injecting a cement mixture into the compromised spots. This ad-hoc solution in itself is not deemed satisfactory, since grouting at one location causes the seepage of subsurface water to move to another location but does not stop it (Ref. 2).

In any case, most of this maintenance was stopped in 2014, after the area was taken over by the forces of the so-called Daesh. Later in 2014 the area passed again under the control of the Peshmerga, the military forces of the autonomous region of Iraqi Kurdistan, but the maintenance has not been fully restarted and fears about the dam's stability have multiplied. According to media reports, the grouting machines have been damaged and there is no cement supply, and even the gates of the overflow spillway (visible on the right of the dam in the photo above) are malfunctioning (Ref. 3). Moreover, as spring advances, the water level is expected to increase from snowmelt, increasing further the pressure on the dam. Another possible threat that has been mentioned is deliberate destruction of part of the dam as a warfare act; this scenario was invoked primarily during the 2003 Gulf war.

In early March 2016 it was announced (Ref. 4) that the Iraqi government had awarded a contract to a European company to resume maintenance and guarding of the dam. It is not clear, however, when the works would actually start. The Iraqi government also announced an experts' mission to assess the dam's stability in late February. (Ref. 5)

Despite many warnings and studies indicating the possible instability of the dam, the official stance of local officials until recently has been reassuring, claiming that the risks were exaggerated (Ref. 3). In late February, however, this was reversed, with the Iraqi Prime Minister advising the population of Mosul to move at least 5km away from the Tigris' river bed in the case of failure (Ref. 6).

## 1.4 Past studies of flood effects by dam failure

The most detailed study until of the possible mechanisms and eventual effects by failure of the Mosul Dam until this day remains the one of Swiss Consultants in 1984, summarised in Ref. 1. In that study a number of dam failure models were developed, based on a progressive breach of various widths and most of the water of the reservoir was emptied in 6 to 8 hours after the initial breach. Most interesting to compare with this present paper is the tracing of the wave downstream. Those results of 1984 can be summarised as follows:

- The initial height of the wave is 55m, decreasing to 45m after the first 20km.

- Mosul city will be affected by the flood 4 hours after the breach; the maximum wave height will be 24m and it will inundate 74 $km^2$ of the Mosul city area.

- The city of Tikrit will be reached after 22h and the maximum height will be 15m, inundating 69 $km^2$.

- Northern Baghdad will be reached after 38 hours and central Baghdad after 44 hours, with a wave of 4m. A total of 217 $km^2$ will be inundated.

No detailed affected population numbers have been calculated in this study; rough estimates in the media mention around 500 000 people in direct risk of loss of life.

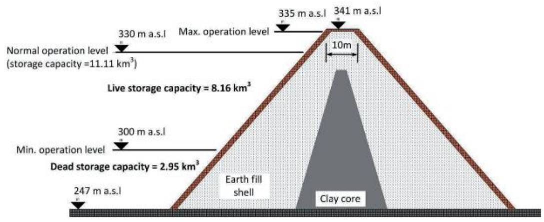
A preliminary study (Ref. 9) on the Mosul dam failure inundation on a much shorter time scale was carried out in early March 2016 by the Institute of Environment and Sustainability of the Joint Research Centre. In this 2-dimensional hydraulic modeling at low resolution, it was calculated that 4.7 million people would be affected, an area of 7,700 square km would be inundated and Mosul would face a mean flood depth of 9.8m affecting 200 000 people.

Another study by Thair et al (Ref. 10) consider a time for the creation of the break. The break time is up to about 4h in the case of 330 m a.s.l.; in this study we assumed an instantaneous opening, in order to assess a worst-case scenario.

## 2 Hydraulic calculations varying the break size

A number of calculations has been performed in order to estimate the dam break propagation from the Mosul dam into the downstream valley in the 6 days following the break event. The calculations have been performed using the HyFlux2 computer code, developed at the JRC (Ref. 7) and routinely used for Tsunami and Storm surge events but originally developed to analyse dam break problems.

In order to execute the calculations some preliminary analysis of the topography and retrieval of dam characteristics have been performed: using those data we proceeded to determine the original topography of the valley where the dam was built (i.e. without the lake's water) and definition of the break characteristics.




The original topography has been obtained by the publication of Elias Issa (Ref. 8) that is reporting the results of a bathymetric survey in the lake performed in 2011. Unfortunately, it was not possible to contact the author and therefore we have used the image below in order to obtain the elevation above the sea level of the lake bottom, i.e. the original topography without the lake. the current better available topography, i.e. SRTM 90 m, consider the lake at an elevation of 307-310 m. We considered the elevation of the lake at 330m that is the maximum normal operational water elevation (and thus taking the worst-case scenario as far as water volume is concerned).

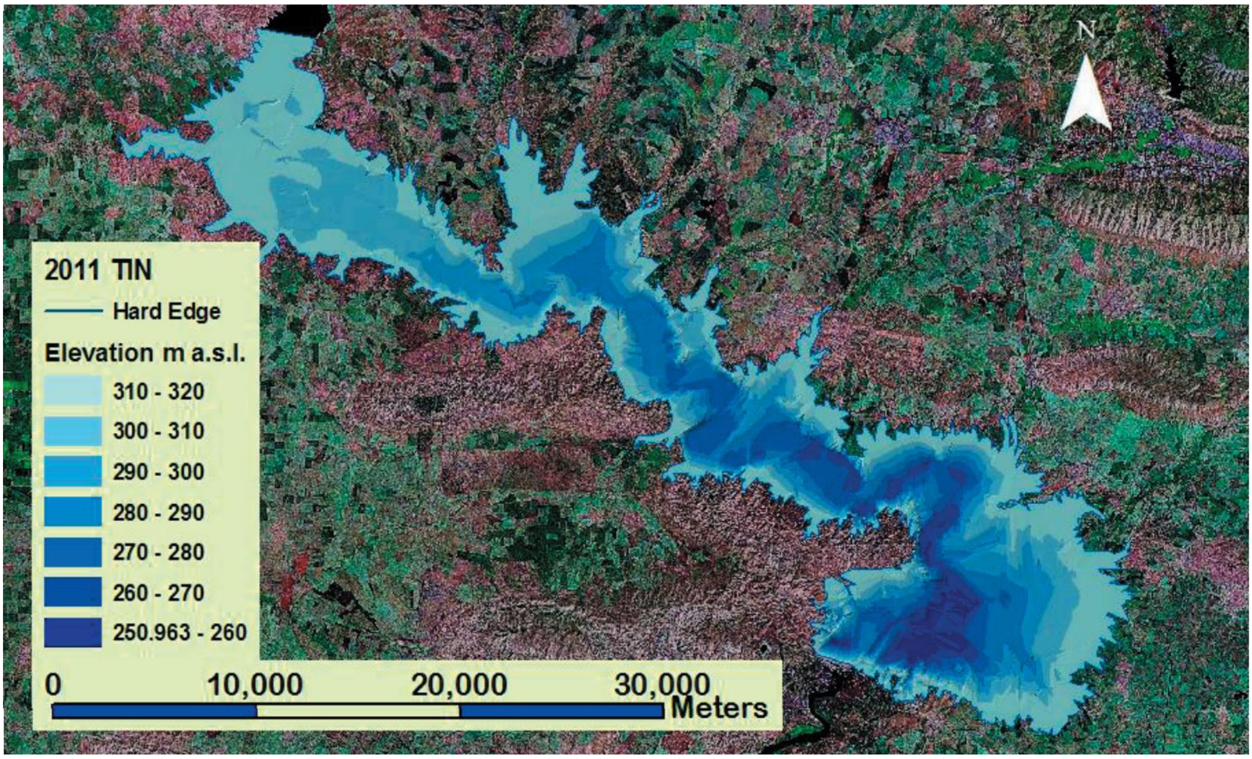
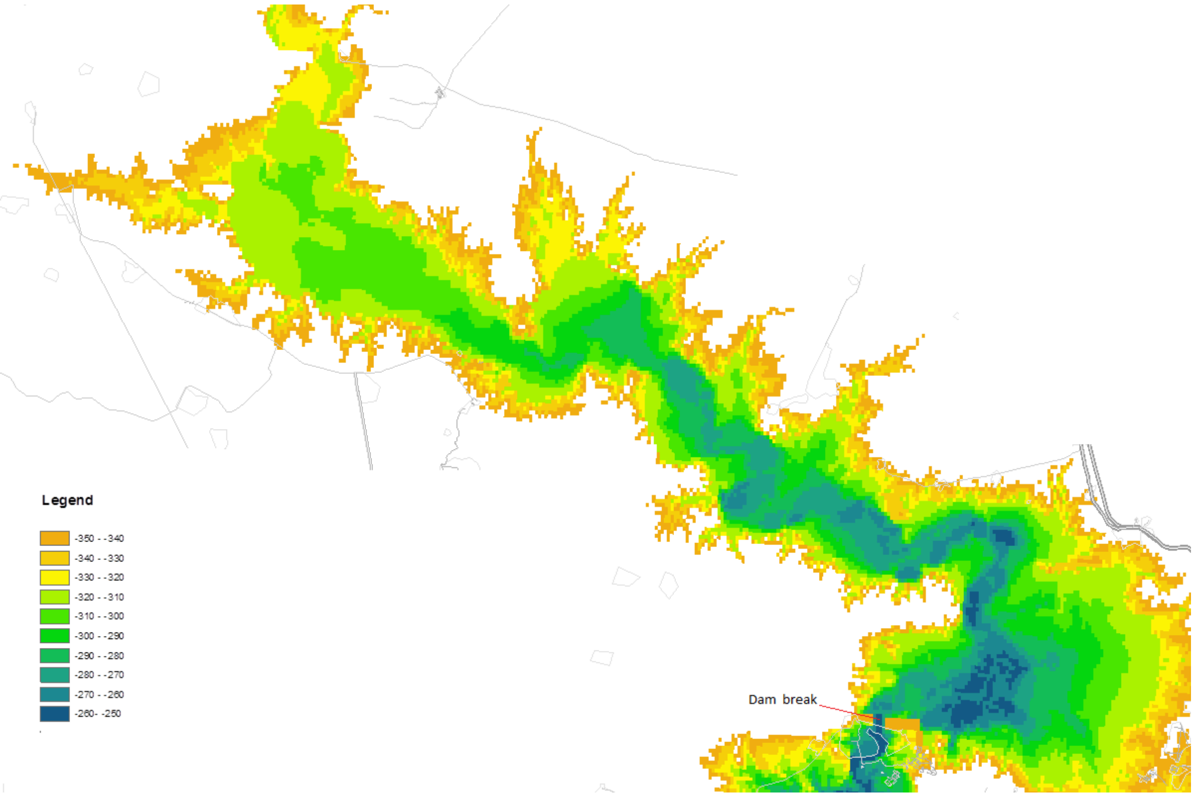



**Figure 2:** Lake bathymetry (from Issa 2015)

From the figure above the dam bottom topography has been obtained, resampled at 90m and substituted to the STRM90 in the area of the lake. The dam break has been simulated by considering a reduction of pixels in the topography so that water could flow out of the lake.

The following figure represents the topography of the dam valley with the dam simulated. To simulate the break, a few pixels of those that play the role of the dam (red squares in the figure) have been substituted by lower pixels in order to allow a direct connection between the lake and the descending section located at 252 m with a jump of 78 m from the lake top, assumed at 330 m.

Considering that the dam to be 2 km long and 78m high (measured from the level of the river), for a total of 156000 m$^2$ the assumed break area is about 26% of the total area and is as high as the total height of the dam.




Lake Bathymetry as obtained for this study

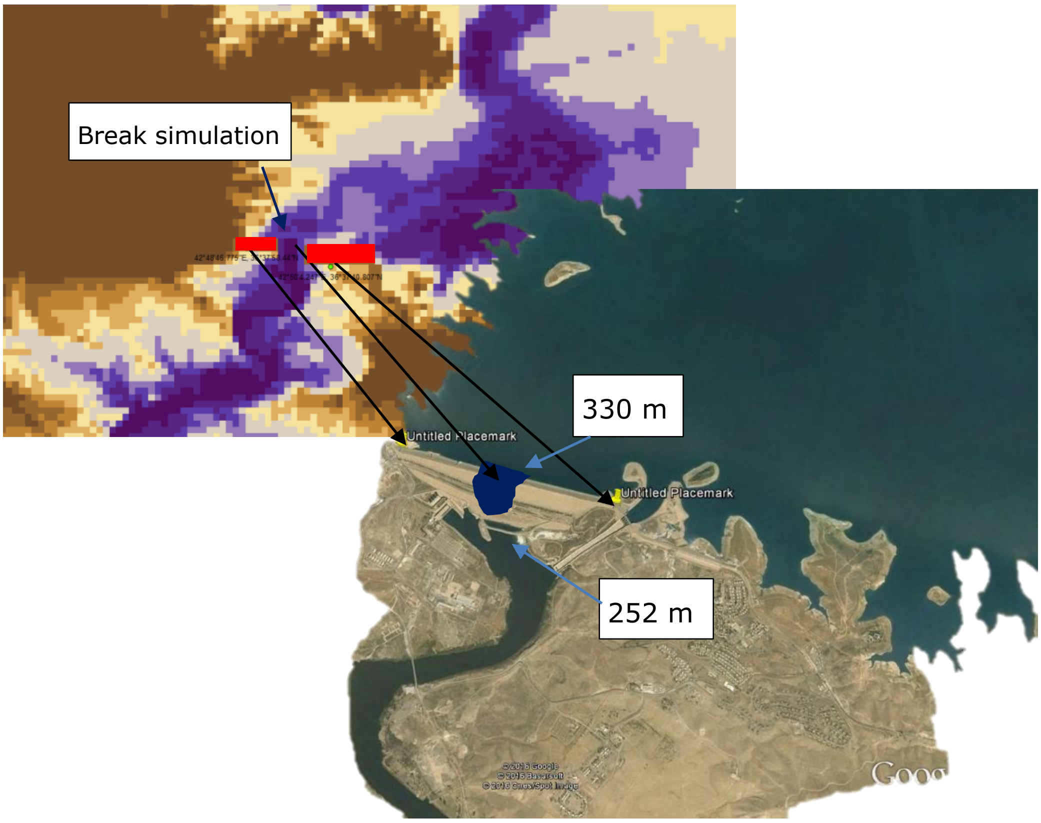



**Figure 4:** Dam breach representation

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 142.8571 | 285.7143 | 428.5714 | 571.4286 | 714.2857 | 857.1429 | 1000 | 1142.857 | 1285.714 | 1428.571 | 1571.429 | 1714.286 | 1857.143 | 2000 |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | -1000 | -857.143 | -714.286 | -571.429 | -428.571 | -285.714 | -142.857 | 0 | 142.8571 | 285.7143 | 428.5714 | 571.4286 | 714.2857 | 857.1429 | 1000 |
| | | | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 270 | 330 | 330 | 330 | 330 | 330 | 330 | 330 |
| | | | **330** | **330** | **330** | **330** | **330** | **263** | **252** | **252** | **275** | **330** | **330** | **330** | **330** | **330** | **330** |
| | | | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 | 252 |
| Remainig area (m2) | **116285.7** | | 11142.86 | 11142.86 | 11142.86 | 11142.86 | 11142.86 | 1571.429 | 0 | 0 | 3285.714 | 11142.86 | 11142.86 | 11142.86 | 11142.86 | 11142.86 | |
| Total Area (m2) | 156000 | | | | | | | | | | | | | | | | |
| Break Area (%) | 25.5 | | | | | | | | | | | | | | | | |

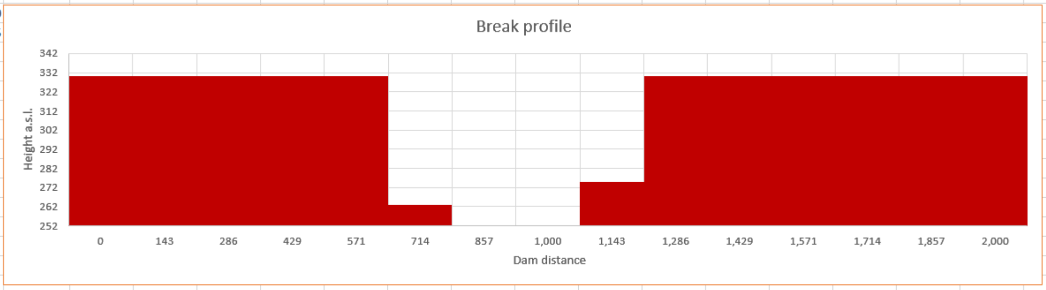
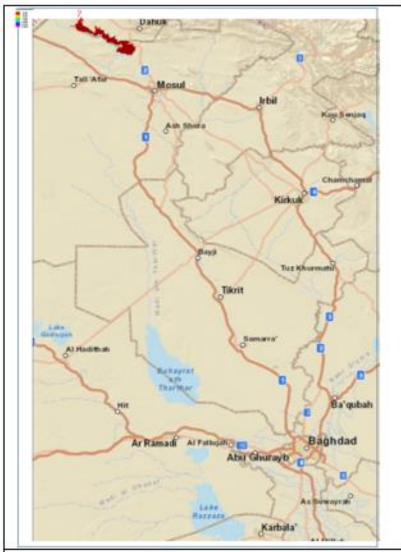



**Figure 3:** Dam breach profile

The above break can be considered a large one, as the total elimination of the whole dam from top to bottom might not be realistic. For a sensitivity analysis, a case with 60% area break was run; the results of this 60% break are not very different from the ones of 26%, used in the rest of the study. A case with a strong reduction of this area was also run, with an area of only 7% limited to the upper part of the dam, to simulate a deliberate explosion. The results of the 26% case here are therefore considered representative of a rather severe break. Indicative results and maps resulting from the other scenarios are given in Appendix I.

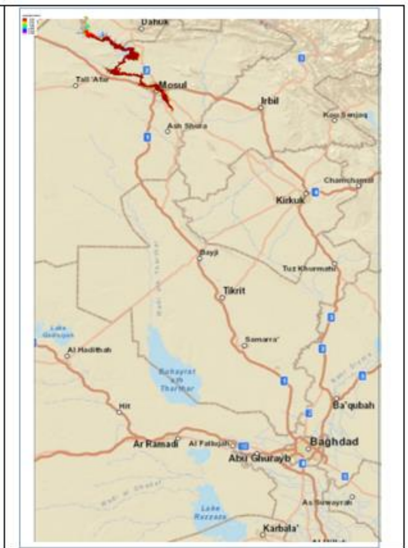
**Results of the dam break event (26% break)**

The propagation of the water flow is indicated in the time sequence below for the 6 days of the simulation. The simulation was run using 10 cores on a Linux machine with a resolution of 180 m per each cell and took about 24 h of CPU time.

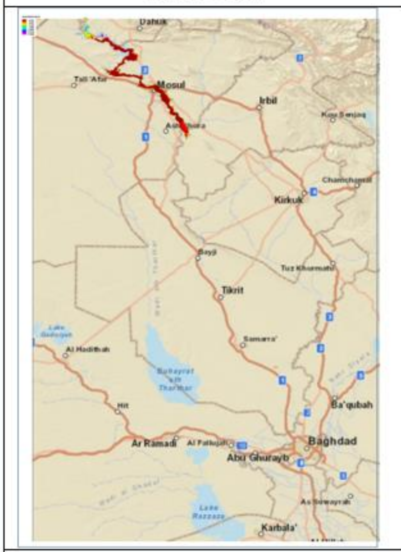


*Time = 0 h*

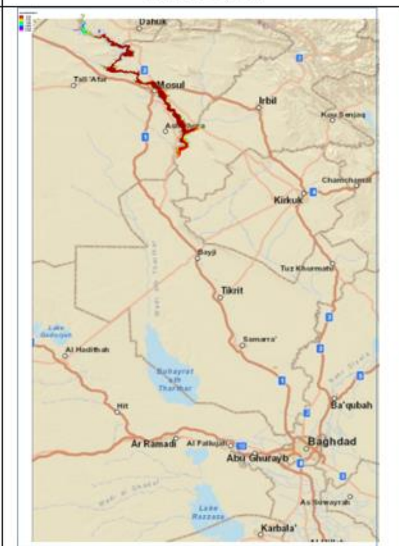
*Time = 2 h*



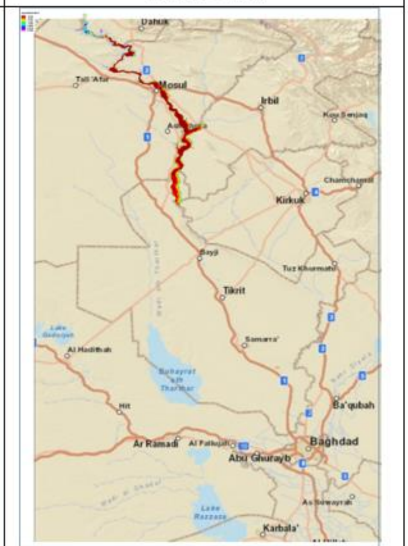
*Time = 4 h*



*Time = 6 h*



*Time = 8 h*



*Time = 12 h*

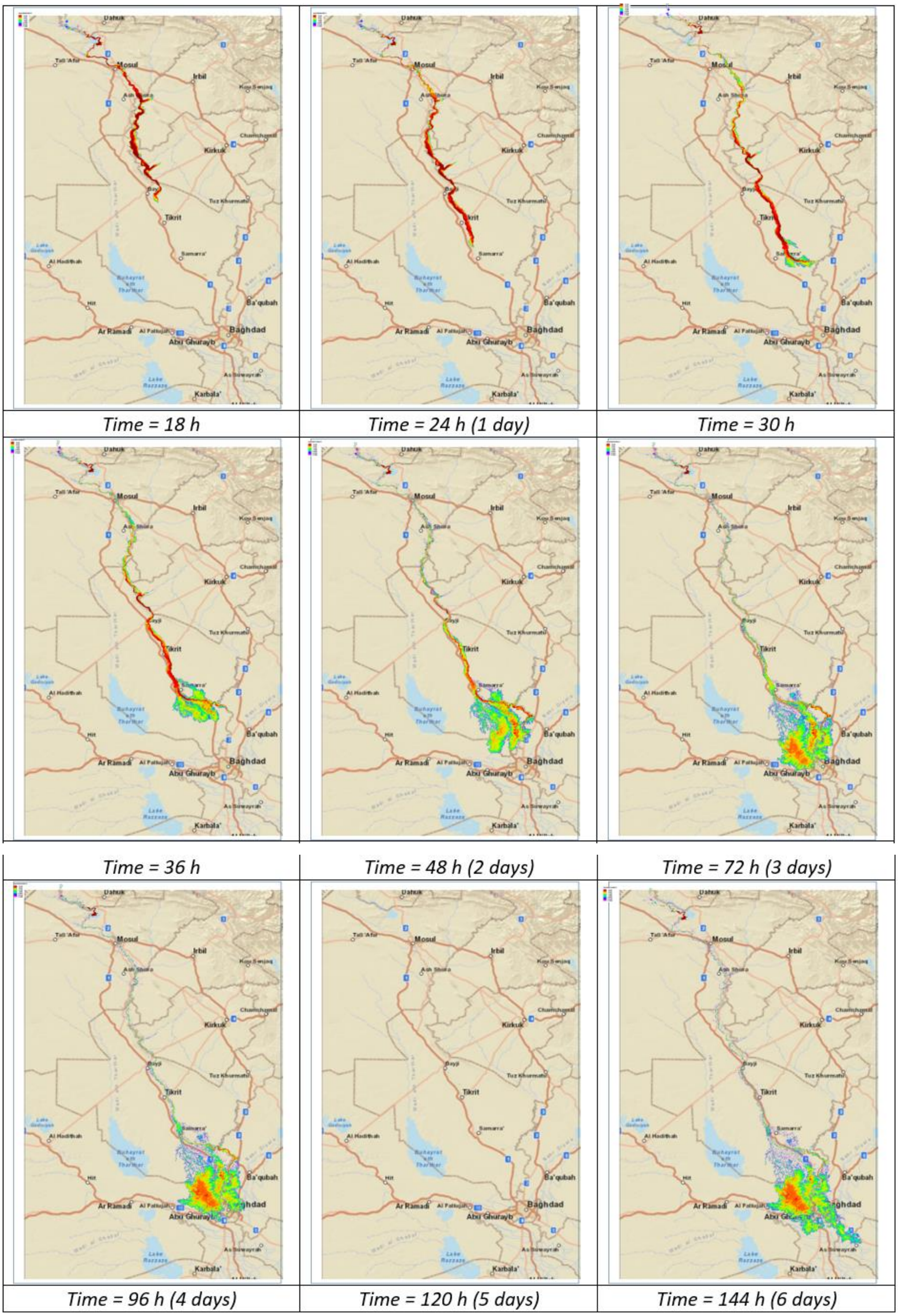



**Figure 5:** Time evolution maps of the water flow.

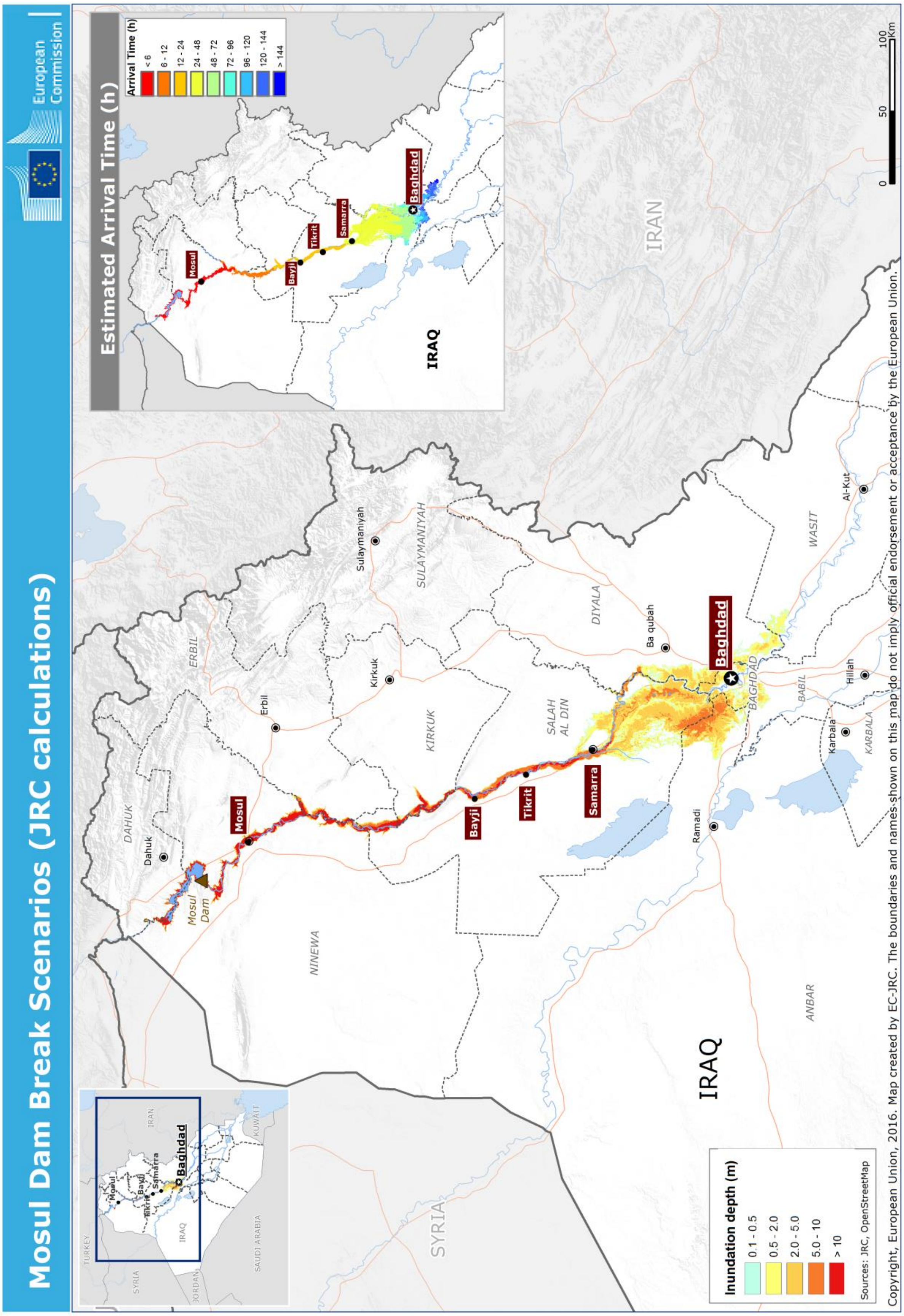



**Figure 6:** Overview map of water flow and travel time (Initial lake level: 330 m)

The progression of the flow in the valley occurs following the average local slope. At the beginning, when the slope is higher the speed is quite large, in the order of 40 km/h. The speed then decreases and finally almost stops in Baghdad where a very flat area exists. As can be seen also from the plot below, at the various cities upstream of Baghdad the water is kept high but for much shorter periods, while in this last city the height of the water is lower but stays for much longer. The flow progression can be visualised as an animation in this URL: http://goo.gl/6CT5ig

| Item | Height (metres a.s.l) | Distance (km)[1] | Slope (%) | Average speed (km/h) | Time of wave arrival (h)[2] | Time of max height (h) | Max Height (m) |
|---|---|---|---|---|---|---|---|
| *Dam break* | *252* | *0* | *-* | | *0* | *0* | *78* |
| Mosul | 217 | 69 | -0.05 | 40. | 1.7 | 6.2 | 26.4 |
| Bayji | 109 | 180 | -0.06 | 11. | 16.8 | 23.5 | 14.3 |
| Tikrit | 89 | 47 | -0.04 | 11. | 21.0 | 26.5 | 14.4 |
| Samarra | 66 | 54 | -0.04 | 18. | 25.8 | 30.8 | 16.1 |
| Bagdad | 38 | 108 | -0.03 | 2.6 | 67.0 | 117.0 | 7.9 |

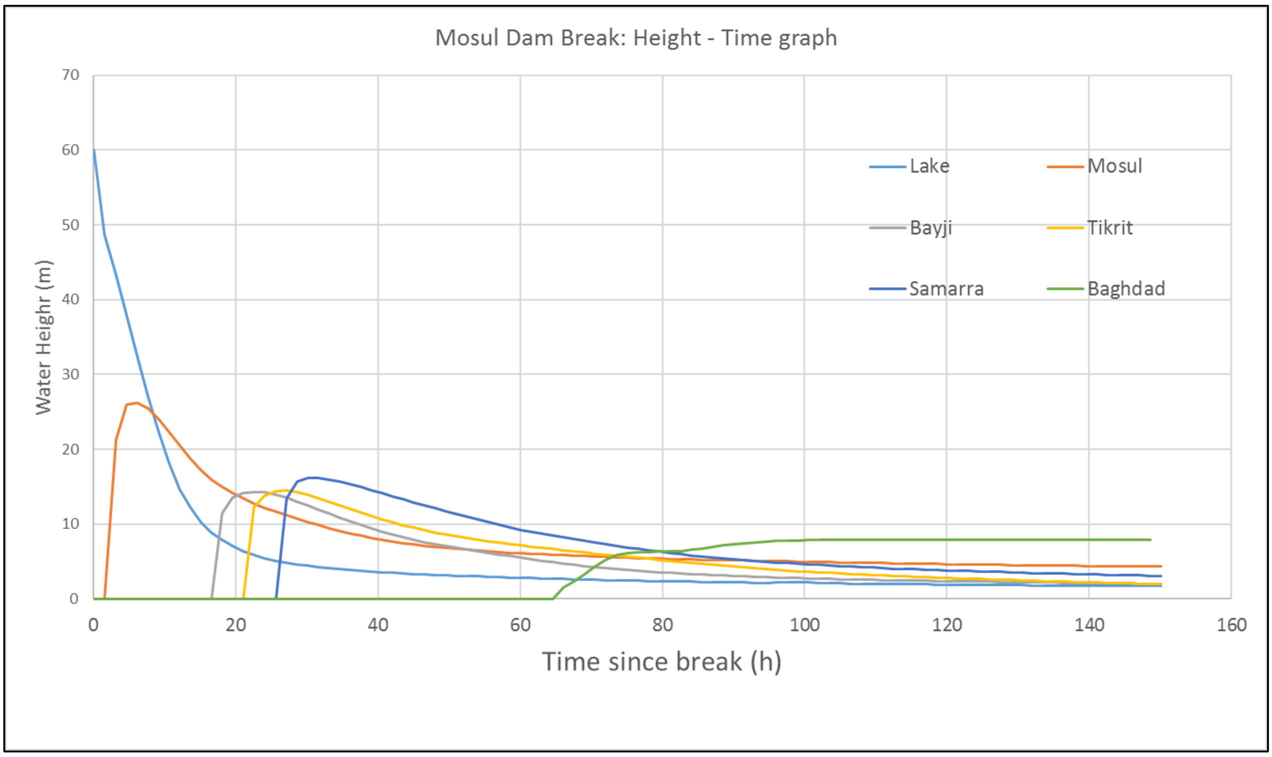



**Figure 7:** Water height versus time for the lake and for the major cities downstream.

[1] Distance between two points
[2] Time of arrival is considered at the city centre. In the case of Baghdad the periphery is reached a few hours earlier

## 2.1 Affected population

For population calculations in this section we use the same scenario as above, i.e. **maximum initial lake level of 330m**. To obtain numbers for the population affected by the flood wave we superimposed the maximum water height maps of the above analysis on the LANDSCAN 2014 Global Population Database, with a resolution of approximately 1km$^2$. Altough SRTM 90m is the best complete available topography layer (Sentinel data are sparse for this region), it is important to mention that the in some areas there could be local errors which could affect the flood depth and flood extent, therefore the maps should be used with caution and always considering real ground conditions. In the estimation of the population possibly affected current refugee camps and displaced people are **not included** and may be included, if available, in a future revision of this document.

The floodwave raster was binned in 5 water height classes, with these limit values: 0.1m, 0.5m, 2m, 5m, 10m. Any area with more than 0.1m of water we consider to be affected by flooding. The total population and area affected by the different water heights is given in the table below:

| 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** |

The total population affected by floodwaters higher than 0.1m is a little over 6 million people or a very significant **16% of the total population** of Iraq. The flooded area is close to 2% of the country's total surface.

A sub-total of more than **half a million people would be exposed to floodwaters of more than 5m high**, thus having their lives at immediate peril; a large percentage of those would have less than two hours warning time, as will be shown below.

Moreover, a very significant surface area will be inundated, with subsequent destruction of critical infrastructure, houses, crops and all livelihood. The cost of the damage is not easy to calculate, but it is easy to understand that the scale of the disaster would be enormous and the economic impact in the country and the whole region would be impossible to bear.

We repeated the above calculation for the greater areas (5 – 10 km from the city centre) of five major cities along the Tigris river and the results are shown in the Table below.

| 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 |
| First wave arrival | 1h 40min | 16h | 21h | 25h | 67h |
| Max wave arrival | 6h | 23h | 27h | 31h | 4-5 days |
| Max wave height | 26m | 14m | 14.5m | 16m | 8m |

The lower part of the Table gives the time for the arrival of the first volume of water, that of the maximum height (that in general has a significant delay of at least a few hours with respect to the first wave) and the maximum water height in meters. (These figures are copied and rounded from the table with the detailed results of the simulations in the previous Section).

It is worthwhile to comment further on the case of Mosul – the reader is also referred to the detailed map of the inundation in each of the above cities, in Appendix I. There are a few points to highlight:

1. The city is built on either side of Tigris, with **densely inhabited neighbourhoods** close to the river. As a result, a very large number of people will be exposed to prodigious heights of floodwater: 183 000 people, **more than 10% of the city's population** of 1.7 million will be affected by **more than 10m wave height**, which could mean complete destruction.
2. The **warning time will be very short**; even if a dam breach is signalled immediately, within 3 hours the water height in Mosul will have already reached close to 20m (see the graph with depth and time reached in the previous chapter). Evacuation of almost 250 000 people from the banks of Tigris in a few hours is very difficult to accomplish.
3. Due to the ground morphology, as can also be seen in the map in Appendix I, the water level drops sharply at around 4 km away from the river bed. A possible evacuation, therefore, would have to be carried out at this distance; the value of 4-5km agrees well with that recommended by the Iraqi government in March 2016.
4. 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 we give 3 hours for 20m and 6 hours for the maximum of 26m.

Significant damage and loss of life should also be expected in the other cities along the river, with very high water levels of more than 10m present. It is interesting to notice that in Samarra, a long way downriver, the maximum height is actually larger than that of Tikrit, higher upstream.

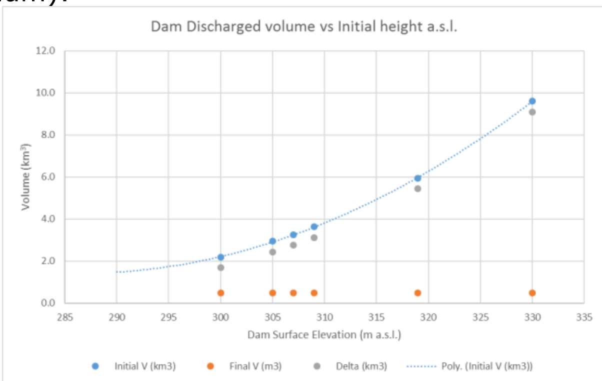
In Baghdad, heights of up to 8m were shown by the calculations in a few places; the mean value in the Baghdad greater area, however, is quite lower, at around 2m. More than 1 million people would be exposed to depths of 2-5m. What is worrying in this case, as can be seen in the height-time graph in the previous section, is that the floodwaters take much longer to drain away from the Baghdad area, owing to the flat ground morphology.

# 3 Sensitivity Analysis on the initial Lake Level

On request of the UNDAC team onsite a number of additional calculations have been performed in order to assess the effect of the lake level reduction on the inundation depth and extent. The initial break size was kept as the intermediate case (26% of the total area) as we saw no large differences with the 60% break and because we considered unrealistic a complete or partly complete destruction of the dam.

The following cases have been considered from 300 m (minimum operational level for the power plant) to 330 m (the base case maximum):

| Elevation (m a.s.l.) | Initial Volume ($km^3$) | Final Volume ($km^3$) | Discharged Volume ($km^3$) |
|---|---|---|---|
| **330** | 9.6 | 0.5 | 9.1 |
| **319** | 5.9 | 0.5 | 5.4 |
| **309** | 3.6 | 0.5 | 3.1 |
| **307** | 3.3 | 0.5 | 2.8 |
| **305** | 2.9 | 0.5 | 2.4 |
| **300** | 2.2 | 0.5 | 1.7 |



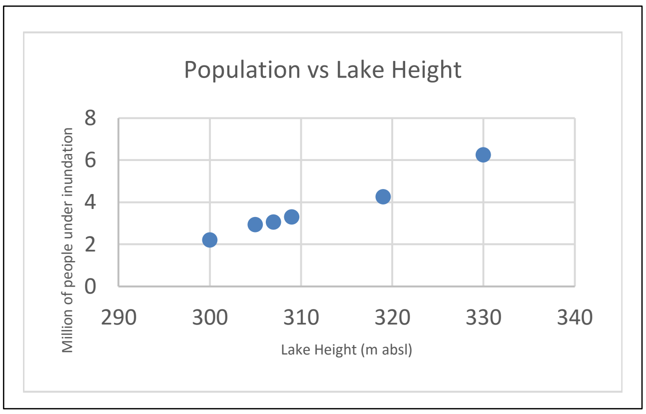

The reduction of the initial water level strongly reduces the amount of water that is discharged in case of break from about 9.1 to 1.7 cubic km; the release time is increased from 12 to 21 hours[3].

The effect on the maximum water height and arrival time can be seen in the following tables and plots.

The effect of the reduction on the maximum height is more evident in Mosul rather than in Baghdad, where the maximum height remains unchanged but the larger effect is on the extent of the flooding as lowering the initial height the flooded area is largely reduced, consistently with the reduction in the discharged volume. The highest lake area cases will be extended beyond 6 days while all the other cases have been run for 12 days.

Appendix B reports all the maps related to these cases. The map below shows the variation of the inundated areas in Baghdad by increasing the lake height. It is possible to note the larger inundation that takes place as the lake height is increased. On the right of the map the arrival times are also shown and it is possible to note how the lake height reduction tends to move the arrow related to 1 day to northern area, which means that the time for arriving to the various locations increases.

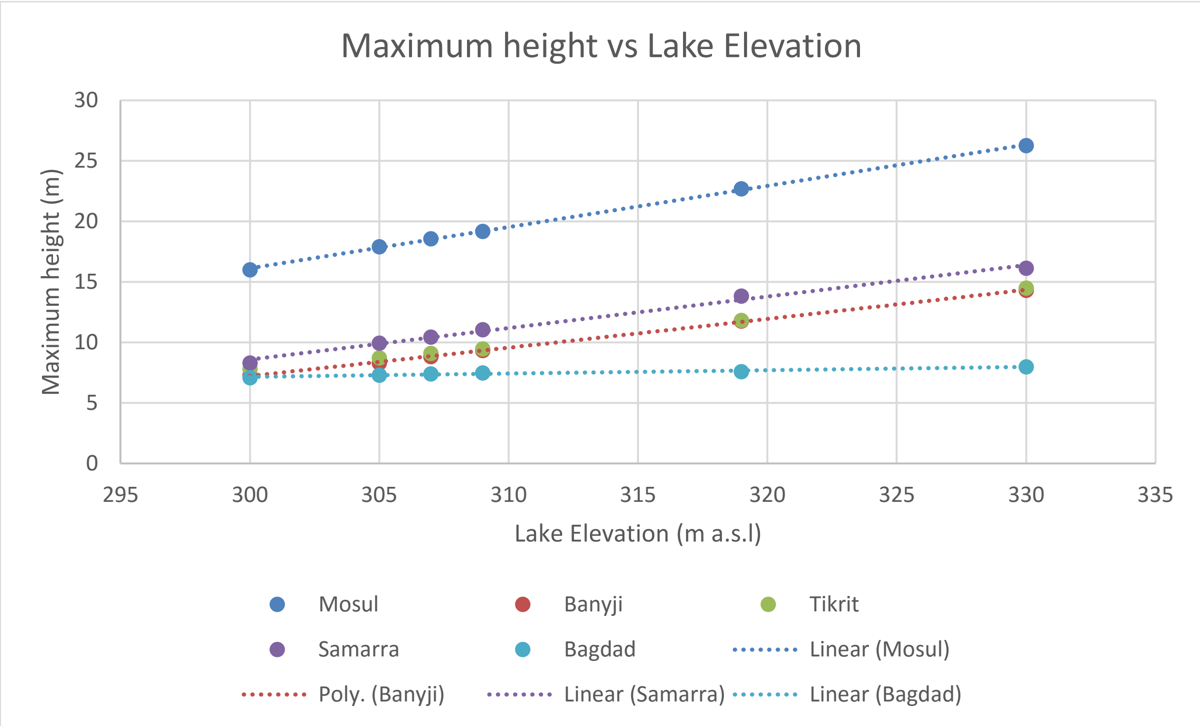
The tables after the next map indicate the population and area affected by varying the lake level. As a whole, from 6.2 million people globally affected the population globally affected reduces to 2.2 million, thus at least 1/3 of the population affected by the largest height. The figure on the right indicates the overall population as a function of the lake height.




[3] Release time is difficult to establish because the level is decreasing exponentially. We consider arbitrarily as the time at which the level is smaller than 1m

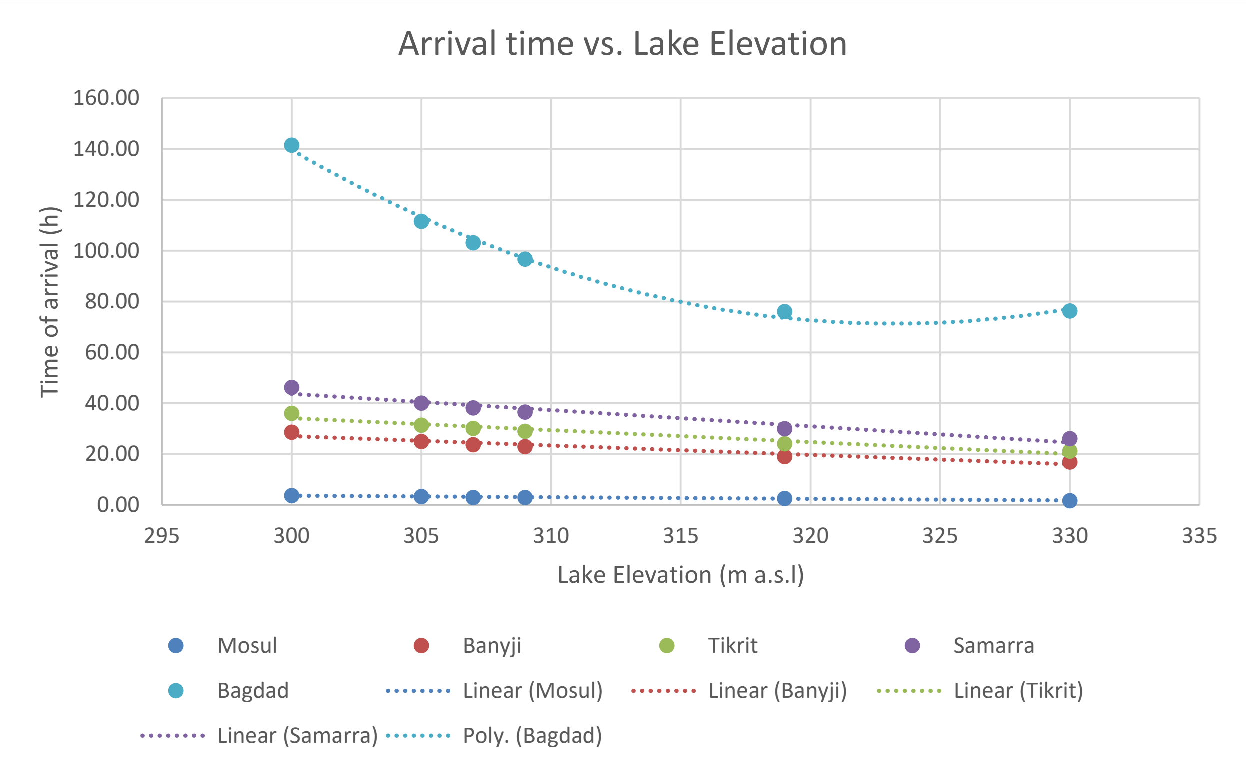
**Maximum Height**

| Lake Elevation | Mosul | Banyji | Tikrit | Samarra | Bagdad |
|---|---|---|---|---|---|
| **330** | 26.3 | 14.3 | 14.5 | 16.1 | 8.0 |
| **319** | 22.7 | 11.8 | 11.8 | 13.8 | 7.6 |
| **309** | 19.2 | 9.3 | 9.5 | 11.1 | 7.5 |
| **307** | 18.6 | 8.9 | 9.1 | 10.4 | 7.4 |
| **305** | 17.9 | 8.3 | 8.7 | 9.9 | 7.3 |
| **300** | 16.0 | 7.3 | 7.8 | 8.3 | 7.1 |

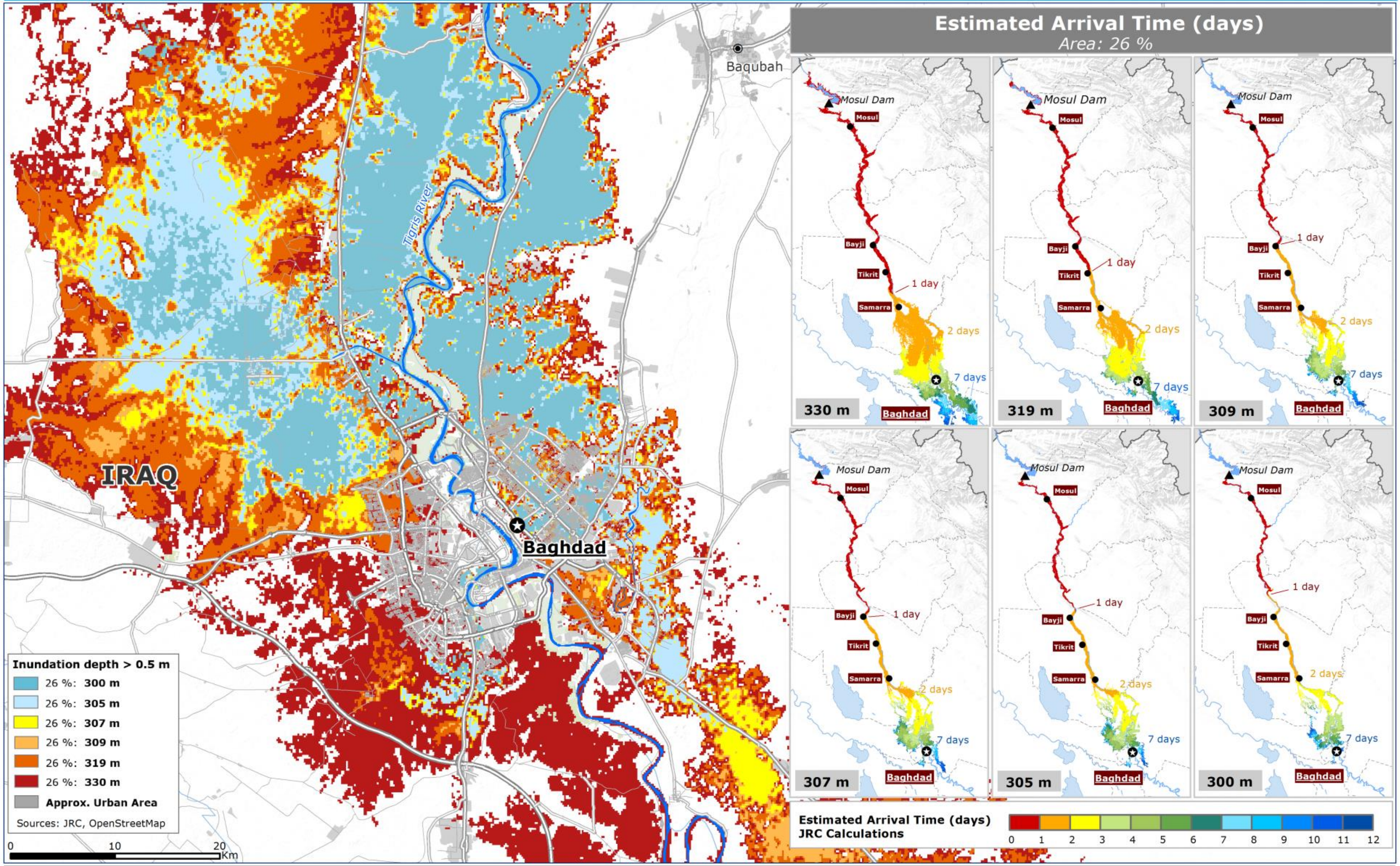


**Arrival times**

| Lake Elevation | Mosul | Banyji | Tikrit | Samarra | Bagdad |
|---|---|---|---|---|---|
| **330** | 1:40 | 16:56 | 21:08 | 26.12 | 76:15 |
| **319** | 2:29 | 18:59 | 24:07 | 30.05 | 76:20 |
| **309** | 2:55 | 22:54 | 29:00 | 36.48 | 96:40 |
| **307** | 2:54 | 23:45 | 30:04 | 38.12 | 103:05 |
| **305** | 3:17 | 24:53 | 31:19 | 40.12 | 111:31 |
| **300** | 3:40 | 28:32 | 35:58 | 46.18 | 141:33 |



# Mosul Dam Break Scenarios (JRC calculations)



| Inundation | Population | Area (km²) |
|---|---|---|
| 0.1 – 0.5m | 715 000 | 440 |
| 0.5 – 2.0m | 1 081 000 | 1057 |
| 2 – 5m | 298 000 | 804 |
| 5 – 10m | 98 000 | 390 |
| > 10m | 13 000 | 100 |
| **Total** | **2 205 000** | **2 791** |

## 300 m – 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* |

| Inundation | Population | Area (km²) |
|---|---|---|
| 0.1 – 0.5m | 723 000 | 518 |
| 0.5 – 2.0m | 1 638 000 | 1295 |
| 2 – 5m | 406 000 | 1084 |
| 5 – 10m | 131 000 | 515 |
| > 10m | 29 000 | 183 |
| **Total** | **2 927 000** | **3 595** |

## 305 m – 12 days

| Inundation | Mosul | Bayji | Tikrit | Samarra | Baghdad |
|---|---|---|---|---|---|
| 0.1 – 0.5m | 13 000 | 2 000 | 0* | 0* | 607 000 |
| 0.5 – 2.0m | 32 000 | 9 500 | 3 000 | 1 000 | 1 174 000 |
| 2 – 5m | 55 000 | 3 000 | 13 000 | 10 000 | 346 000 |
| 5 – 10m | 73 000 | 1 000 | 1 000 | 500 | 66 000 |
| > 10m | 31 000 | 0* | 0* | 0* | 0* |

| Inundation | Population | Area (km²) |
|---|---|---|
| 0.1 – 0.5m | 543 000 | 558 |
| 0.5 – 2.0m | 1 904 000 | 1 370 |
| 2 – 5m | 425 000 | 1 215 |
| 5 – 10m | 146 000 | 555 |
| > 10m | 34 000 | 225 |
| **Total** | **3 052 000** | **3 923** |

## 307 m – 12 days

| 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* |

| Inundation | Population | Area (km²) |
|---|---|---|
| 0.1 – 0.5m | 664 000 | 594 |
| 0.5 – 2.0m | 1 904 000 | 1 465 |
| 2 – 5m | 521 000 | 1 335 |
| 5 – 10m | 150 000 | 602 |
| > 10m | 52 000 | 272 |
| **Total** | **3 291 000** | **3 672** |

## 309 m – 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 |

| Inundation | Population | Area (km²) |
|---|---|---|
| 0.1 – 0.5m | 891 000 | 648 |
| 0.5 – 2.0m | 2 311 000 | 1 886 |
| 2 – 5m | 1 032 000 | 1 988 |
| 5 – 10m | 219 000 | 850 |
| > 10m | 139 000 | 560 |
| **Total** | **4 592 000** | **5 932** |

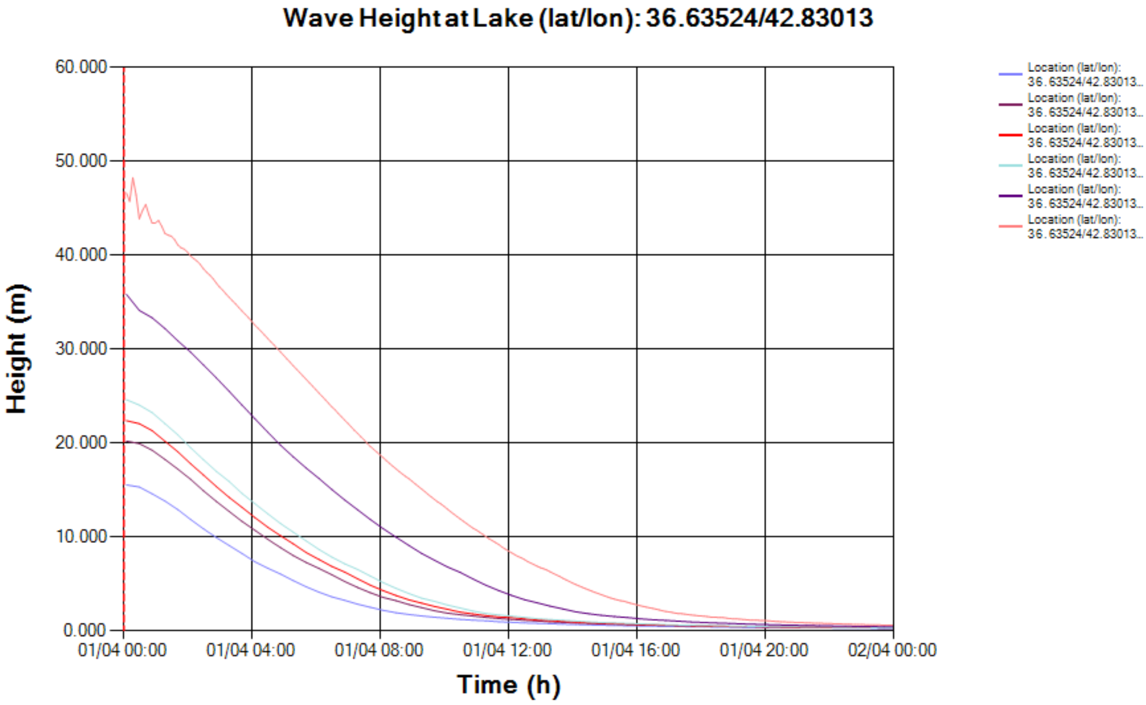
## 319 m – 12 days

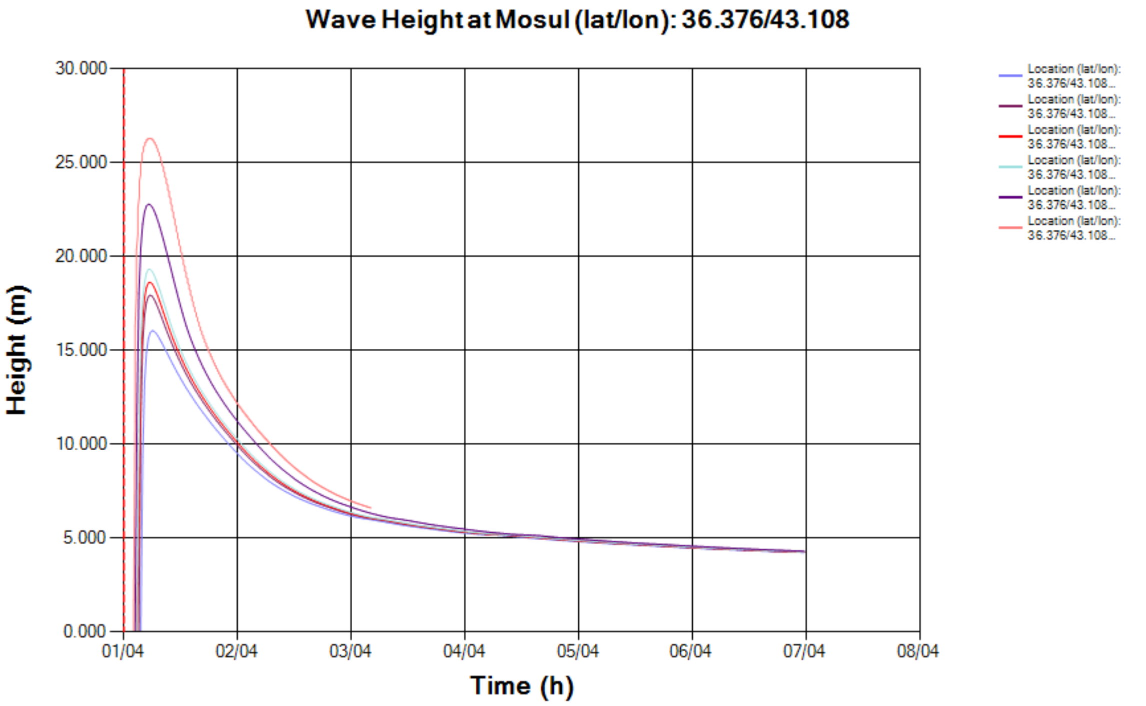
| Inundation | Mosul | Bayji | Tikrit | Samarra | Baghdad |
|---|---|---|---|---|---|
| 0.1 – 0.5m | 26 000 | 0 | 0 | 0 | 893 000 |
| 0.5 – 2.0m | 12 000 | 500 | 100 | 0 | 1 906 000 |
| 2 – 5m | 51 000 | 15 000 | 3 500 | 1 000 | 786 000 |
| 5 – 10m | 66 000 | 4 500 | 14 000 | 10 000 | 78 000 |
| > 10m | 125 000 | 0 | 500 | 500 | 0 |

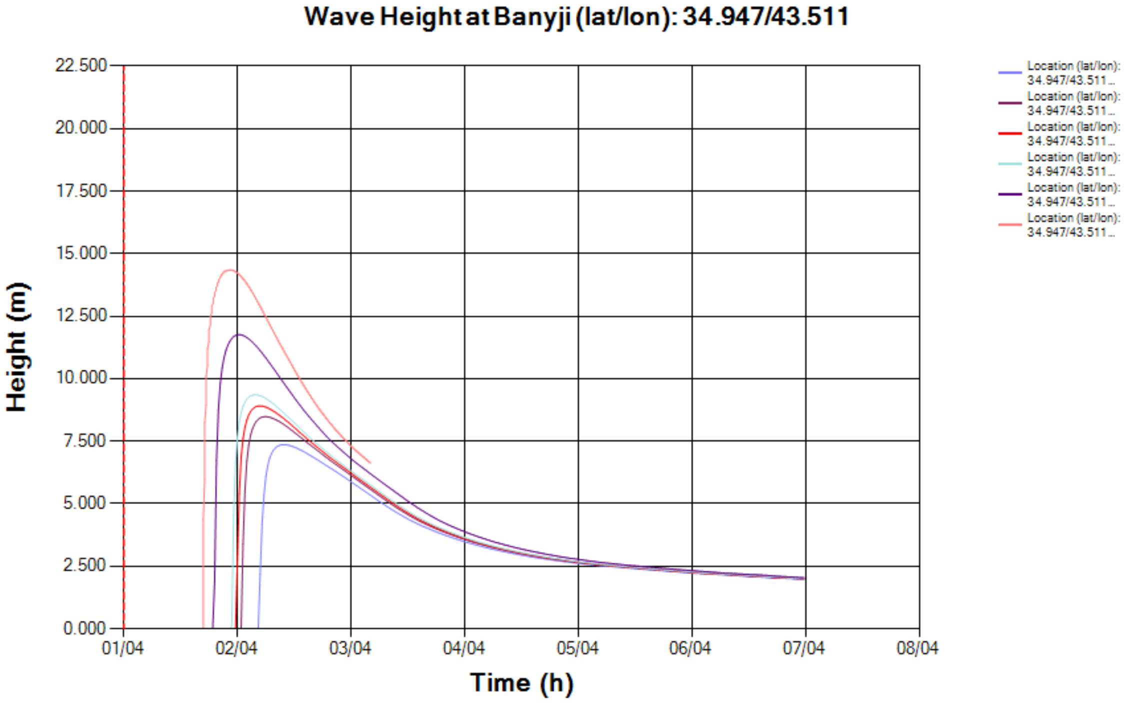
| Inundation | Population | Area (km²) |
|---|---|---|
| 0.1 – 0.5m | 948 000 | 637 |
| 0.5 – 2.0m | 3 144 000 | 2 022 |
| 2 – 5m | 1 626 000 | 2 482 |
| 5 – 10m | 260 000 | 1 150 |
| > 10m | 270 000 | 916 |
| **Total** | **6 248 000** | **7 202** |

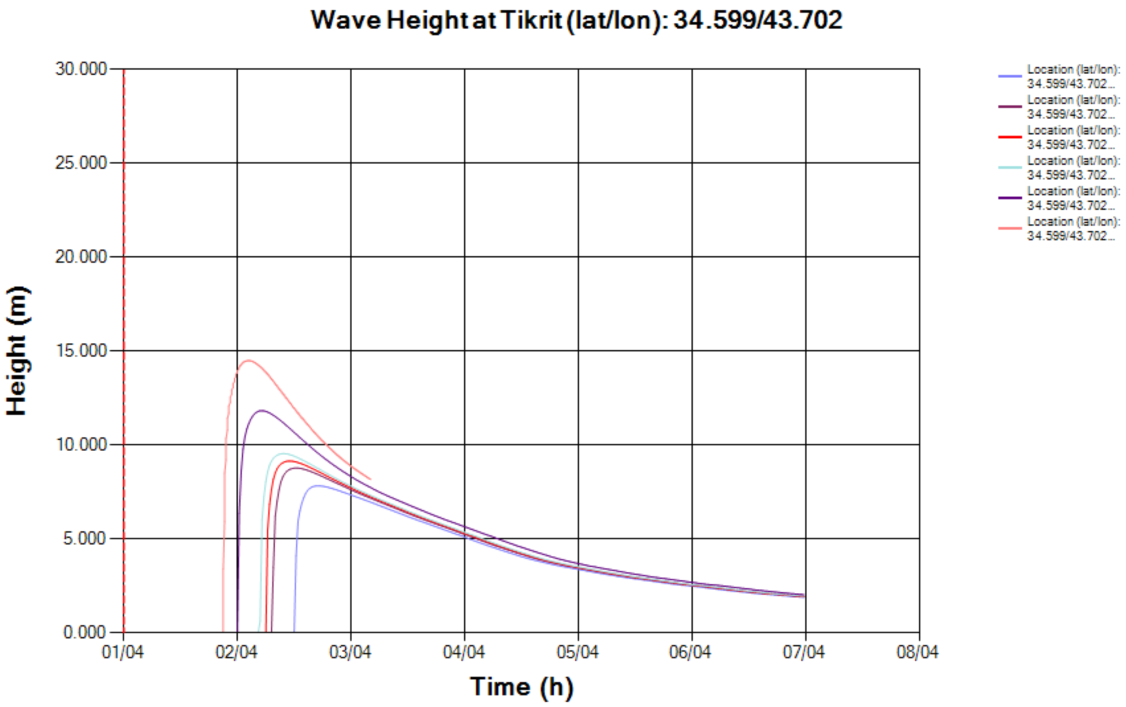
## 330 m – 6 days

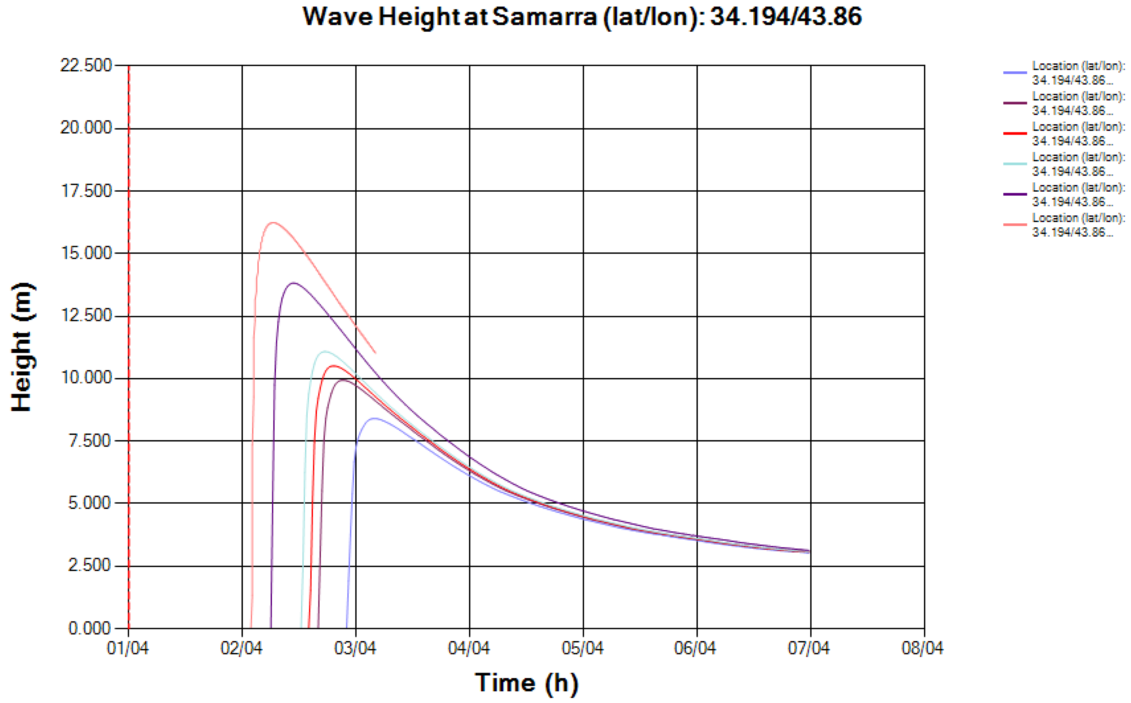
| Inundation | Mosul | Bayji | Tikrit | Samarra | Baghdad |
|---|---|---|---|---|---|
| 0.1 – 0.5m | 21 000 | 0 | 0 | 0 | 746 000 |
| 0.5 – 2.0m | 55 000 | 300 | 100 | 3 000 | 2 949 000 |
| 2 – 5m | 41 000 | 400 | 2 500 | 100 | 1 134 000 |
| 5 – 10m | 60 000 | 17 000 | 14 000 | 5 500 | 26 000 |
| > 10m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

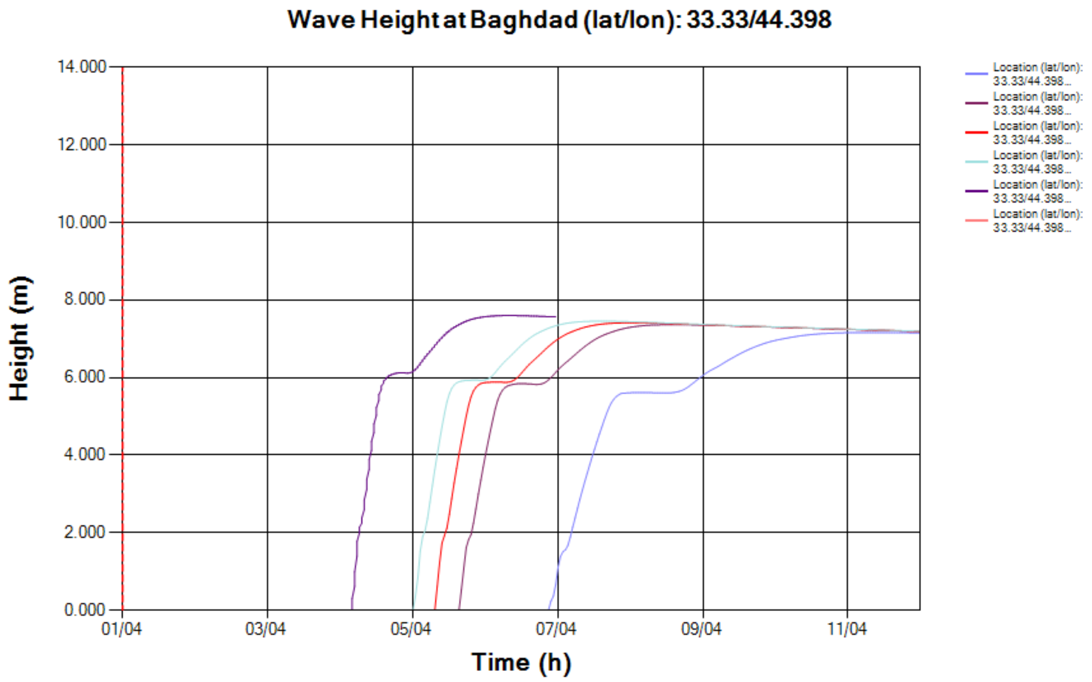

Wave Height at Lake (lat/lon): 36.63524/42.83013
Height (m)
60.000
50.000
40.000
30.000
20.000
10.000
0.000
01/04 00:00
01/04 04:00
01/04 08:00
01/04 12:00
01/04 16:00
01/04 20:00
02/04 00:00
Time (h)
Location (lat/lon): 36.63524/42.83013...
Location (lat/lon): 36.63524/42.83013...
Location (lat/lon): 36.63524/42.83013...
Location (lat/lon): 36.63524/42.83013...
Location (lat/lon): 36.63524/42.83013...
Location (lat/lon): 36.63524/42.83013...


Wave Height at Mosul (lat/lon): 36.376/43.108
Height (m)
30.000
25.000
20.000
15.000
10.000
5.000
0.000
01/04
02/04
03/04
04/04
05/04
06/04
07/04
08/04
Time (h)
Location (lat/lon): 36.376/43.108...
Location (lat/lon): 36.376/43.108...
Location (lat/lon): 36.376/43.108...
Location (lat/lon): 36.376/43.108...
Location (lat/lon): 36.376/43.108...
Location (lat/lon): 36.376/43.108...


Wave Height at Banyji (lat/lon): 34.947/43.511
Height (m)
22.500
20.000
17.500
15.000
12.500
10.000
7.500
5.000
2.500
0.000
01/04
02/04
03/04
04/04
05/04
06/04
07/04
08/04
Time (h)
Location (lat/lon): 34.947/43.511...
Location (lat/lon): 34.947/43.511...
Location (lat/lon): 34.947/43.511...
Location (lat/lon): 34.947/43.511...
Location (lat/lon): 34.947/43.511...
Location (lat/lon): 34.947/43.511...


Wave Height at Tikrit (lat/lon): 34.599/43.702
Height (m)
30.000
25.000
20.000
15.000
10.000
5.000
0.000
01/04
02/04
03/04
04/04
05/04
06/04
07/04
08/04
Time (h)
Location (lat/lon): 34.599/43.702...
Location (lat/lon): 34.599/43.702...
Location (lat/lon): 34.599/43.702...
Location (lat/lon): 34.599/43.702...
Location (lat/lon): 34.599/43.702...
Location (lat/lon): 34.599/43.702...


Wave Height at Samarra (lat/lon): 34.194/43.86
22.500
20.000
17.500
15.000
12.500
10.000
7.500
5.000
2.500
0.000
Height (m)
01/04
02/04
03/04
04/04
05/04
06/04
07/04
08/04
Time (h)
Location (lat/lon): 34.194/43.86...
Location (lat/lon): 34.194/43.86...
Location (lat/lon): 34.194/43.86...
Location (lat/lon): 34.194/43.86...
Location (lat/lon): 34.194/43.86...
Location (lat/lon): 34.194/43.86...


Wave Height at Baghdad (lat/lon): 33.33/44.398
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
Height (m)
01/04
03/04
05/04
07/04
09/04
11/04
Time (h)
Location (lat/lon): 33.33/44.398...
Location (lat/lon): 33.33/44.398...
Location (lat/lon): 33.33/44.398...
Location (lat/lon): 33.33/44.398...
Location (lat/lon): 33.33/44.398...
Location (lat/lon): 33.33/44.398...

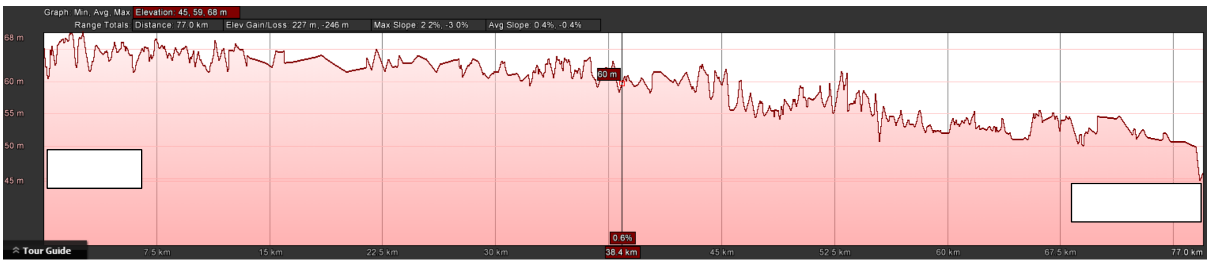
# 4 Role of the connecting channel between Samarra and Tharthar Lake

After the performance of the previous calculations, the preliminary assessment by the UN team onsite with the local authorities pointed out that in the calculations the presence of the connecting channel between Samarra, at the location where a dam on the Tigris river is located and the Tharthar Lake was not considered. The presence of this channel could, in principle, relieve the amount of water coming from the Mosul dam reservoir in the direction of Baghdad, diverting it towards the lake and thus reducing the inundation of the Baghdad plane. According to local engineers the maximum flow in this channel is in the order of 30 000 $m^3/s$, which however seems not realistic.

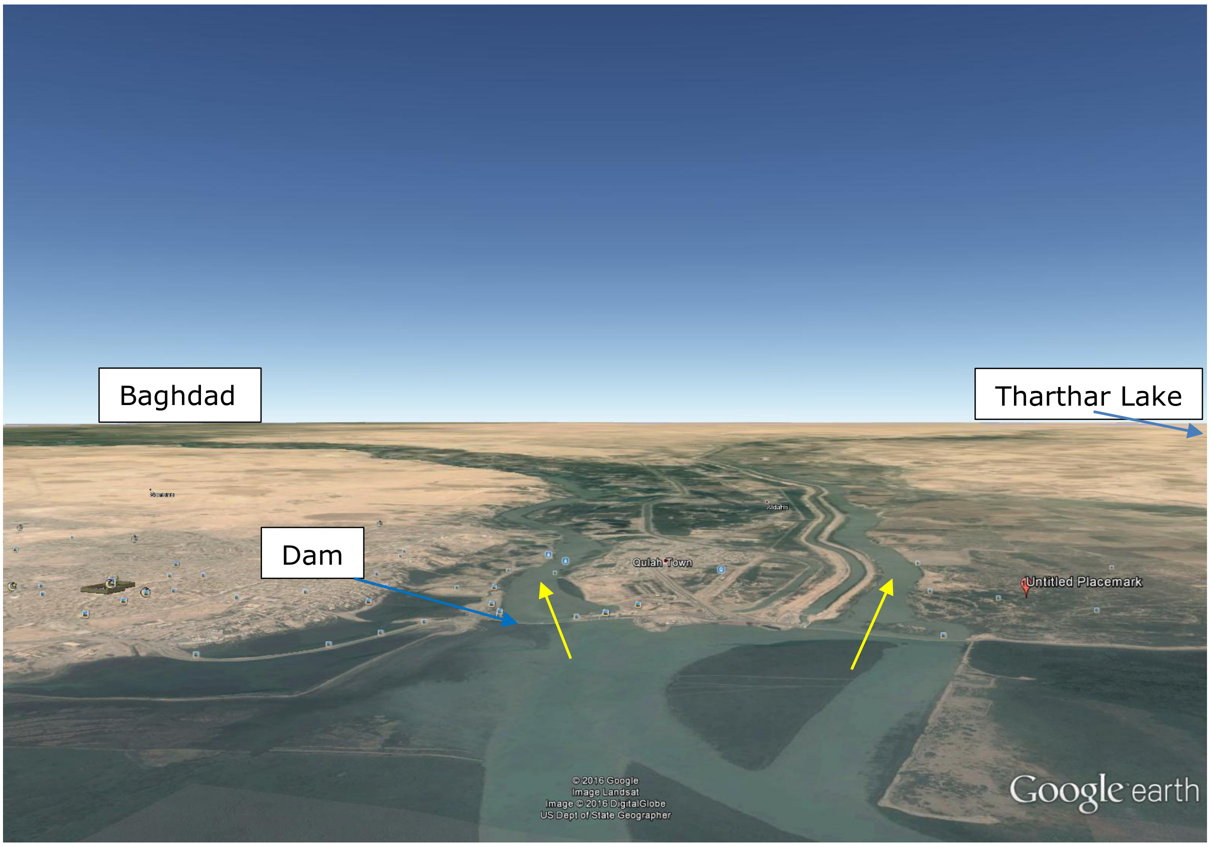
For these reasons, and due to the fact that the newly decided lake level was decreased from 319 to 315 m, it was decided to perform additional calculations taking into account this additional detail.

## 4.1 The channel

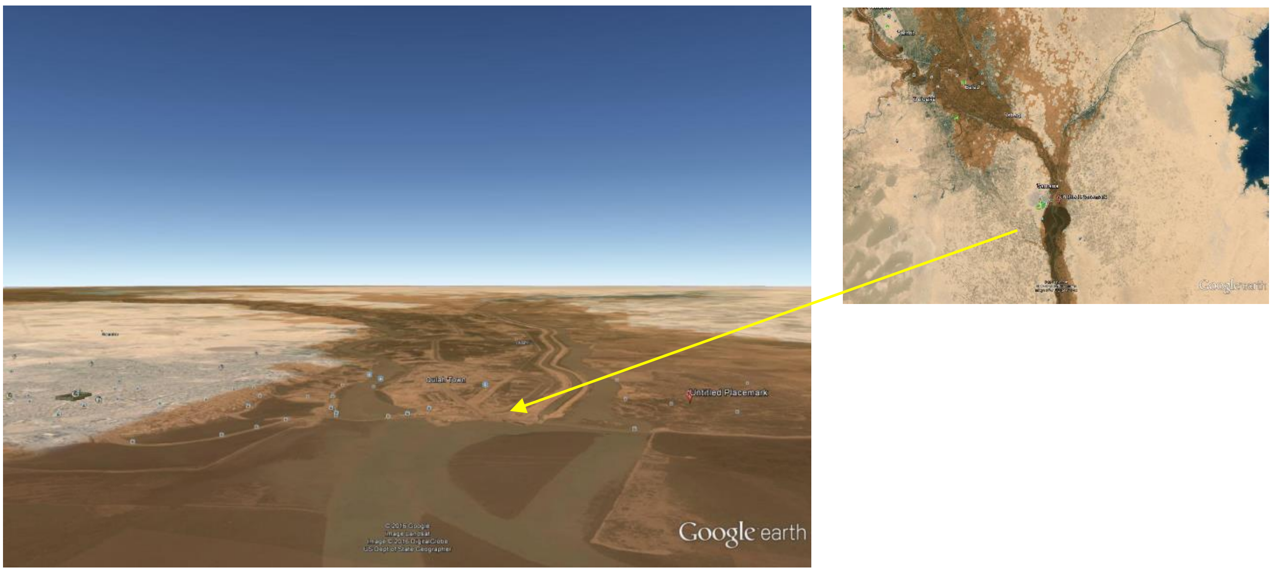
The channel in question is visible in the image below obtained by Google Earth. The length of the channel is about 77 km and the width ranges between 40 and 130 m, as indicated in the image. The height drops from 62 to 44 m, i.e. 18 m for an average slope of 0.23 % and a max slope of about 2%.

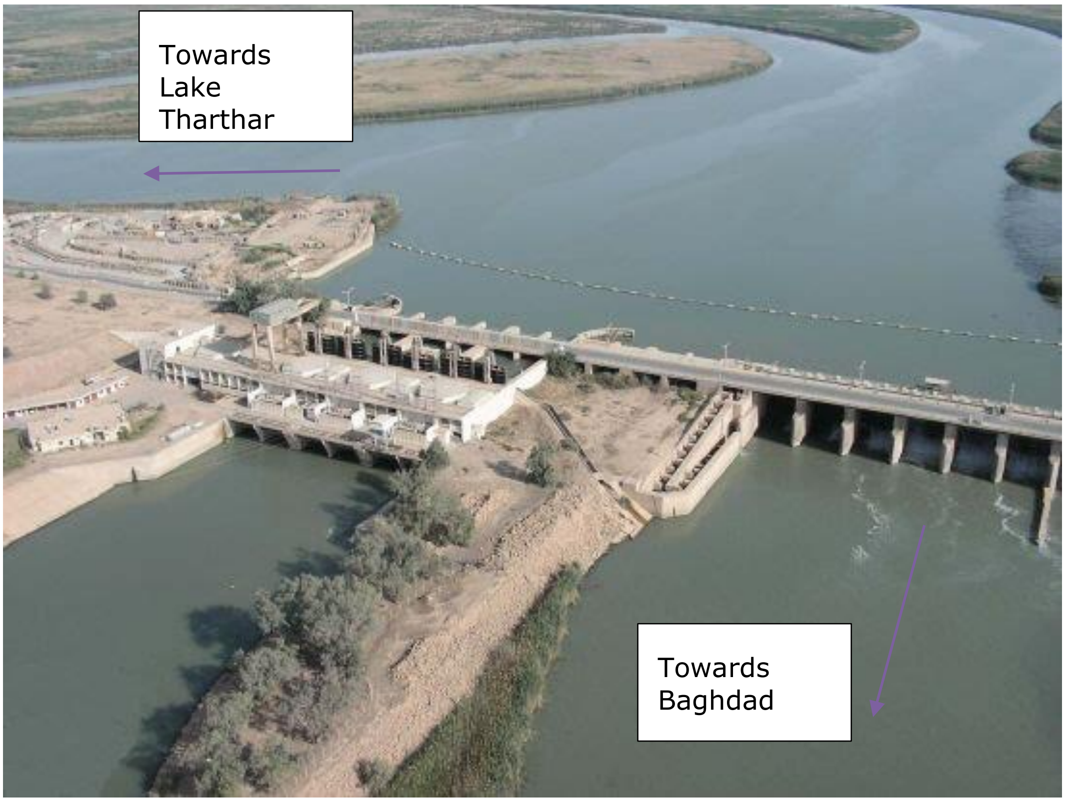
The image below shows the point where the channel starts, Qulah Town. On the left a Hydropower dam creates the lake but after the dam a jump of about 10 m is present which means that (considering the flood wave height at this location of about 8 m) the dam does not offer a great protection for the locations downstream, and most of the water would naturally flow on the left, toward Baghdad. On the right lies the entrance to the channel in question towards Tharthar lake, which flows for a long distance at the same elevation (62-64 m) before losing large part of the 18 m in the last part of its trajectory.




The image below shows superimposed the inundation corresponding to 319m of Lake elevation to show that all this area is largely inundated. It is however not clear how much water tends to flow towards Baghdad and how much would be spilled away through the channel.

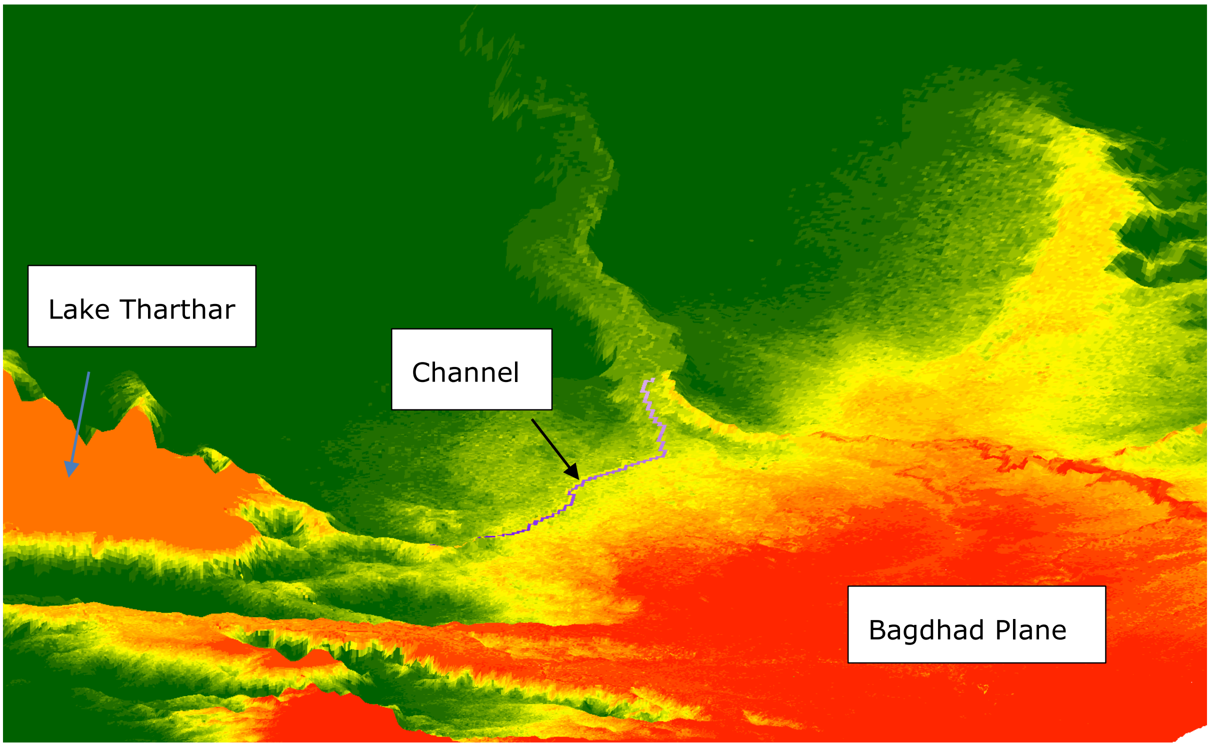


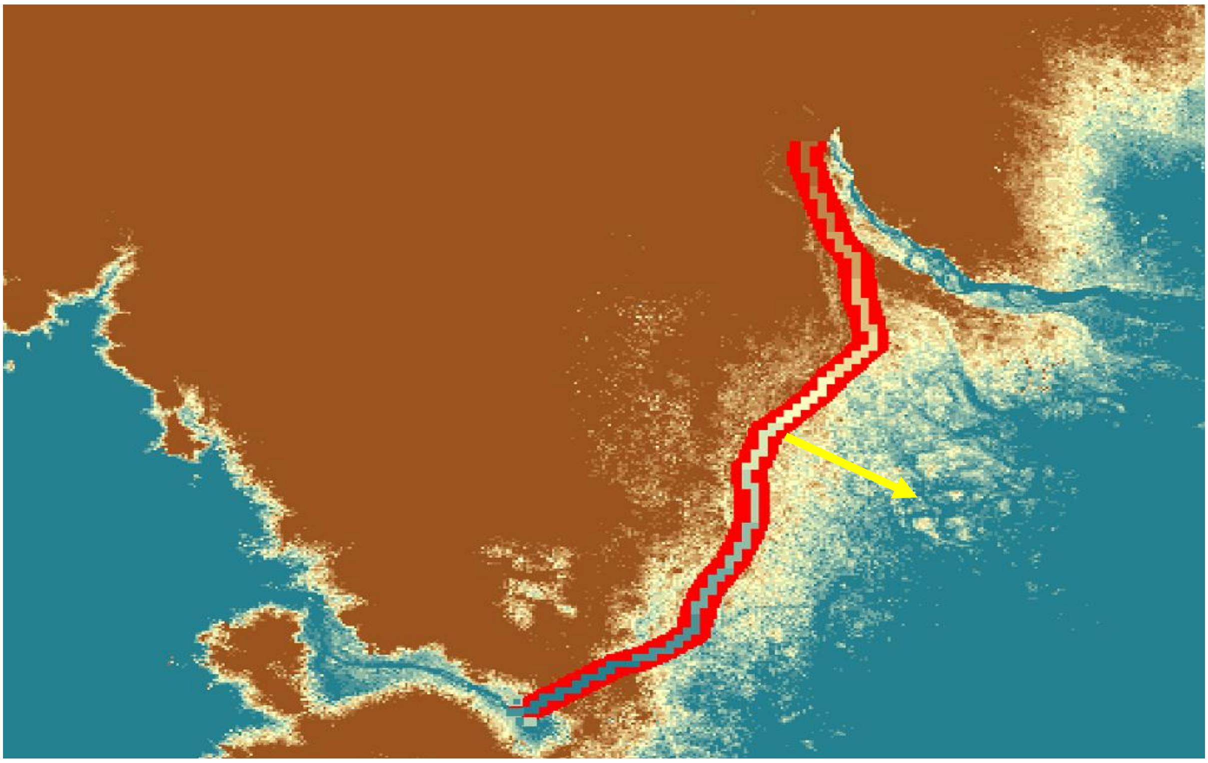
The Samarra dam is constructed with a wall of about 10m and it is not clear how much is the height of the dam above the normal water level upstream. We assumed it to be in the order of 2 m.



## 4.2 Modelling of the channel

The original SRTM bathymetry (90m) does not show clearly the presence of the channel even if the overall plane is present. In order to maximize the flow from the channel towards the lake, the channel has been modelled considering the original path, a continuous decreasing elevation from 64 to 44 m and including walls of maximum height 64 m to contain the water in the channel.



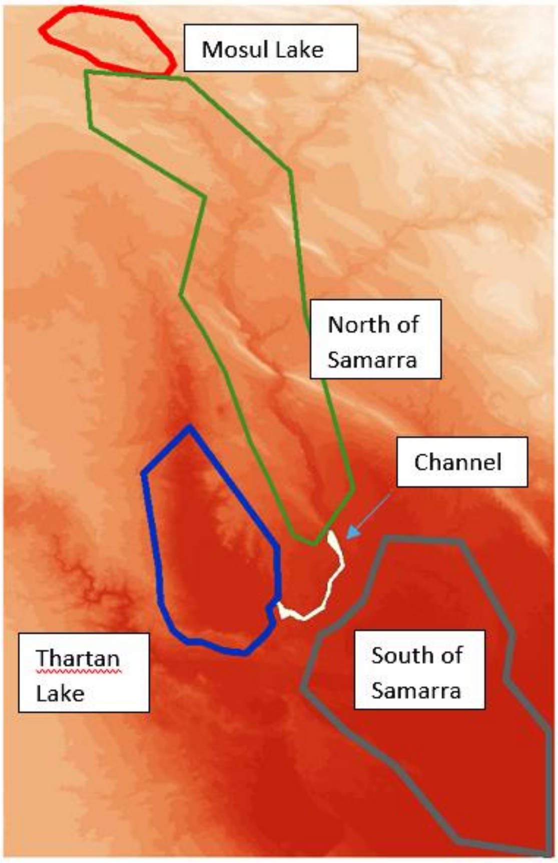



The width of the channel is 2 pixels (184x2=368 m) which is much more than in reality but we wanted to be sure that the water could flow even at this resolution. The presence of the walls (red in the figure above) is important to avoid that part of the water could flow down on the right, as indicated by the yellow arrow in the previous figure.

In order to prevent an immediate flow towards Baghdad, the dam has been raised by 2 m above the initial water level but given the very high flow and velocity some doubts exist that this dam could resist the large moment of water arriving. Nevertheless, it was maintained for the whole calculation.

## 4.3 Dam break calculations with the channel simulated and with 315 m initial lake elevation

In order to understand the various overall water movements, the calculation space has been subdivided in 5 zones, as indicated in the figure on the right.



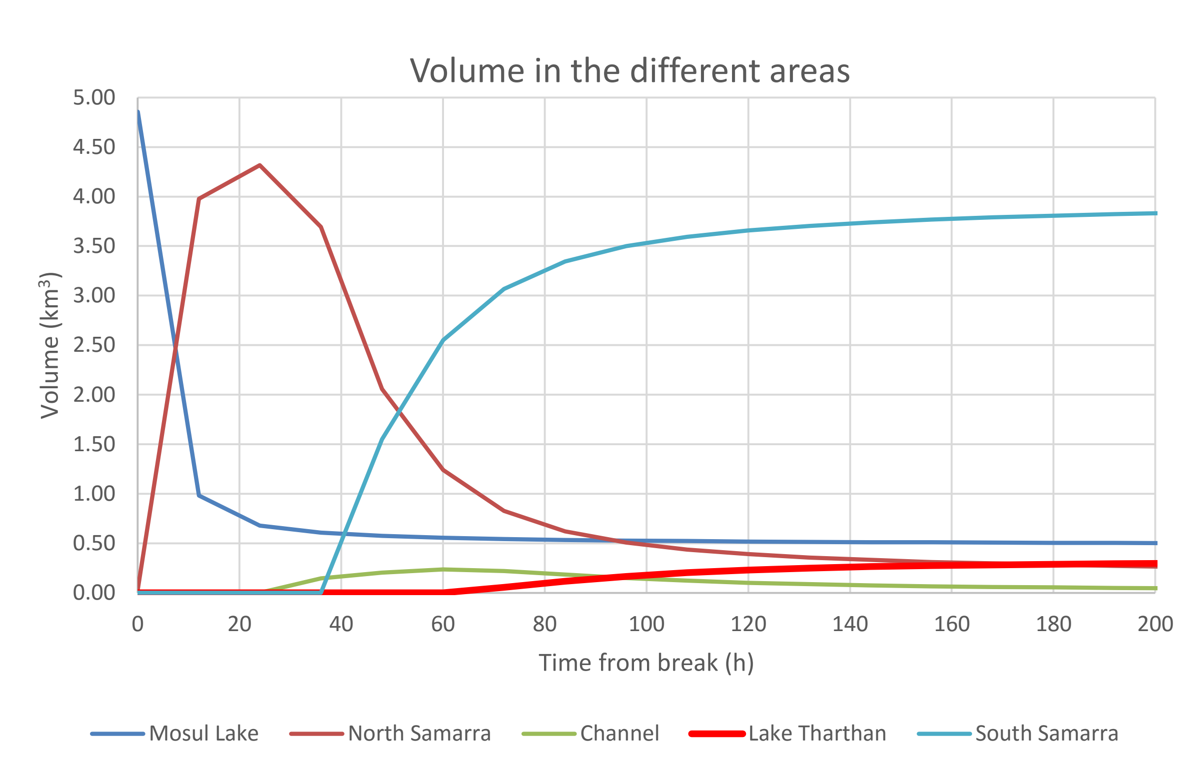

The results of the calculations are reported in terms of volume in each section and derivative of the volume, i.e. the volumetric flow change per second. For volumes with only one connection like Mosul lake, South Samarra and Tharthar Lake this quantity represents the flow inlet while for North of Samarra and the channel it represents the inlet/outlet difference.

It is interesting to note that the Lake discharges a huge initial flow, i.e. 89000 $m^3/s$, the inlet flow into the South of Samarra has an inflow peaking at 35000 $m^3/s$ and therefore the channel, whole maximum flow is 3.4 $m^3/s$, is insufficient to prevent the inundation of the district South of Samarra.

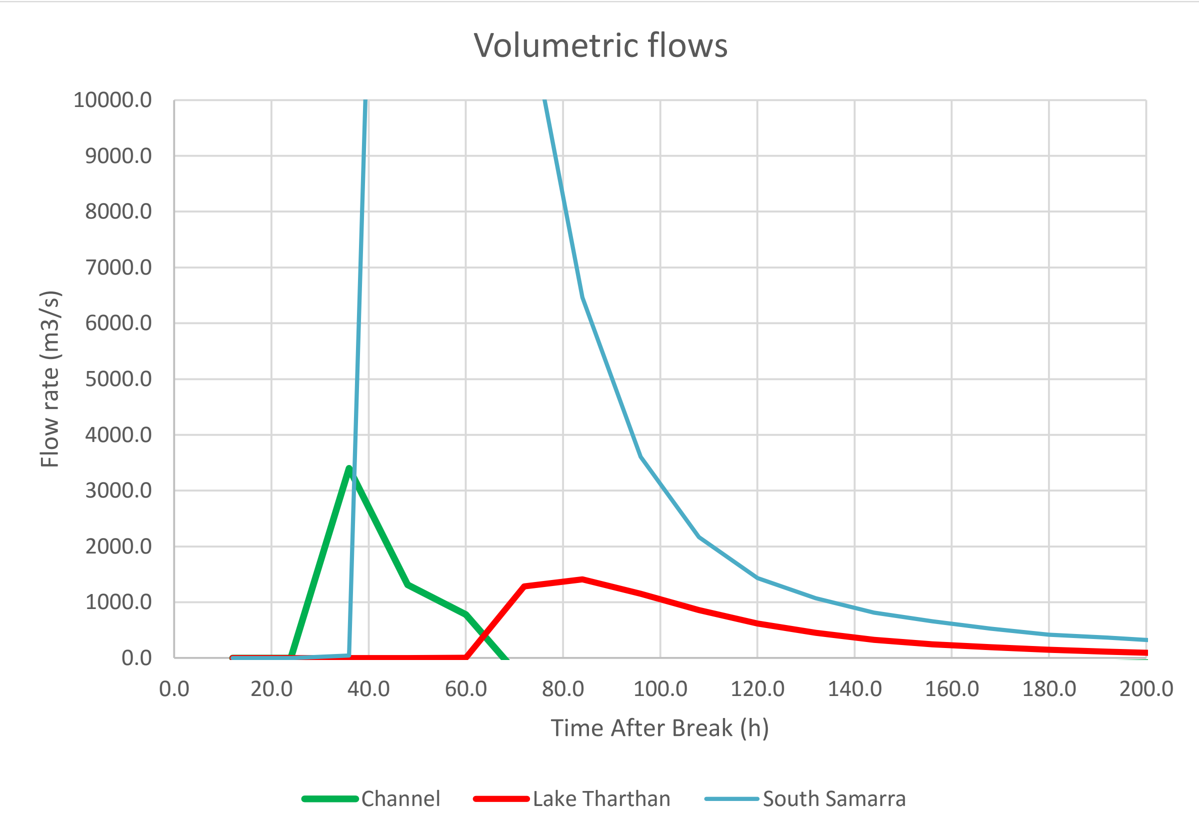
After the first hours however the channel can relief less and less and at the end of the transient condition the Tharthar lake will absorb only 0.3 $km^3$ against 3.9 $km^3$ of South Samarra.

Even if the modelling of the channel could be improved with a more detailed medullisation of the flow, we don't think that the flow rate should be much larger than what indicated. One should also consider that the size of the channel is in reality much narrower than what here assumed.

Further maps below show the difference in the inundation between the case with or without the contribution of the relief channel. It is obvious to consider that any further increase of the initial water level would probably increase the amount of water travelling in the channel but at the same time the flow to South of Samarra is even larger; again, we do not expect a large contribution of this channel to relieving the water volume flowing toward Baghdad.



Volume in the different areas
Volume (km3)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
20
40
60
80
100
120
140
160
180
200
Time from break (h)
Mosul Lake
North Samarra
Channel
Lake Tharthan
South Samarra

Volumetric flows
Flow rate (m3/s)
10000.0
9000.0
8000.0
7000.0
6000.0
5000.0
4000.0
3000.0
2000.0
1000.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Time After Break (h)
Channel
Lake Tharthan
South Samarra

## Volumes in the various areas ($km^3$)

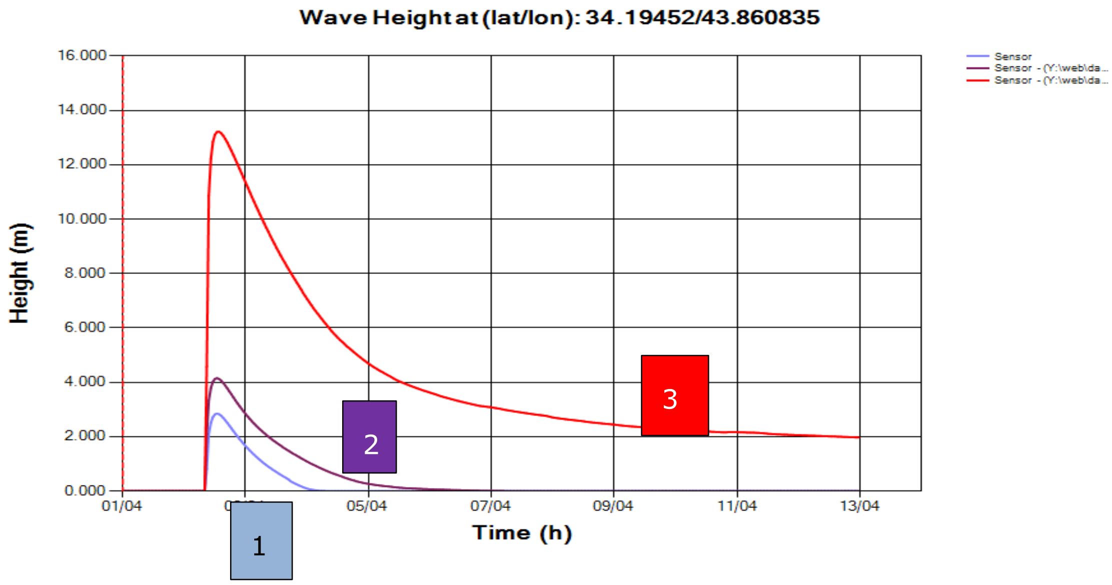
| *Time (h)* | Mosul Lake | North Samarra | Channel | Lake Tharthar | South Samarra |
|---|---|---|---|---|---|
| *0* | 4.85 | 0.04 | 0.00 | 0.00 | 0.00 |
| *12* | 0.98 | 3.98 | 0.00 | 0.00 | 0.00 |
| *24* | 0.68 | 4.32 | 0.00 | 0.00 | 0.00 |
| *36* | 0.61 | 3.69 | 0.15 | 0.00 | 0.00 |
| *48* | 0.58 | 2.06 | 0.20 | 0.00 | 1.55 |
| *60* | 0.56 | 1.24 | 0.24 | 0.00 | 2.55 |
| *72* | 0.54 | 0.83 | 0.22 | 0.06 | 3.07 |
| *84* | 0.53 | 0.62 | 0.18 | 0.12 | 3.35 |
| *96* | 0.53 | 0.51 | 0.15 | 0.17 | 3.50 |
| *108* | 0.52 | 0.44 | 0.12 | 0.20 | 3.59 |
| *120* | 0.52 | 0.39 | 0.10 | 0.23 | 3.66 |
| *132* | 0.51 | 0.36 | 0.09 | 0.25 | 3.70 |
| *144* | 0.51 | 0.33 | 0.08 | 0.26 | 3.74 |
| *156* | 0.51 | 0.31 | 0.07 | 0.27 | 3.77 |
| *168* | 0.51 | 0.30 | 0.06 | 0.28 | 3.79 |
| *180* | 0.51 | 0.28 | 0.05 | 0.29 | 3.81 |
| *192* | 0.50 | 0.27 | 0.05 | 0.29 | 3.82 |
| *204* | 0.50 | 0.26 | 0.05 | 0.30 | 3.84 |
| *216* | 0.50 | 0.26 | 0.04 | 0.30 | 3.85 |
| *228* | 0.50 | 0.25 | 0.04 | 0.30 | 3.86 |

Note the effect of the dam: the channel is filling but no water is still going to South Samarra

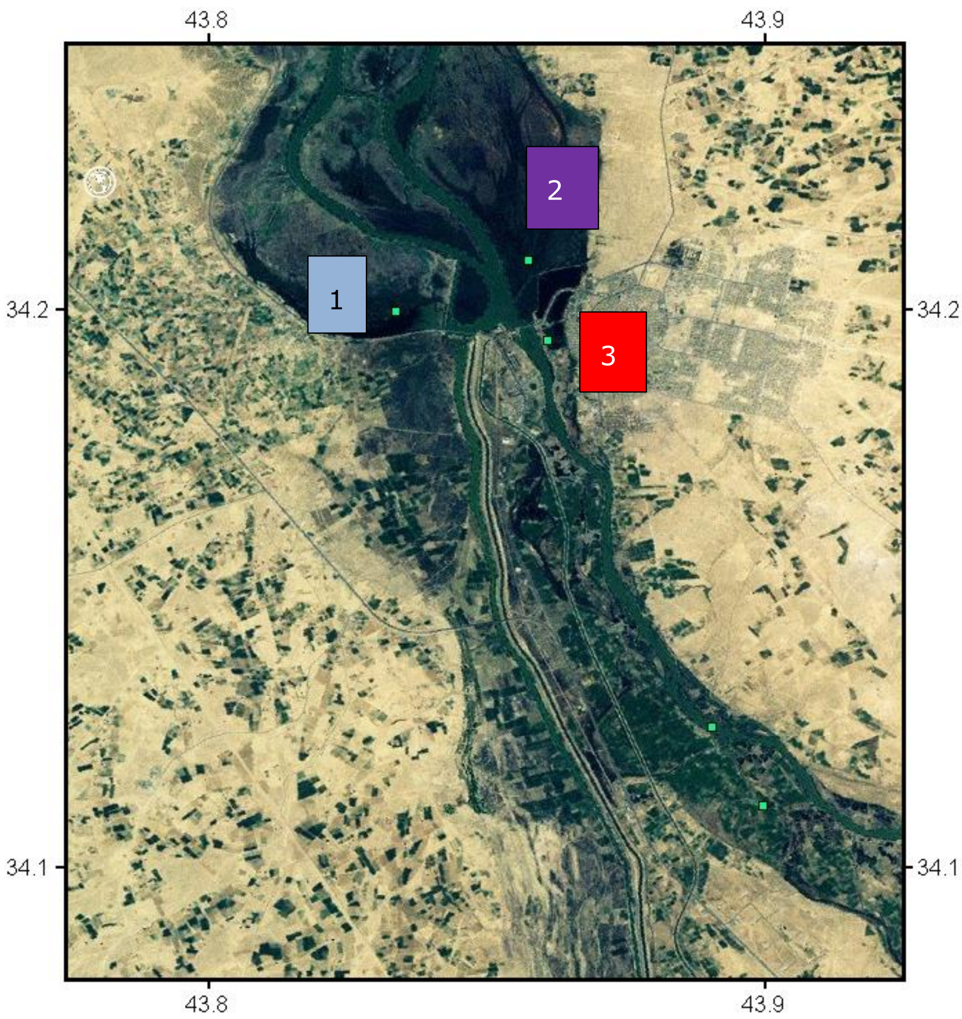
## Volumetric flow in the areas (inflow-outflow, $m^3/s$)

| *Time (h)* | Mosul Lake | North Samarra | Channel | Lake Tharthar | South Samarra |
|---|---|---|---|---|---|
| *0.0* | | | | | |
| *12.0* | -89611.5 | 91239.6 | 0.0 | 0.0 | 0.0 |
| *24.0* | -7036.7 | 7868.4 | 0.0 | 0.0 | 0.0 |
| *36.0* | -1638.0 | -14490.8 | **3397.7** | 0.0 | 44.6 |
| *48.0* | -761.5 | -37812.9 | 1314.6 | 0.0 | 35803.5 |
| *60.0* | -448.3 | -18940.9 | 780.3 | 2.9 | 23219.7 |
| *72.0* | -295.0 | -9530.3 | -422.3 | 1283.0 | 11915.4 |
| *84.0* | -211.4 | -4810.9 | -829.3 | 1411.7 | 6461.3 |
| *96.0* | -160.7 | -2636.1 | -788.8 | 1153.7 | 3606.5 |
| *108.0* | -124.2 | -1598.2 | -621.5 | 857.2 | 2166.5 |
| *120.0* | -98.6 | -1086.2 | -468.9 | 621.3 | 1434.7 |
| *132.0* | -80.9 | -778.5 | -353.5 | 451.4 | 1074.0 |
| *144.0* | -68.3 | -590.3 | -263.6 | 328.7 | 812.3 |
| *156.0* | -57.8 | -456.1 | -203.0 | 245.3 | 659.0 |
| *168.0* | -49.4 | -362.5 | -161.1 | 191.4 | 527.0 |
| *180.0* | -42.5 | -298.4 | -126.4 | 147.7 | 420.1 |
| *192.0* | 37.0 | -248.6 | -95.8 | 111.2 | 364.0 |
| *204.0* | -32.5 | -212.0 | -75.8 | 86.4 | 303.3 |
| *216.0* | -28.0 | -185.8 | -60.8 | 68.3 | 258.9 |
| *228.0* | -24.7 | -160.1 | -51.6 | 55.7 | 232.3 |

This is the only period in which the channel is active and can absorb water. Once the flow is passed the channel empties



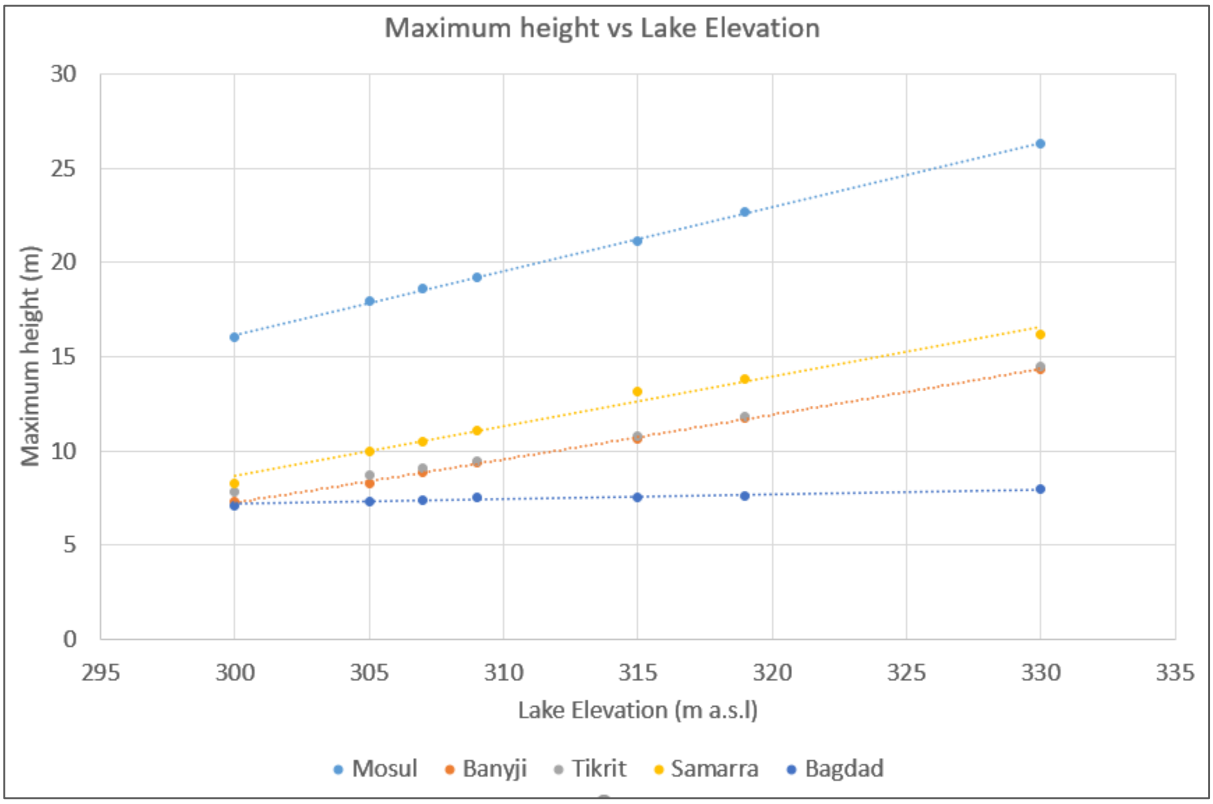

*Flow depth at the positions identified below*



## 4.4 Overall results of all the cases, including the 315 m

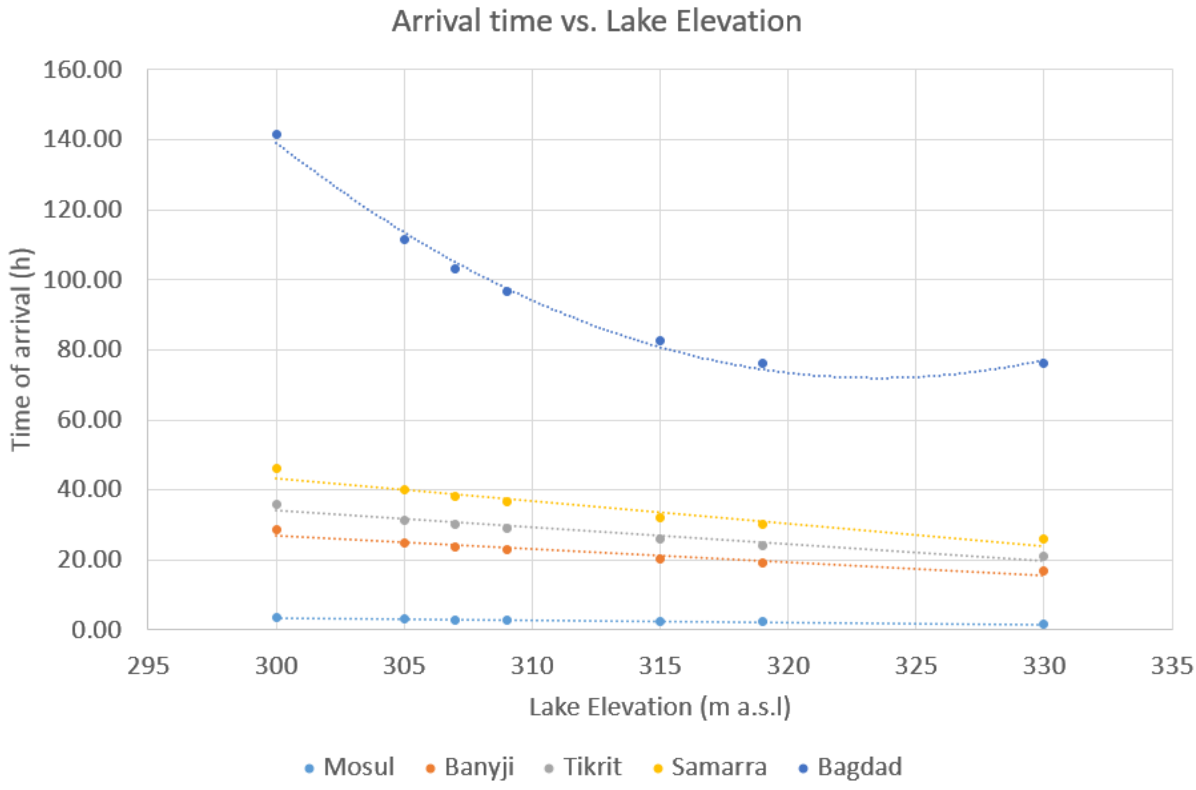
**Maximum Height**

| Lake Elevation | Mosul | Bayji | Tikrit | Samarra | Bagdad |
|---|---|---|---|---|---|
| **330** | 26.3 | 14.3 | 14.5 | 16.1 | 8.0 |
| **319** | 22.7 | 11.8 | 11.8 | 13.8 | 7.6 |
| **315** | 21.1 | 10.6 | 10.8 | 13.2 | 7.5 |
| **Channel 315** | = | = | = | = | 7.5 |
| **309** | 19.2 | 9.3 | 9.5 | 11.1 | 7.5 |
| **307** | 18.6 | 8.9 | 9.1 | 10.4 | 7.4 |
| **305** | 17.9 | 8.3 | 8.7 | 9.9 | 7.3 |
| **300** | 16.0 | 7.3 | 7.8 | 8.3 | 7.1 |



**Arrival times (hours)**

| Lake Elevation | Mosul | Banyji | Tikrit | Samarra | Bagdad |
|---|---|---|---|---|---|
| **330** | 1:40 | 16:56 | 21:08 | 26.12 | 76:15 |
| **319** | 2:29 | 18:59 | 24:07 | 30.05 | 76:20 |
| **315** | 2:35 | 20.19 | 25:50 | 32.13 | 83.30 |
| **Channel 315** | = | = | = | = | 83.52 |
| **309** | 2:55 | 22:54 | 29:00 | 36.48 | 96:40 |
| **307** | 2:54 | 23:45 | 30:04 | 38.12 | 103:05 |
| **305** | 3:17 | 24:53 | 31:19 | 40.12 | 111:31 |
| **300** | 3:40 | 28:32 | 35:58 | 46.18 | 141:33 |



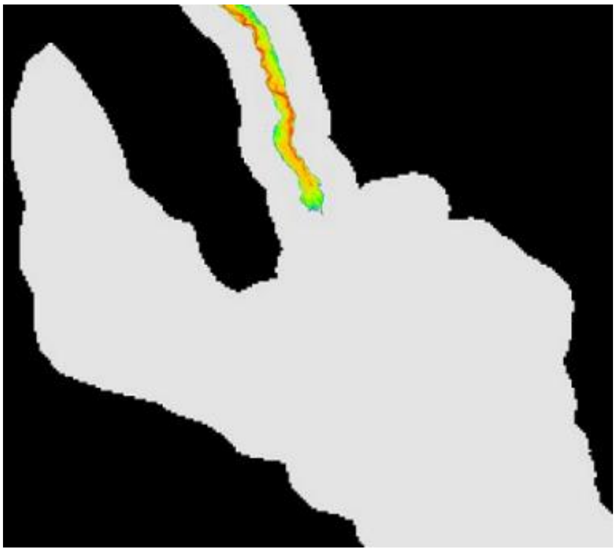
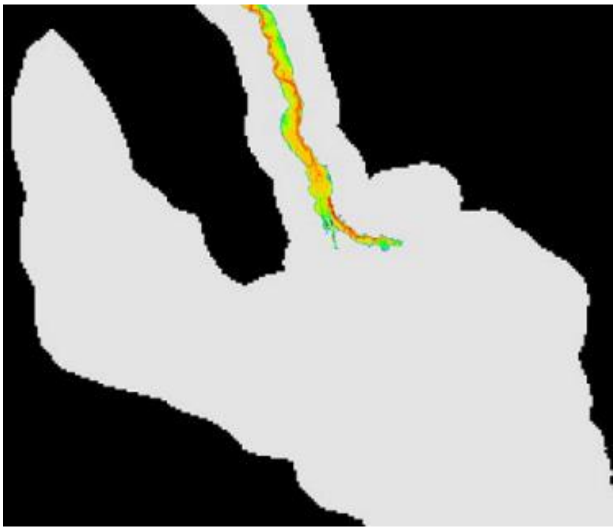
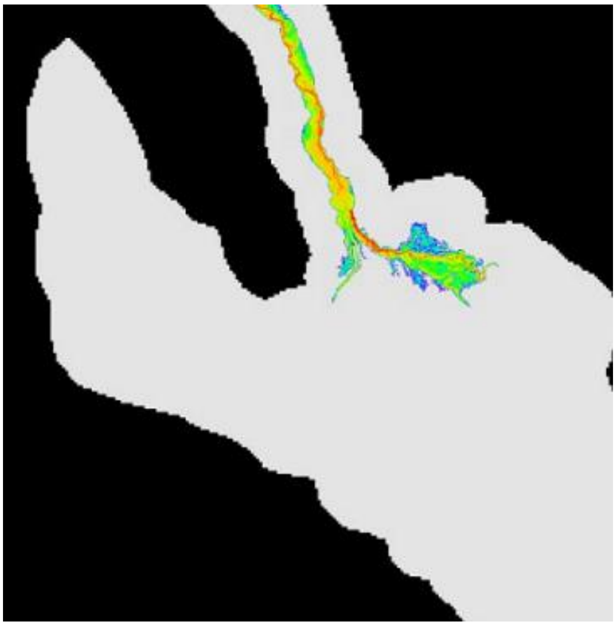
| Inundation | Population | Area (km²) |
| --- | --- | --- |
| 0.1 – 0.5m | 735 000 | NC (Tharthar) |
| 0.5 – 2.0m | 2 183 000 | NC (Tharthar) |
| 2 – 5m | 692 000 | 1 636 |
| 5 – 10m | 188 000 | 736 |
| > 10m | 101 000 | 422 |
| **Total** | **3 899 000** | **-** |

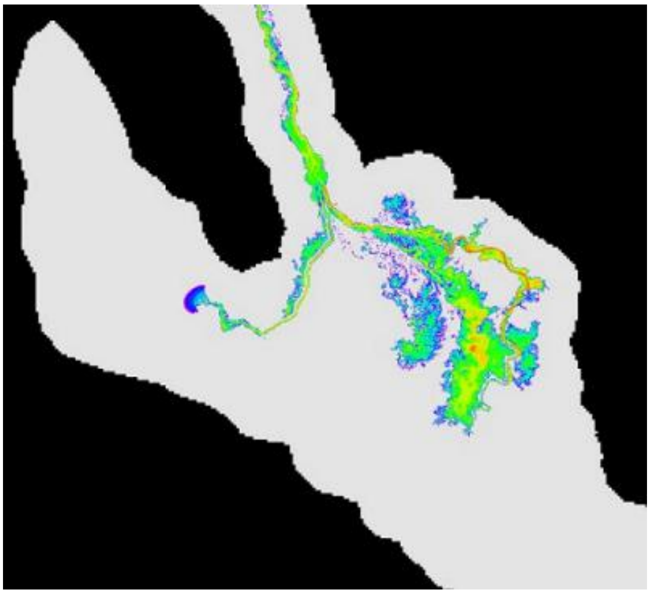
# 315 m – 12 days – including the Samarra channel

| Inundation | Mosul | Bayji | Tikrit | Samarra | Baghdad | *Baghdad (*)* |
| --- | --- | --- | --- | --- | --- | --- |
| 0.1 – 0.5m | 10 000 | 500 | 0 | 0 | 787 000 | *752 000* |
| 0.5 – 2.0m | 46 000 | 5 000 | 500 | 0 | 1 580 000 | *1 665 000* |
| 2 – 5m | 19 000 | 10 000 | 9 000 | 4 000 | 547 000 | *588 000* |
| 5 – 10m | 116 000 | 4 000 | 8 000 | 8 000 | 81 000 | *81 000* |
| > 10m | 54 000 | 0 | 0 | 0 | 0 | *0* |

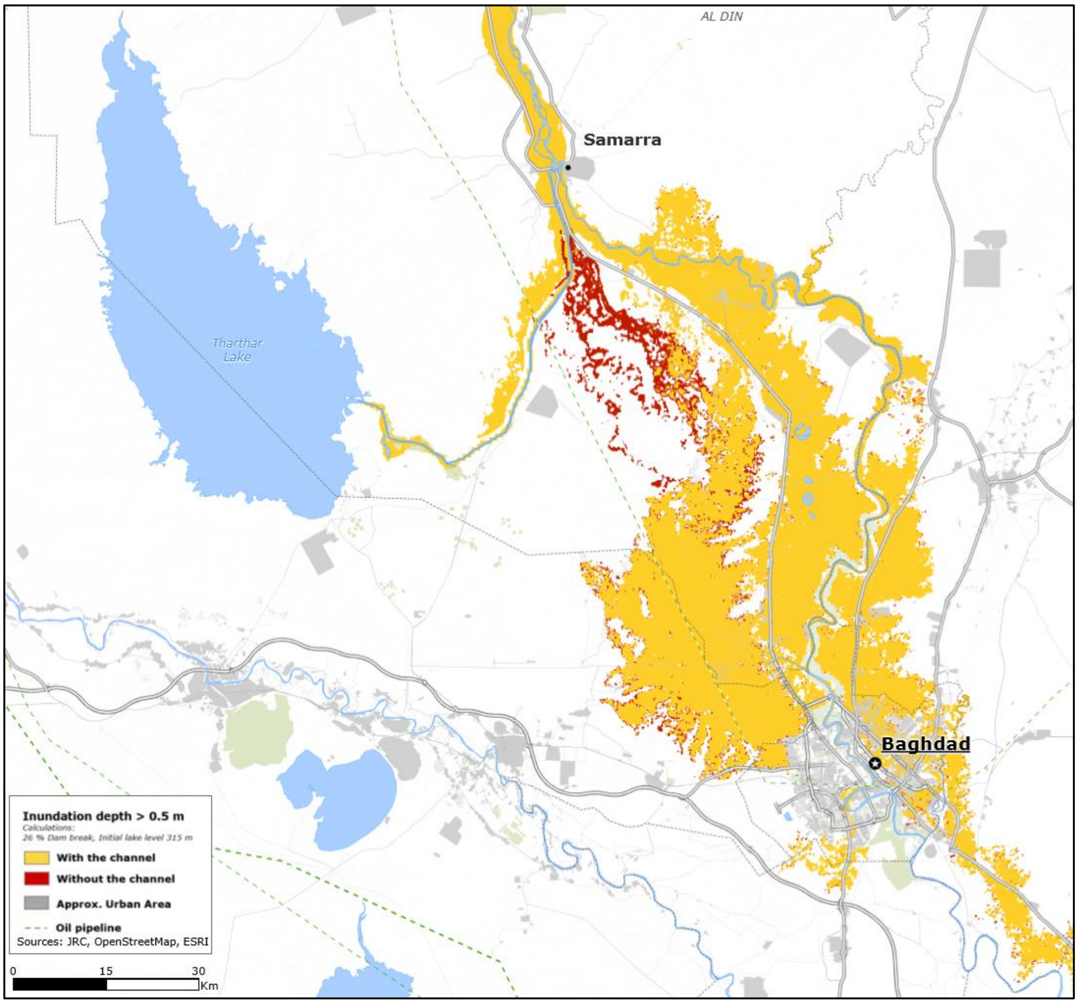
The affected population figures in the scenario where the existence of the channel leading to the Tharthar lake is included in the simulations. The last column marked with an asterisk (*) is the figures in Baghdad **not** considering the channel, given here for comparison. It can be seen that the difference is quite small.

In the column with the area affected, the two first classes (0.1-0.5m and 0.5-2m) are left empty since the area of lake Tharthar would enter in these classes, rendering them too large and quite meaningless.

| | |
|---|---|
|  | **Time=1d 9 h**<br><br>The water accumulates at Samarra dam |
|  | **Time=1 d 12 h**<br><br>Water overpasses the dam and starts to flow towards Baghdad and towards the lake |
|  | **Time=1 d 16 h**<br><br>The amount of water flowing towards Baghdad is definitely much larger than the one going towards the lake |

| | |
|---|---|
|  | Time=2d 17 h<br>When the lake is reached, most of the Baghdad plane is already flooded. |

This animation is available at: http://goo.gl/RrlhWe ; the map below indicates the comparison with and without the channel. There is only a small area (in red) that is inundated more if the channel is not included but the large part of Baghdad is inundated in both cases.



# 5 Conclusions

In this study we present numerical simulations of the flood wave following a breach of the Mosul dam, long known to be potentially unstable due to the water-permeable ground in which it was built. A few scenarios were run, within the time-limits set by this rapid-assessment report, considering the worst case scenario of a full reservoir and varying the percentage of dam surface destruction. Most conclusions are drawn from the case where the lake is at its maximum level of 330m and 26% of the dam is destroyed; while larger break percentages don't show siginficant differences. The focus of this study is the time-evolution and the characteristics of the flood wave and its effects on the population on the banks of the river Tigris.

Our calculations show the following:

1. The floodwave will reach the city of Mosul in less than two hours, it will attain heights of more than 20m in around 3hours and its maximum height at the city, 26m, after 6 hours. An area housing about 180 000 people, almost 10% of the city's population, would be exposed to a floodwave of more than 10m, thus risking complete annihilation.
2. The water wil continue downstream, having still a very significant height that is only slowly reduced and affect a total of about 6 million people. A total of more than 500 000 people (including Mosul) would be exposed to floodwaves of more than 5 metres in height. An area of 7 200 square km would be inundated, with a huge economic and social cost.
3. According to these simulations, in the case of Mosul, an evacuation within 4 to 5 km from the river would be advisable.
4. Our results are in good agreement with results of previous studies. Here we add a detailed time profile of the floodwave's height and an up-to-date estimate of the affected population using GIS. We also provide detailed maps of the potentially affected cities.
5. The analysis of the presence of the connecting channel between Samarra and Thartar lake indicates that the maximum relief flow through this channel (that was not initially considered), does not have a significant influence; the inundation of Baghdad takes place approximately at the same extent with or without the channel.

Further analyses have been performed by varying the initial lake height in order to identify the effect of the lake height reduction on the maximum flow depth and the extent of inundation and affected population. The results show that the **lake height reduction plays a very important role in the reduction of both quantities and also in the times elongation so that more time is available for the population to evacuate from the possibly affected areas:** as a matter of fact the arrival time in Bagdhad increases from 3 to 6 days by reducing the lake height from 330 to 300 m with obvious improvements in the possible consequences.

# 6 Limitations and Uncertainties in this study

There are a number of factors that can influence the numerical results and the conclusions of this study. These should always be kept in mind when considering the results, and especially if life-or-death decisions are to be taken based on them. Uncertainties and errors can be introduced by the following factors.

1. Errors in the elevation data and low resolution of the ground topography: In this study we used ground data of 180m resolution that can "smooth out" particular ground features. This can also affect the times and depths reported for the flood wave. The authors expect to be able to run simulations of higher resolution (that are quite time-consuming) in the near future.
2. Errors in the data and changes in the population numbers: In the first draft of this study we used the population data of LANDSCAN 2014 with a rather low resolution of around 1 km2 and we continued using this set for consistency. More importantly, this data set cannot possibly take into account recent population movements caused by warfare. The population data we give should be considered under these restrictions. Future modelling would use more detailed population data sets recently made available, such as the Global Human Settlement Layer (GHSL).
3. Modelling of the dam failure: As mentioned in the text, these simulations model the dam break to be almost instantaneous; it might be more realistic to introduce a gradual failure, as has been done in other studies. This would lower the maximum flood-wave height and the arrival time of this maximum (but would have lesser effects on the inundation extent). It is not the intention of this study to model the dam break with precision, but rather to estimate the affected population in a rapid-assessment manner.
4. The lake bathymetry was deduced by digitising a raster image in the study of Issa (2015). A more precise bathymetry would render the water volumes and the flow-out times more accurate.
5. The modelling of the connecting channel between Samarra and the Lake should be done by including the right dimensions whcih are not well known at the moment.

## References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9. Hojas-Gascon, Bianchi, Alfieri, Dottori, Salamon, JRC/ERCC report, 4/3/2016, private communication. K
10. Thair M. Al-Taiee 1 and Anass M. M. Rasheed – "Simulation Tigris River Flood Wave in Mosul City due to a Hypothetical Mosul Dam Break" - Thirteenth International Water Technology Conference, IWTC 13 2009, Hurghada, Egypt


## Acknowledgements


The authors would like to thank Giovanni Franchello for his help with setting up the Hyflux2 code and Andrea Gerhardinger for the digitalisation of the bathymetry maps and general GIS support.

## List of figures

# 7 Appendix I: Different scenarios of dam failure

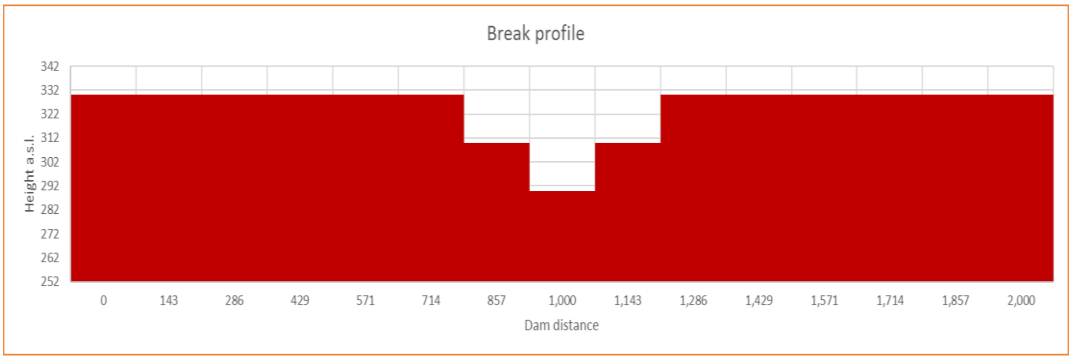
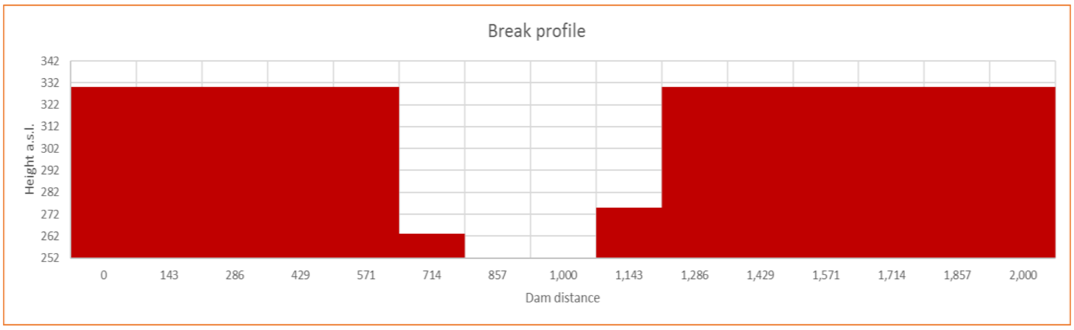
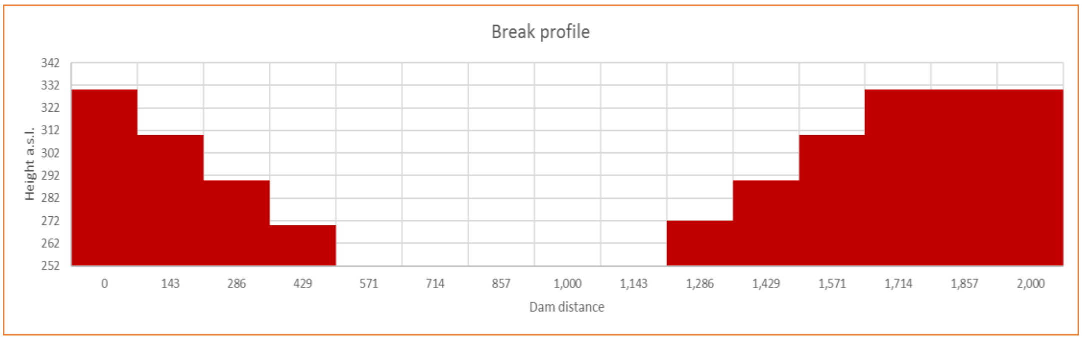
<table>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>7% Case<br><br>Only the upper part of the dam is broken for a length of about 500 m</td></tr>
<tr><td>
</td><td>26% deep<br><br>The dam is broken down to the bottom but to a limited horizontal extent</td></tr>
<tr><td>

Figure 8: Dam failure profiles for the different scenarios run. The dam is seen face-on.</td><td>60% deep<br><br>The dam is largely broken all the way to the bottom part</td></tr>
</table>

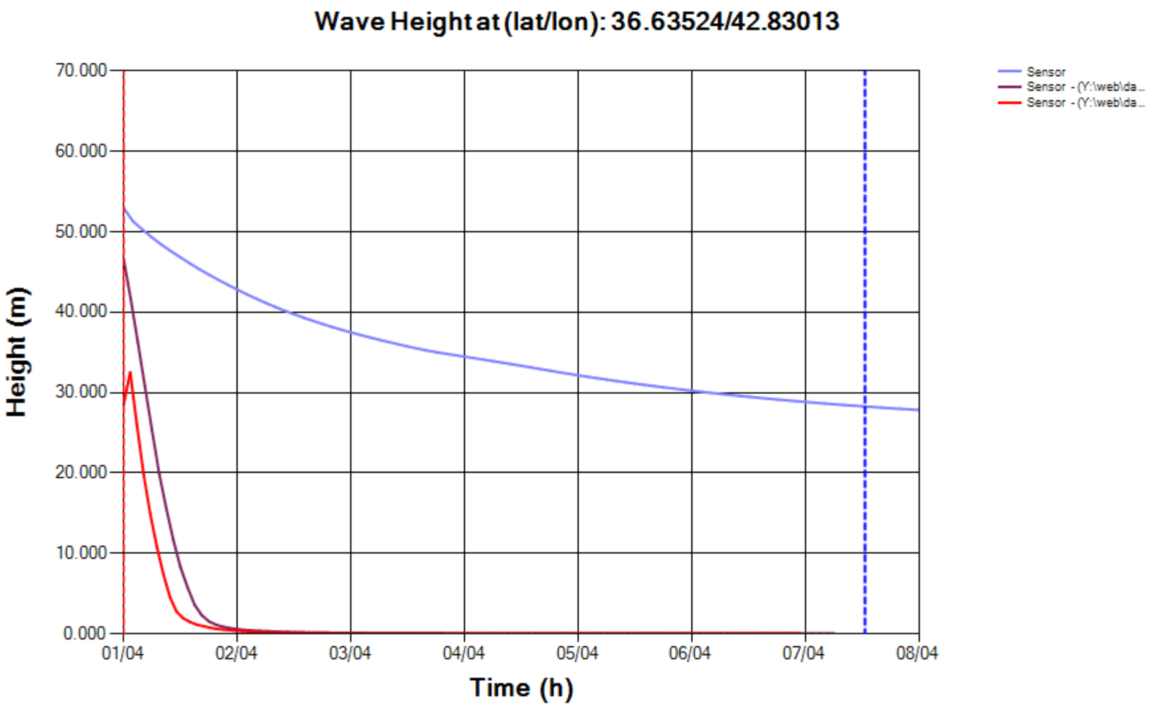



**Figure 9:** Height-Depth graph for the lake, for the three scenarios: 7% damage (blue), 26% damage (brown), 60% damage (red)

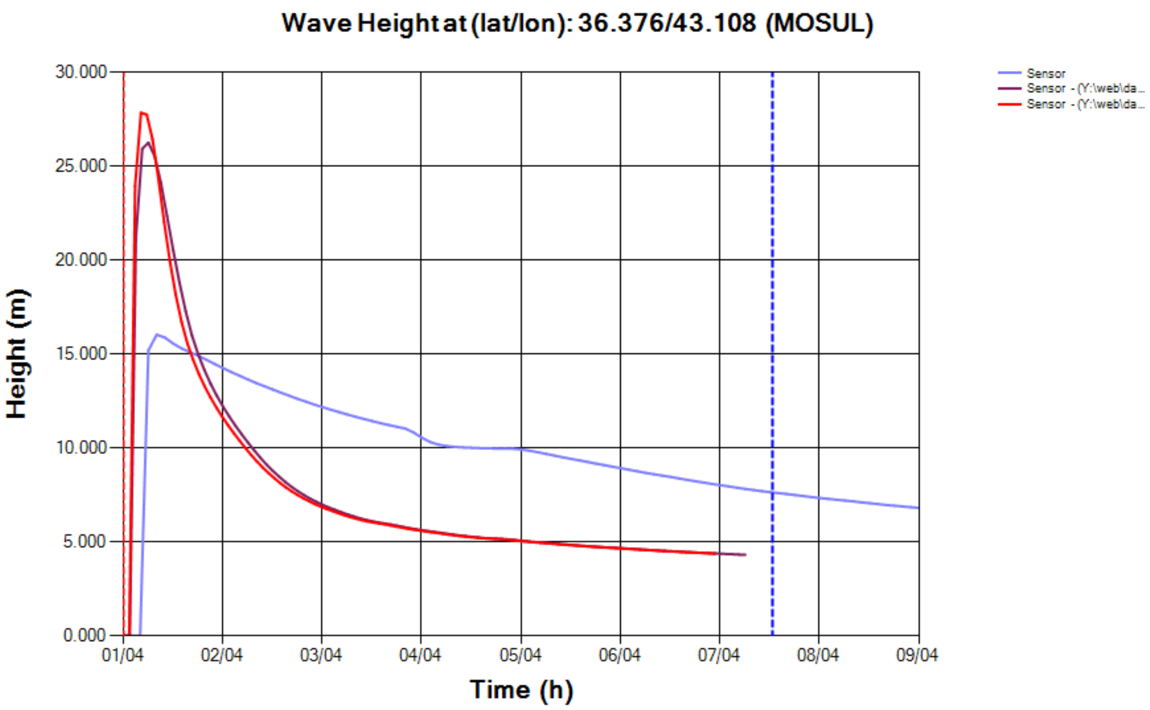



**Figure 10:** Height-Time graph for Mosul, for the three scenarios: 7% damage (blue), 26% damage (brown), 60% damage (red)

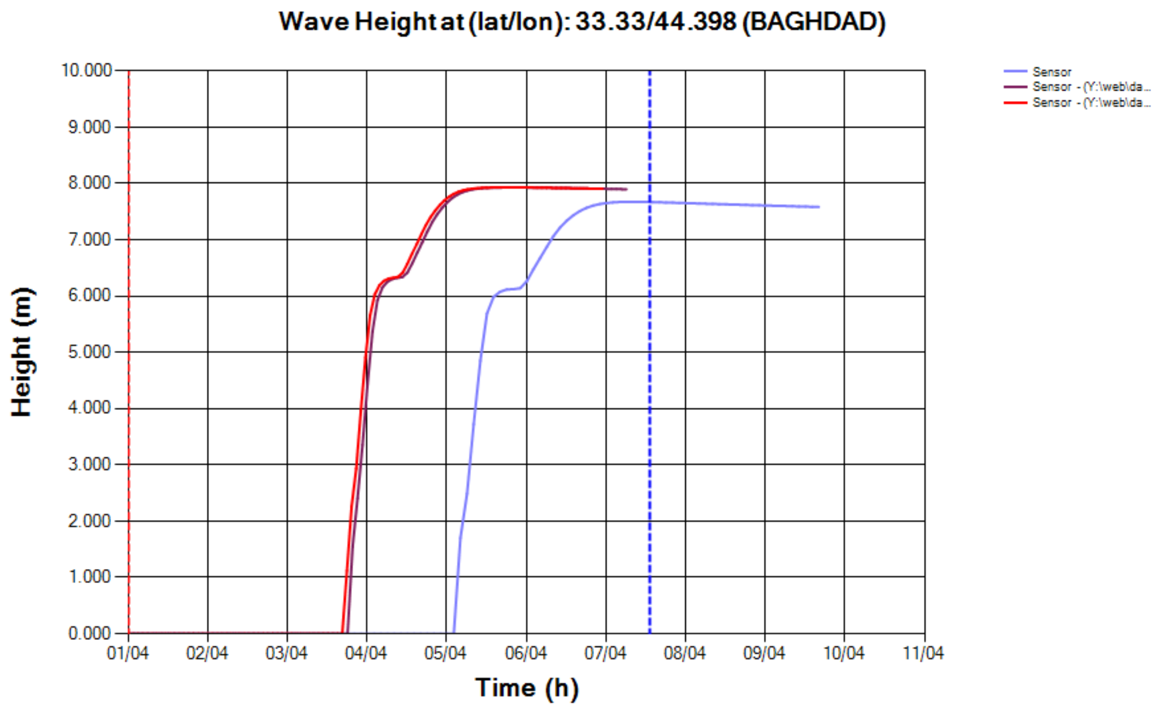



**Figure 11:** Height-Time graph for Baghdad, for the three scenarios: 7% damage (blue), 26% damage (brown), 60% damage (red)

| | 7% break | 26% break | 60% break |
|---|---|---|---|
| **ORIGINAL LAKE VOLUME (km³)** | 9.6 | 9.6 | 9.6 |
| **Residual Volume After Break** | 3.2 | 0.5 | 0.5 |
| **LOST WATER VOLUME** | 6.4 | 9.1 | 9.1 |

The table above shows that the final amount of water expelled in the 28 and 60% cases is the same, while the one with 7% is 30% less; the emptying time is also much longer and this explains the much smaller dynamic and final height in Baghdad.

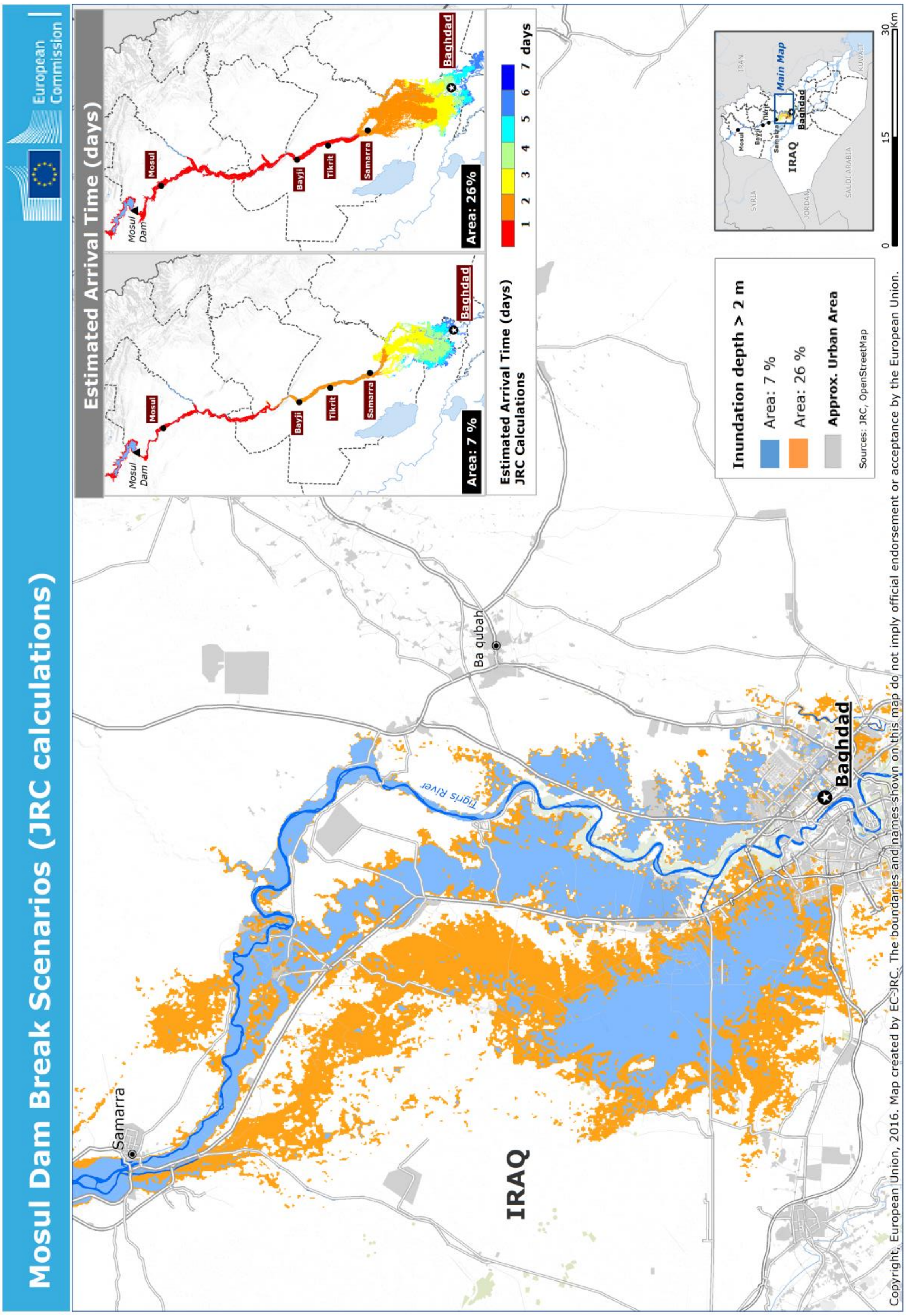
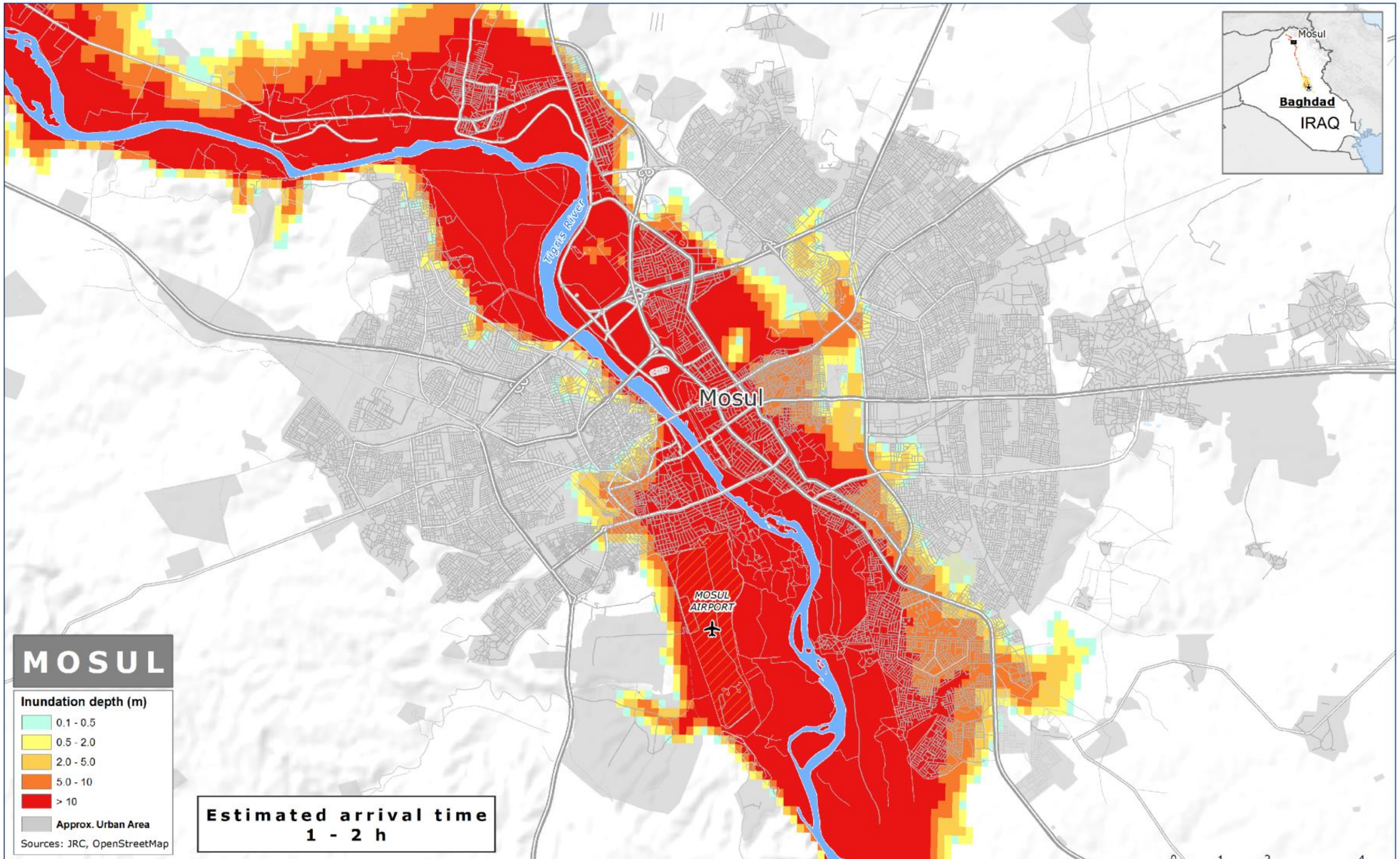


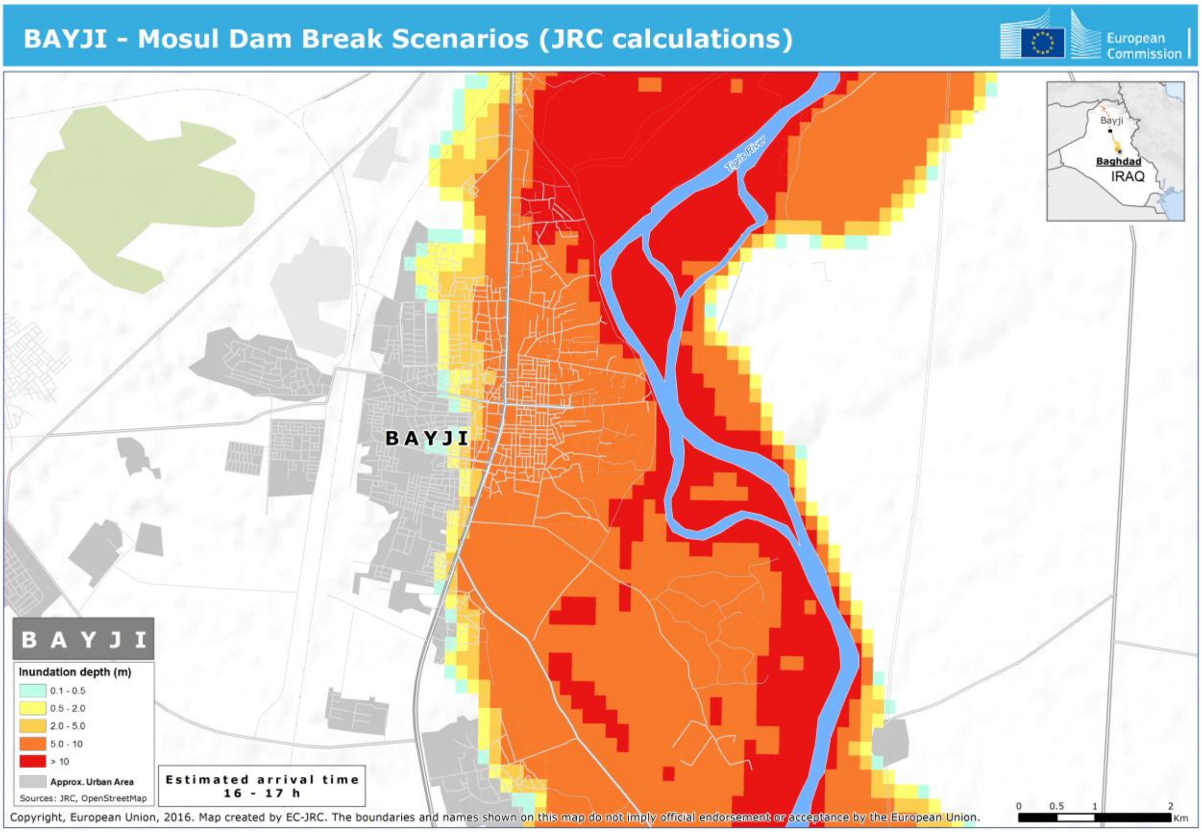

**Figure 12:** Comparison of the inundation maps for two scenarios: 7% (blue) and 26% damage (orange area).

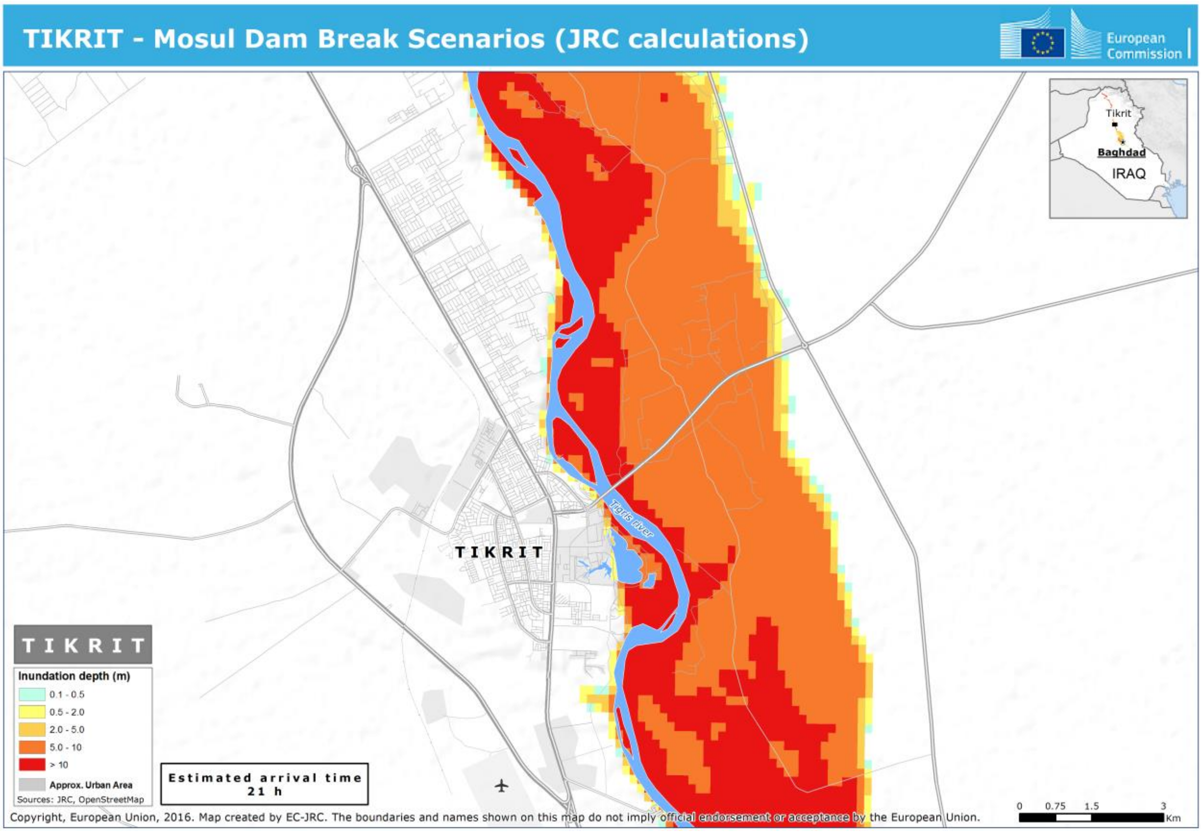
# 8 Appendix II: Inundation maps of major cities

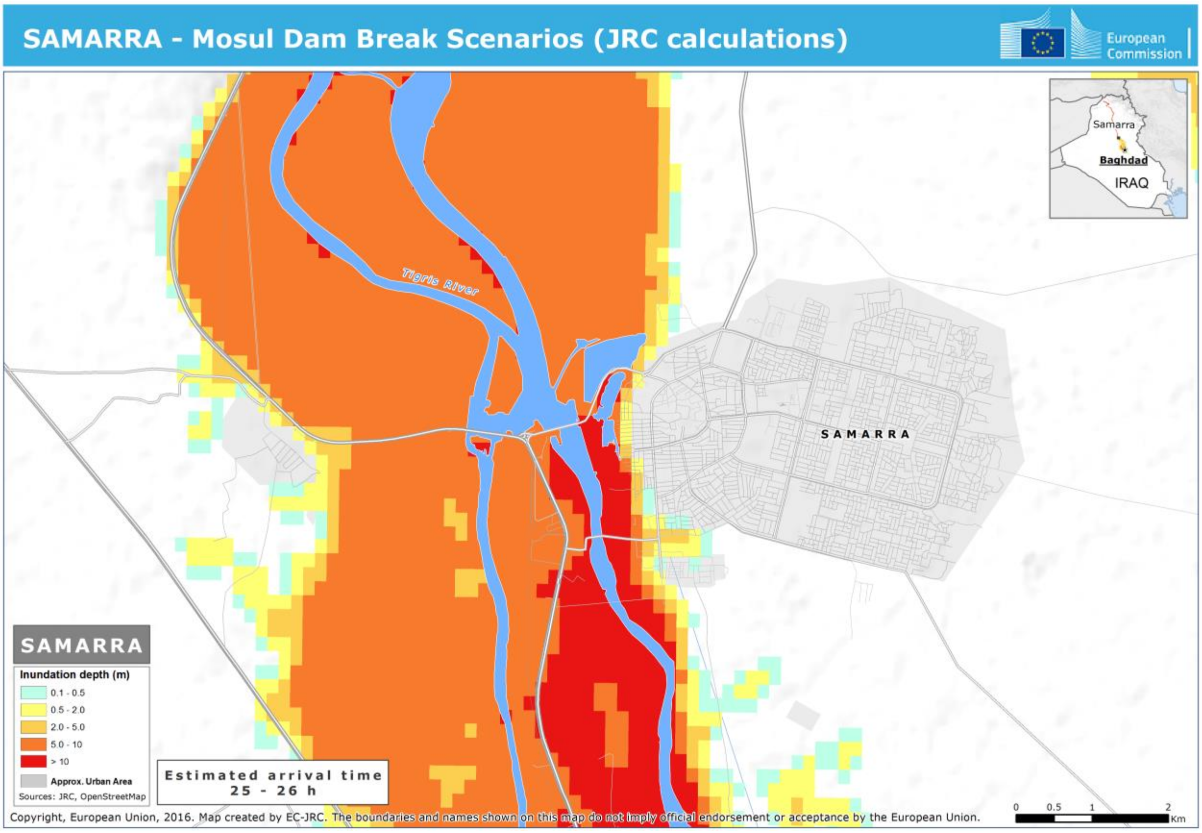
These maps show the flood wave height contours superimposed on maps of the cities. All maps in this Appendix use the results of the 26% damage scenario with the **maximum initial level of the lake, 330m**. Background data were extracted from OpenStreetMap (OSM). We used the city's streets and (where enough data were available) the land-use classification to indicate the approximate extent of the inhabited urban areas. As inhabited areas (shown in light grey) we used the following classes of OSM: Residential, Commercial, Industrial, Military, Cemetery. In places where the flood wave colours overshadow those of the urban areas, one could consider the existence of city-like streets as a rough indicator of inhabited areas.

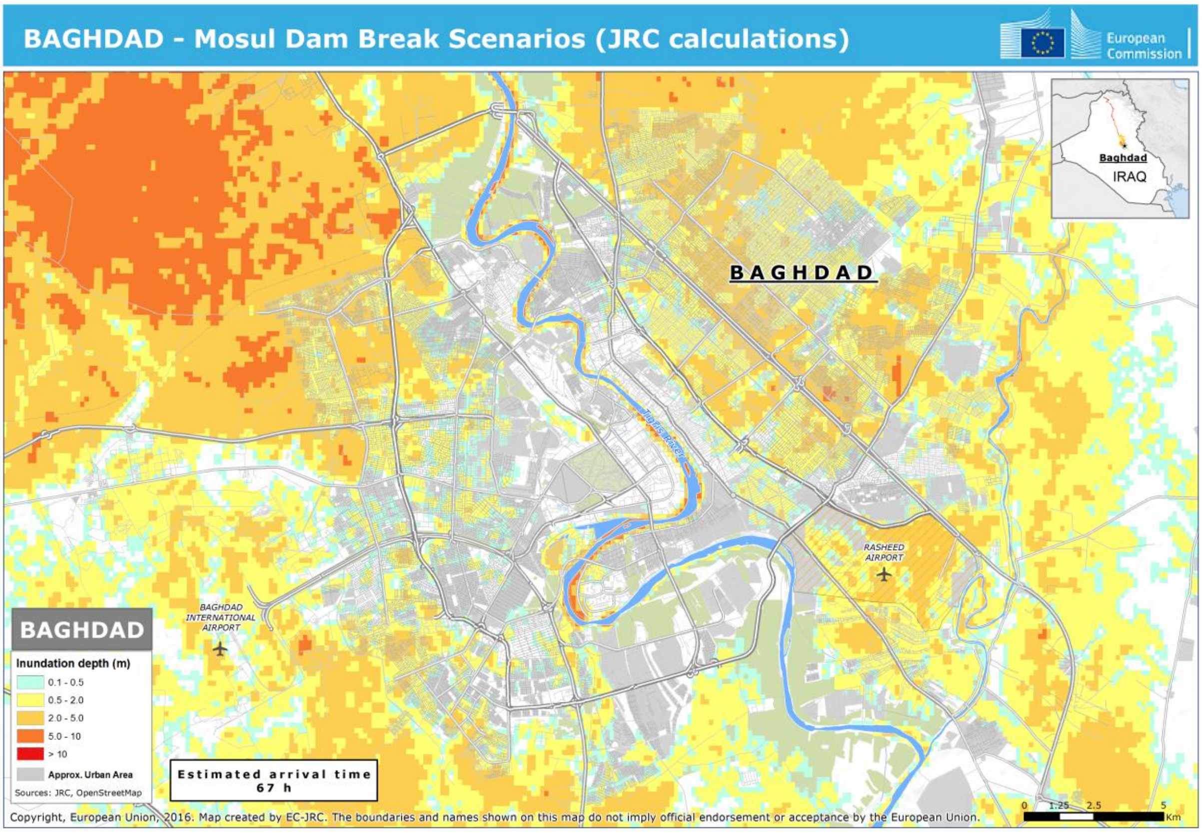
# MOSUL - Mosul Dam Break Scenarios (JRC calculations)




BAYJI - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Tigris River
Bayji
Baghdad
IRAQ
BAYJI
BAYJI
Inundation depth (m)
0.1 - 0.5
0.5 - 2.0
2.0 - 5.0
5.0 - 10
> 10
Approx. Urban Area
Sources: JRC, OpenStreetMap
Estimated arrival time
16 - 17 h
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
0 0.5 1 2 Km

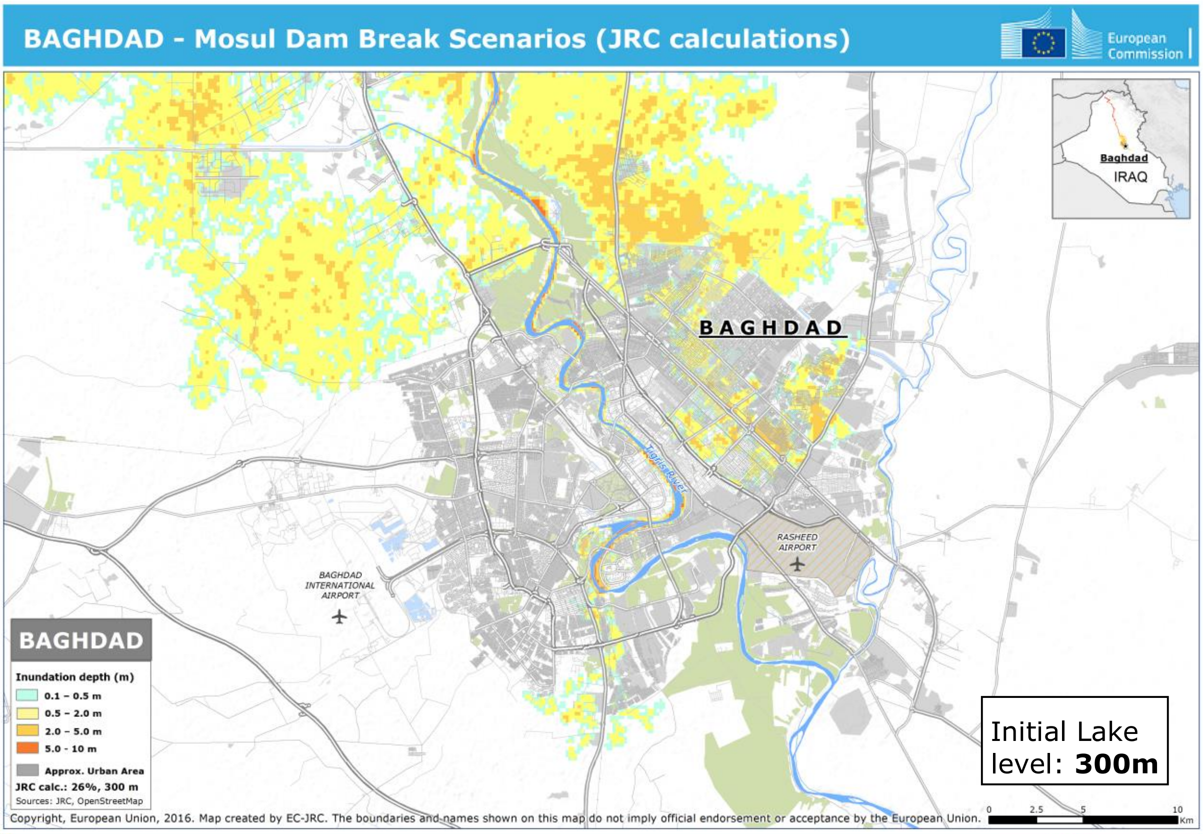

TIKRIT - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Tikrit
Baghdad
IRAQ
Tigris River
TIKRIT
TIKRIT
Inundation depth (m)
0.1 - 0.5
0.5 - 2.0
2.0 - 5.0
5.0 - 10
> 10
Approx. Urban Area
Sources: JRC, OpenStreetMap
Estimated arrival time
21 h
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
0 0.75 1.5 3 Km

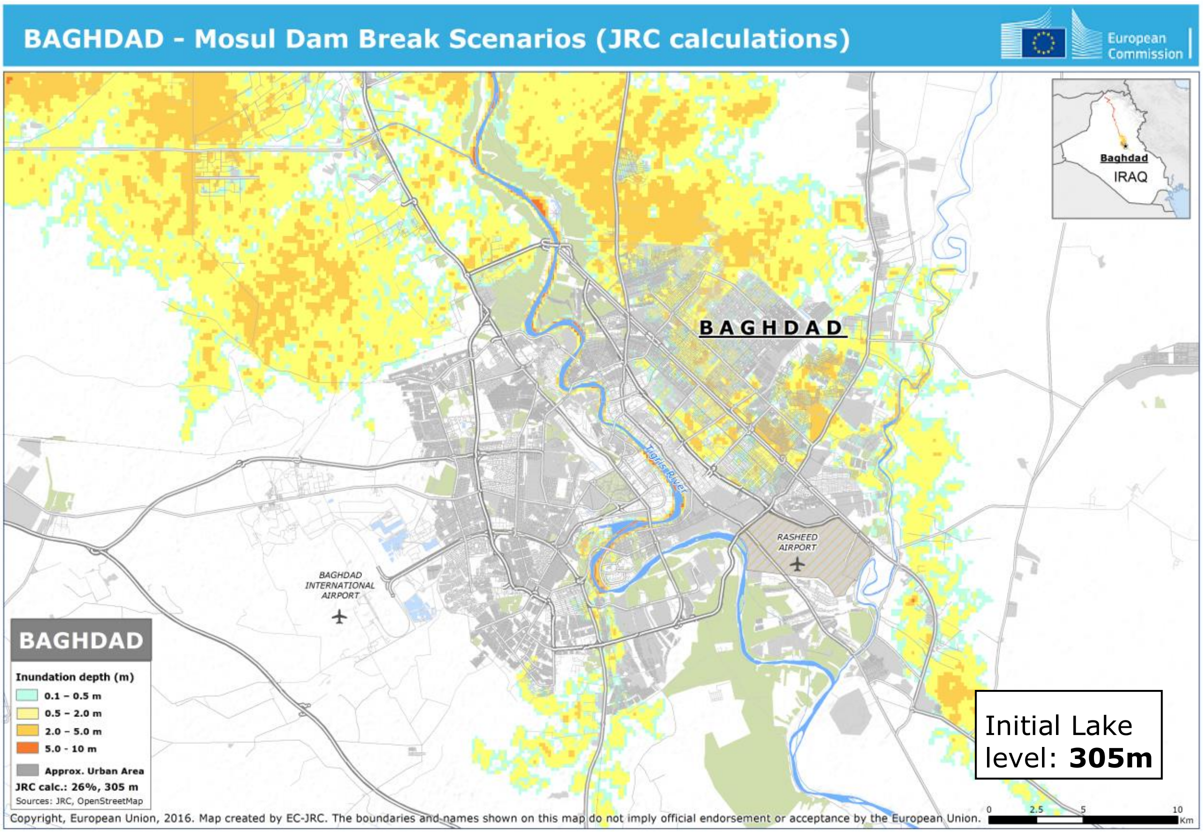

SAMARRA - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Samarra
Baghdad
IRAQ
Tigris River
SAMARRA
SAMARRA
Inundation depth (m)
0.1 - 0.5
0.5 - 2.0
2.0 - 5.0
5.0 - 10
> 10
Approx. Urban Area
Sources: JRC, OpenStreetMap
Estimated arrival time
25 - 26 h
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
0 0.5 1 2 Km

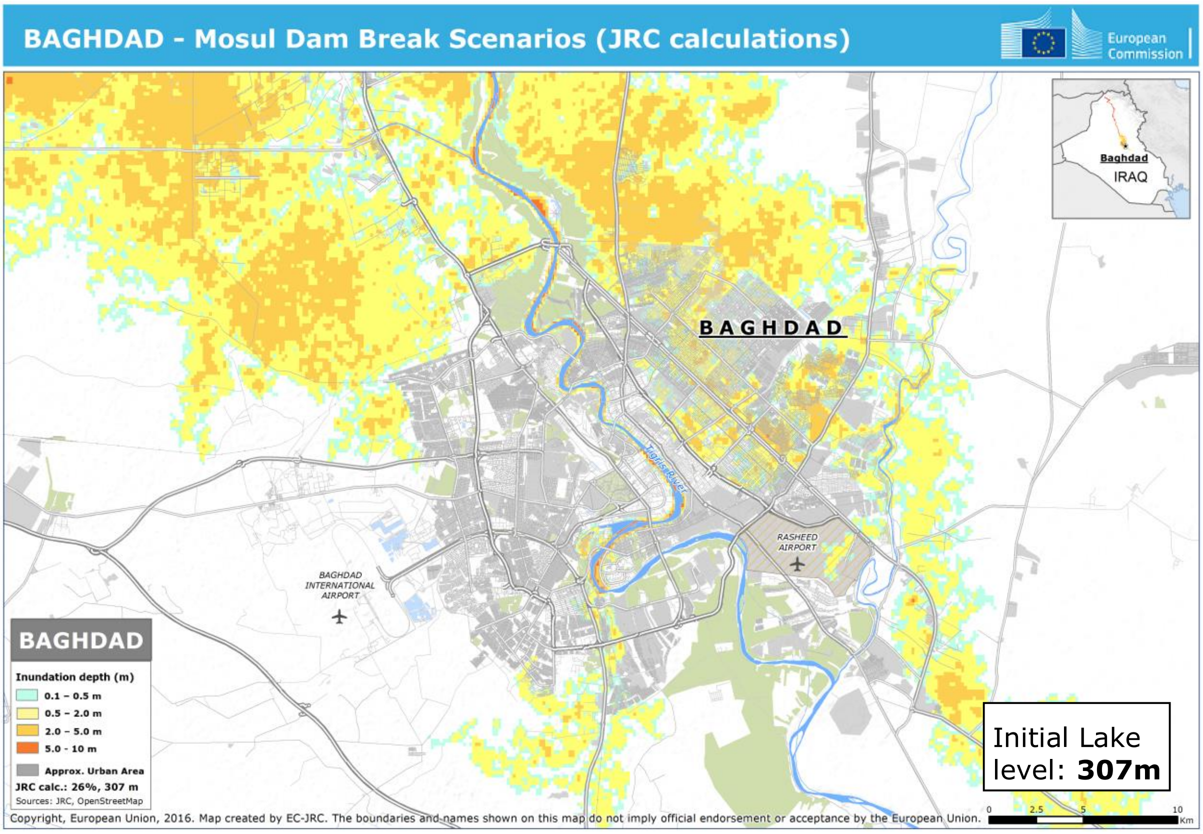

BAGHDAD - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Baghdad
IRAQ
BAGHDAD
RASHEED AIRPORT
BAGHDAD INTERNATIONAL AIRPORT
BAGHDAD
Inundation depth (m)
0.1 - 0.5
0.5 - 2.0
2.0 - 5.0
5.0 - 10
> 10
Approx. Urban Area
Sources: JRC, OpenStreetMap
Estimated arrival time
67 h
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
0 1.25 2.5 5 Km

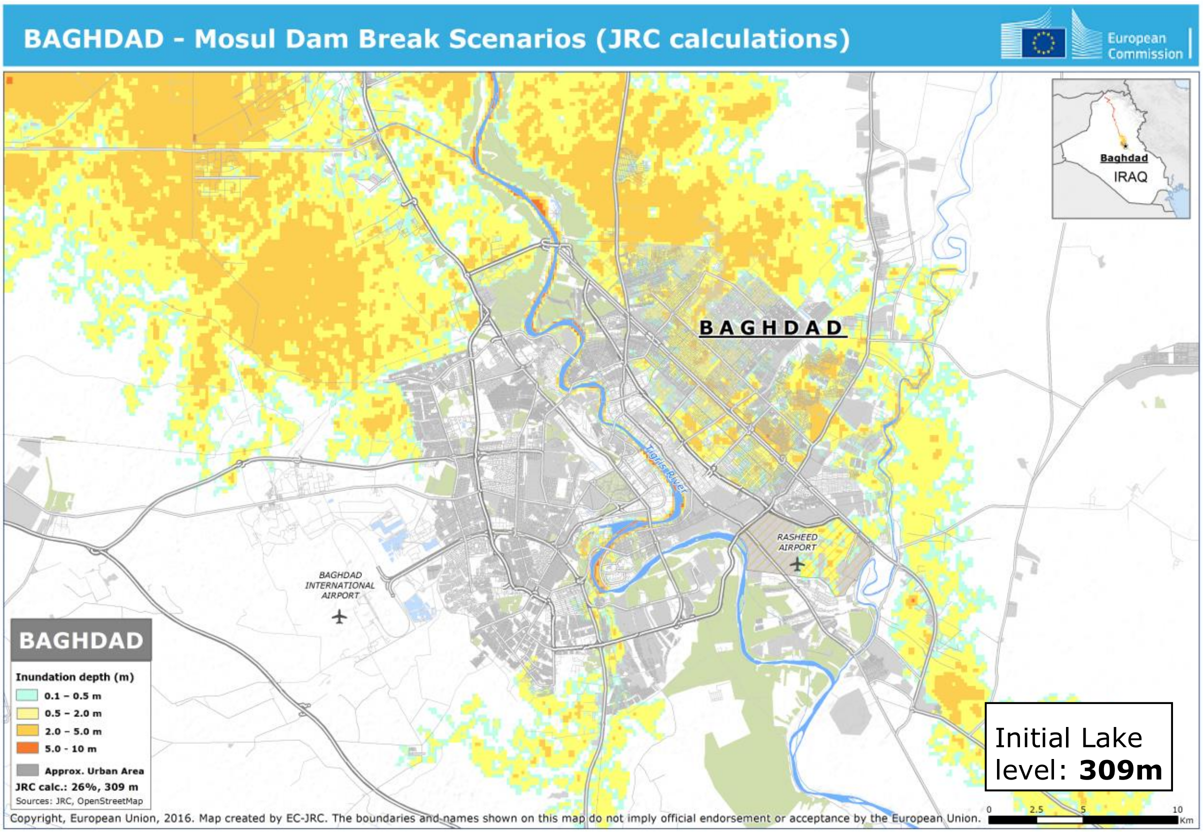
# 9 Appendix III – Maps related to Lake Level Sensitivity Analysis

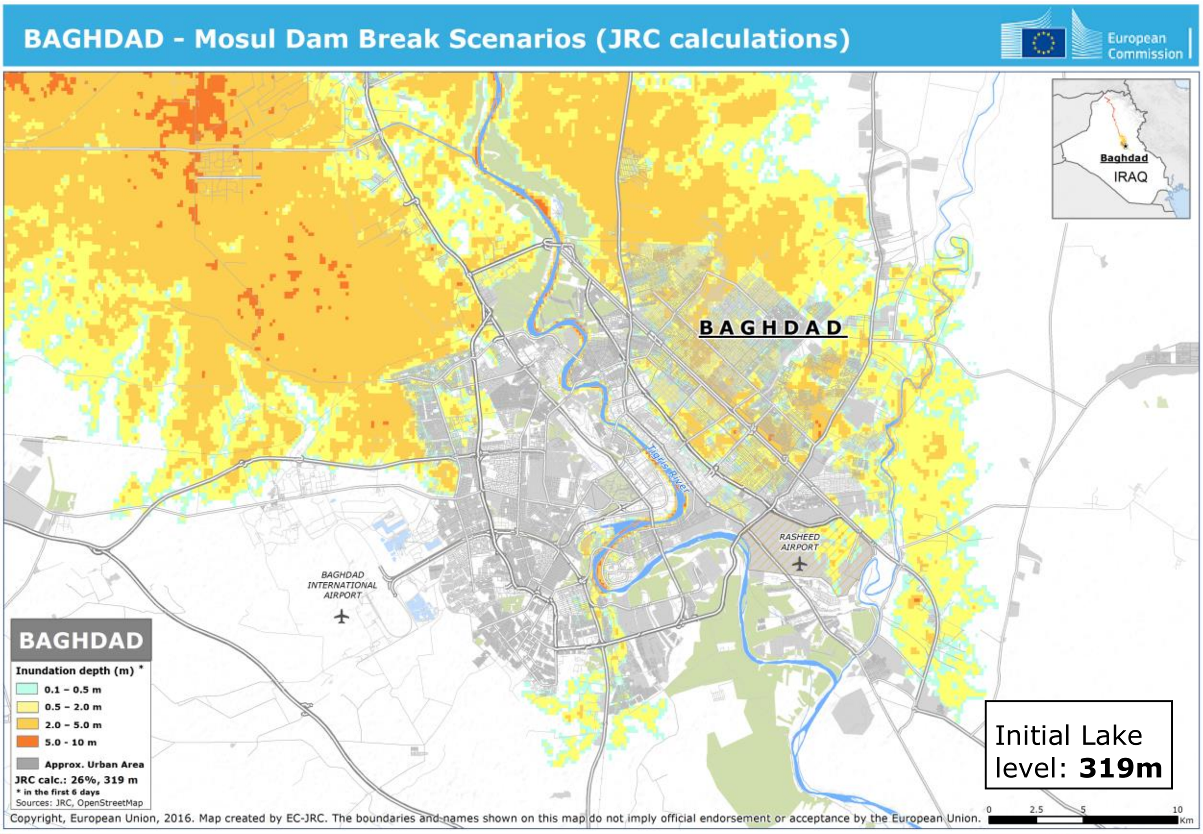
In this Appendix we show maps of the expected inundation in Baghdad, depending on the level of the lake when the breach occurs; as previously, the levels considered are 300, 305, 307, 309, 319 (current level) and 330m (maximum level).

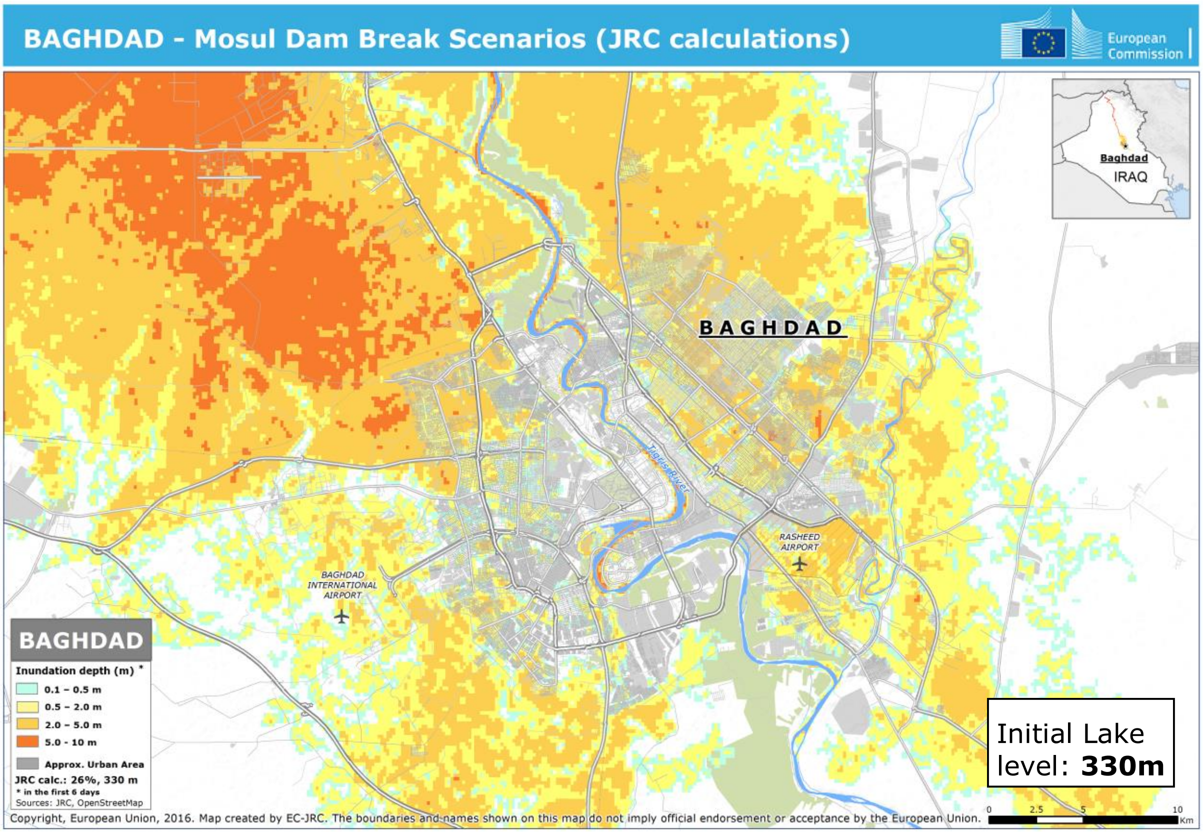



BAGHDAD - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Baghdad
IRAQ
BAGHDAD
RASHEED AIRPORT
BAGHDAD INTERNATIONAL AIRPORT
BAGHDAD
Inundation depth (m)
0.1 – 0.5 m
0.5 – 2.0 m
2.0 – 5.0 m
5.0 - 10 m
Approx. Urban Area
JRC calc.: 26%, 307 m
Sources: JRC, OpenStreetMap
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
Initial Lake level: 307m


BAGHDAD - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Baghdad
IRAQ
BAGHDAD
RASHEED AIRPORT
BAGHDAD INTERNATIONAL AIRPORT
BAGHDAD
Inundation depth (m)
0.1 – 0.5 m
0.5 – 2.0 m
2.0 – 5.0 m
5.0 - 10 m
Approx. Urban Area
JRC calc.: 26%, 309 m
Sources: JRC, OpenStreetMap
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
Initial Lake level: 309m


BAGHDAD - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Baghdad
IRAQ
BAGHDAD
RASHEED AIRPORT
BAGHDAD INTERNATIONAL AIRPORT
BAGHDAD
Inundation depth (m) *
0.1 – 0.5 m
0.5 – 2.0 m
2.0 – 5.0 m
5.0 - 10 m
Approx. Urban Area
JRC calc.: 26%, 319 m
* in the first 6 days
Sources: JRC, OpenStreetMap
Initial Lake level: **319m**
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
0 2.5 5 10 Km


BAGHDAD - Mosul Dam Break Scenarios (JRC calculations)
European Commission
Baghdad
IRAQ
BAGHDAD
RASHEED AIRPORT
BAGHDAD INTERNATIONAL AIRPORT
BAGHDAD
Inundation depth (m) *
0.1 – 0.5 m
0.5 – 2.0 m
2.0 – 5.0 m
5.0 - 10 m
Approx. Urban Area
JRC calc.: 26%, 330 m
* in the first 6 days
Sources: JRC, OpenStreetMap
Initial Lake level: **330m**
Copyright, European Union, 2016. Map created by EC-JRC. The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.
0 2.5 5 10 Km

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