

Chemical, Petroleum and Environmental Engineering

**Current and Modified Flood Discharge Capacity of a Reach of Tigris River
between Kut and Amarah Barrages**

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ABSTRACT

This study was conducted to examine the discharge capacity of the reach of the Tigris River between Kut and Amarah Barrages of 250km in length. The examination includes simulation the current capacity of the reach by using HEC-RAS model. 247 cross sections surveyed in 2012 were used in the simulation. The model was calibrated using observed discharges of 533, 800, 1025 and 3000m³/s discharged at Kut Barrage during 2013, 1995, 1995 and 1988, respectively, and its related water level at three gauge stations located along the reach. The result of calibration process indicated that the lowest Root Mean Square Error of 0.095 can be obtained when using Manning's n coefficient of 0.026, 0.03 for the Kut- Ali Al Garbi and Ali Al Garbi- Amarah reaches respectively, and 0.03 for the flood plain of the whole reach under study. The reach under study has two lateral inflow streams, UmAljury, which joins Tigris River at station 51km, and Aljabab, which joins Tigris River at station 57km. The discharge of Aljabab varies between 0 and 400m³/s and the discharge of UmAljury varies between 0 and 50m³/s. The results showed that the current capacity of the main channel of the reach of the Tigris River between Kut and Amarah Barrages is 400m³/s. The water levels kept less 1m than both levees in case of discharging 1800m³/s from Kut Barrage, with no lateral inflows, and 1700m³/s with lateral inflow. The reach of Tigris River fails to accommodate the flood discharge of 3300m³/s which is the discharge of the flood of 1988 measured at Kut Barrage. It can be concluded that the reach had large amount of sediment for the period from 1988 to 2012 and the reach capacity reduced to about half its capacity of 1988 during this period. The results of removing 12 islands and 2 sidebars by reshaping the current condition into trapezoidal cross-section will decrease the surface water levels by 20cm and flow of 1900m³/s can be discharged safely at Kut Barrage without any lateral inflow and 1800m³/s with lateral inflow from the tributaries. While, expand 58 narrow cross-sections that choking the flow, the water levels along the reach are lowered by an average of 20cm in addition to that 20cm when modifying the cross-sections at the islands and sidebars. In this case, flow of 2100m³/s can safely

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be discharged from Kut Barrage without any lateral inflow and $1900m^3/s$ with lateral inflow. The result when modifying additional 111 cross-sections showed that the reach can safely accommodate a flood wave of $3300m^3/s$ from Kut Barrage without any lateral inflow and $3000m^3/s$ with lateral inflow.

Keywords: Tigris River, HEC-RAS model, Flood simulation and Manning's coefficient

الاستيعابية الحالية والمطورة لامتداد نهر دجلة بين سدتي الكوت والعمارة

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الخلاصة

تناولت هذه الدراسة اختبار سعة التصريف الحالية لامتداد نهر دجلة بين سدتي الكوت والعمارة بطول 250 كم. الاختبار تضمن محاكاة السعة الحالية للنهر باستخدام النموذج الاحادي البعد HEC-RAS (Version 5.0.3). 247 مقطع عرضي تم مسحها في عام 2012. اشترت نتيجة المعايرة بأن أقل معدل للجذر التربيعي للخطأ في المناسيب المقاسة والمقدرة يساوي 0.095 عند استخدام معامل ماننك 0.026 و 0.03 لكل من الامتداد من الكوت إلى علي الغربي ومن علي الغربي إلى العمارة، على التوالي، و 0.03 للمجرى الفيضاني لكل الامتداد.

النتائج بينت بان الاستيعابية الحالية لمجرى النهر بين سدتي الكوت والعمارة تبلغ $400m^3/s$. وان منسوب الماء يبقى دون 1 م من السداد الفيضانية في حالة التصريف $1800m^3/s$ من سدة الكوت مع عدم وجود تصاريح داخلية، و $1700m^3/s$ في حالة وجود تصاريح داخلية. ان النهر لا يستوعب موجة فيضانية بتصريف $3300m^3/s$ والمخطط لها ضمن الدراسة الاستراتيجية في كل الاحوال من الواضح ان النهر تلقى كميات كبيرة من الترسبات خلال الفترة من 1988 إلى 2012 وان سعة النهر قد انخفضت للنصف مقارنة بسعته في عام 1988.

كانت نتيجة إزالة 12 جزيرة وسطية و 2 ترسبات جانبية بواسطة إعادة تشكيل المقطع الحالي الى شبه منحرف سوف تقلل منسوب الماء إلى 20 سم. في حين، توسيع 58 مقطع عرضي من المتسببة في اعاقه الجريان، فان مناسيب المياه في النهر ستخفض كمعدل إلى 20 سم بالإضافة إلى 20 سم نتيجة إزالة الجزرات الوسطية والترسبات الجانبية. تبين من خلال تطوير 111 مقطع عرضي إضافي بإمكانية إمرار تصريف مقداره $3300m^3/s$ في حال عدم وجود تصاريح داخلية و $3000m^3/s$ في حال وجود تصاريح داخلية من مجرى ام الجري والجباب .

الكلمات الرئيسية: نهر دجلة، نموذج HEC-RAS، نمذجة الفيضان، معامل ماننك

1. INTRODUCTION

The Tigris River is one of the two main rivers in Iraq. Its catchment area covers about $221000km^2$ distributed across Iran, Turkey, Syria, and Iraq. The total length of the river is about $1850km$. The river originates at the Taurus Mountains in Turkey. It flows towards southeastern parts of Turkey along the borders strip of Turkey and Syria then enters Iraq at Fiesh Khabur City northern of Iraq. The river joins Euphrates River at Qurna City south of Iraq to form Shatt Al Arab River. The Rivers has five main tributaries that are: Khabur, Greater Zab, Lesser Zab, Adhaim, and Diyala.

The flow hydrograph of Tigris River was changed dramatically as a result of the construction of several dams on the river main streams and its tributaries, the climate change, and increased water demand. The climate change has led to irregular rainfall periods, having severe drought for years followed by an extensive flood in short period. The expansion in construction of dams in Turkey and Iran decreased the incoming flow measured at the Iraqi borders. As a result, both of the water level and the flow velocity of Tigris Rivers were reduced. This allows reducing the capacity of cross-sections due to deposition of suspended load over the years, especially in the southern part of Tigris River. Under this condition, it's essential to estimate the current flood capacity of Tigris River and to make modification to the cross-sections to account for future expected extensive flood.

Several studies were conducted on the Tigris River focusing on bed sediment load, computing Manning's coefficient, water quality models, comparing cross-sections of the river with different periods and computing current capacity for the river by using mathematical models. Most of these studies were conducted on the Tigris River within Baghdad. There is a lack of studies aimed to specify the capacity of Tigris River under normal operating conditions and during floods in the current conditions of the river's cross-section.

Generally, this study is conducted to evaluate and modify the flood capacity of the Tigris River between Kut and Amarah Barrages. This reach of the river is of 250km in length, and it contains many growing alluvial islands and sidebars which led in narrowing the cross-sectional area of flow. The extreme recorded discharge of Tigris River downstream Kut Barrage is 3000m³/s recorded during 1988 and 200m³/s recorded during 2010.

2. DESCRIPTION OF THE REACH OF TIGRIS RIVER UNDER STUDY

The reach of Tigris River is located between Kut and Amarah Barrages, **Fig. 1**, and is of about 250km long. Kut and Amarah Barrages are main cross regulators controlling the flow of Tigris River. The elevation of the levee of the river at the upstream of reach, just close to Kut Barrage, is as high as 20m.a.m.s.l. This elevation gradually decreases to 9m.a.m.s.l. at the downstream of the reach, just close to Amarah Barrage. The average longitudinal water surface slope is approximately 4cm/km, (**Directorate of Wasit Water Resources, DWWR, 2017**).

There are two flood escapes within reach under study to protect the reach under study from flooding especially the reach has a mild slope and runs within a flat region. These flood escapes are the Almusandak and the Kunit flood escapes. Almusandak Escape is located at right side of the reach at about 87km downstream of Kut Barrage. This escape is an earth channel of 400m top width joins Tigris River with Uda Marsh, (**Al-Rubaie, 2008**). During the flood of 1974, the authorities opened this escape to discharge 1800m³/s to reduce flood pressure on the downstream reach, (**Ministry of Irrigation previously, IMI, 1988**). The Kunit flood escape is located at station 148km downstream of Kut Barrage joint the left side of Tigris River with AsSanna'f Marsh. This escape was used to discharge 140 to 350m³/sec during the flood of 1974 and 1988 to protect Amarah City, (**IMI, 1988**).

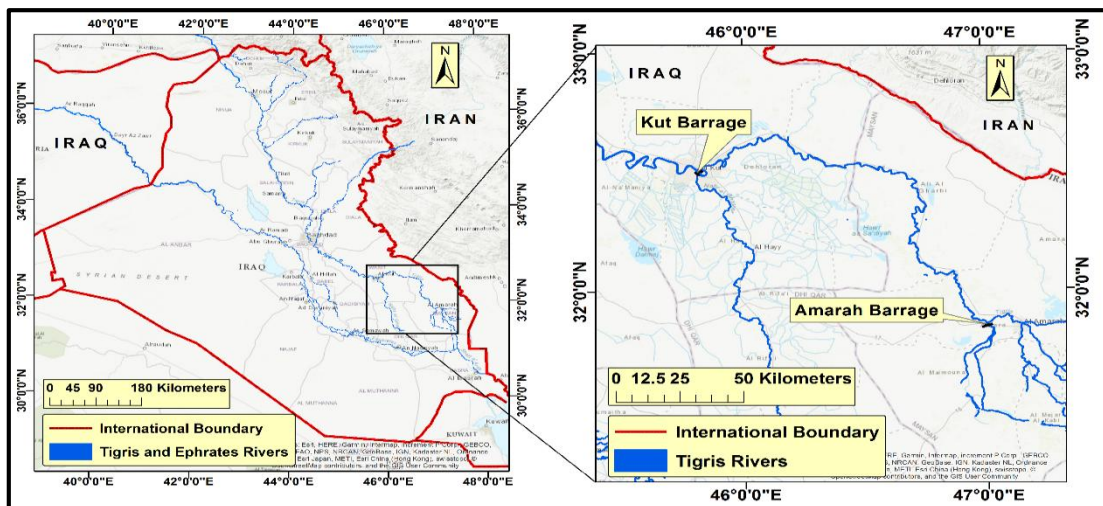


Figure 2. Tigris River between Kut and Amarah Barrages, (DWWR, 2017).



The reach under study has two lateral inflow streams, UmAljury, which joins Tigris River at station 51km, and Aljabab, which joins Tigris River at station 57km. The discharge of Aljabab varies between 0 and 400m³/s, and the discharge of UmAljury varies between 0 and 50m³/s. The reach has many lateral intakes of irrigation canals distributed along the left and right banks of reach. These intakes are used to supply water to large agricultural areas of approximately 100,000 hectares. Amarah Barrage regulates the water flow of the main stream of Tigris River, Musharrah and Kahla Rivers located upstream of barrage. **Table 1, (MoWR, 2017)**, shows data of the flood escapes and intakes within the study reach.

Table 1. Detailed data for tributaries and intakes within the study reach, (MoWR, 2017).

Name	Type	Station <i>km</i>	Discharge <i>m³/s</i>	Invert level <i>m.a.m.s.l.</i>
UmAljury	Tributary	51+150	0 to 50	---
Aljabab	Tributary	57+150	0 to 400	---
Almusandak	Regulated flood escape	87+000	1050*	6
Kumit	Weir flood escape	197+000	350*	7
Buteira	Regulated intake	232+000	700*	2
Areedh	Regulated intake	232+000	700*	2
Musharrah	Regulated intake	250+100	150*	3
Kahla	Regulated intake	250+100	500*	2

3. DISCHARGES OF THE TIGRIS RIVER

The historical data of flow measurements for the Tigris River within the study area covers the period between 1988 and 2017 with some missing daily flow records. These data were provided by National Center for Water Resources Management, (NCWRM, 2017). They were measured at three gauge stations along the Tigris River within the study reach, which are the Kut Barrage, Ali Al Garbi, which is located at 105km downstream Kut Barrage, and Amarah Barrage gages stations.

Major flood events sets at different dates were obtained from the provided historical data records, including water level and discharge data at the three measuring stations, as shown by **Table 2**. The flood with a maximum discharge took place during 1988 of 3000m³/s on 30 March. Actions were taken to reduce the discharge of this wave by using the flood escapes and flooding some agriculture areas so that just 270m³/s of the wave reached Amarah City, (NCWRM, 2017).



Table 2. Details of the sets of historical floods discharges.(*NCWRM, 2017*)

Data set number	Station Name	Discharge, m^3/s	Stage, <i>m.a.m.s.l.</i>	Date
1	Downstream Kut Barrage	3000	18.8	30/03/1988
	Ali Al Garbi	1100	13.02	30/03/1988
	Upstream Amarah Barrage	270	8.22	30/03/1988
2	Downstream Kut Barrage	1025	15	02/01/1995
	Ali Al Garbi	800	11.78	02/01/1995
	Upstream Amarah Barrage	260	8.21	02/01/1995
3	Downstream Kut Barrage	800	14.7	01/06/1995
	Ali Al Garbi	450	11	01/06/1995
	Upstream Amarah barrage	275	8.17	01/06/1995
4	Downstream Kut Barrage	533	13.35	05/02/2013
	Ali Al Garbi	300	9.55	05/02/2013
	Upstream Amarah Barrage	150	6.63	05/02/2013
5	Downstream Kut Barrage	355	12.7	1/5/2017
	Ali Al Garbi	290	9.5	1/5/2017
	Upstream Amarah Barrage	145	7.4	1/5/2017

4. USED SOFTWARE

The well-known United States Army Corps of Engineers- Hydrologic Engineering Center’ River Analysis System, HEC-RAS, has been widely used to simulate and analyze the steady and unsteady flow in natural and artificial open channels as well as sediment transport.

The procedure of computing the one-dimensional steady-state gradually varied flow used in HEC-RAS Software is based on the standard step method to obtain the water-surface profiles and energy grade lines. It is an iterative solution of the fundamental equations of open channel hydraulics, including the energy equation, continuity equation, and flow resistance equation, in addition to the Froude Number. Details of the standard step method used in HEC-RAS can be found in, (**U.S. Army Corps of Engineers, 2010**).

The main data required to simulate the steady flow by using the HEC-RAS model are a series of complete cross-sections along the channel, the flow conditions at the boundary, the lateral inflow and outflow along the channel and the Manning’s roughness coefficient.



After the computations of steady flow are completed, the output of the data results will be viewed including longitudinal and cross-sections profiles. Also, the computations showed other hydraulic components.

5. INPUT DATA

To perform the computations of the one-dimensional steady-state gradually varied flow within the 250km reach of Tigris River between Kut Barrage and Amarah Barrage by using the HEC-RAS(Version 5.0.3) model, the following data were defined to perform these computations:

- Schematic layout of Tigris River: it was sketched in the positive direction of flow from Kut Barrage at the upstream to Amarah Barrage at the downstream end of the study reach. Flow values, **Table 1**, at each of these locations were balanced so that the continuity equation is satisfied.

- Cross-sections geometry: the 247 cross-sections were located and their data were defined. The data of cross-sections include: station along with the cross-section and elevation data, banks, levees and lengths of downstream reach, Manning's n roughness coefficient of the main stream and the right and left banks and coefficients of expansion and contraction of the main channel. Interpolation was conducted for cross-sections in HEC-RAS model to provide accuracy in computation of friction losses using maximum distance between two sections of 250m.

- Boundary conditions: in a subcritical flow, the model requires the boundary at downstream of studied channel. Whereas, in supercritical flow, the model requires the boundary at upstream of the studied channel. In addition, the HEC-RAS model requires the amount of flow at upstream of channel for successful run. The boundary conditions that were used in the model is the discharge at the upstream of study reach and rating curve at downstream of reach at station 251+00, which is cross-section number zero and is located at the upstream of Amarah, **Fig. 2**. Depending on the data of *MoWR* for the period from February 2016 to April 2017, the formula of the equation of the rating curve was computed with a good agreement, $R^2 = 0.9393$, that is **Eq. (1)**:

$$WL = 1.52 Q^{0.31} \tag{1}$$

Where:

WL = water level, *m.a.m.s.l*,

Q = discharge, m^3/s .

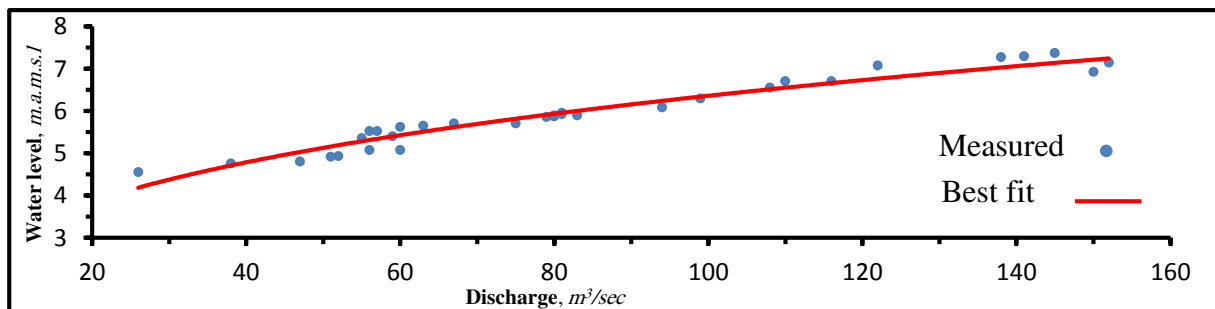


Figure 2. The rating curve at upstream of Amarah Barrage, *MoWR*, 2017.

6. DESIGN OF RUNS

The HEC-RAS mathematical model was implemented to simulate and analyze water flow through the Tigris River between Kut and Amarah Barrages based on the surveyed cross-sections and recorded data of the flow.



Calibration is needed to define appropriate values for the Manning coefficients for the main channel and floodplain. The Root Mean Square Error, RMSE, was used to test the compare the computed and the observed water surfaces

Calibration of the model was achieved by using stage measurements along Kut-Amarah reach at three gaging stations. Four sets of data were used in the calibration. These sets are: set number 1 to 4, which represent the data with heigh flow varied between 3000 and $533m^3/s$ discharged from Kut Barrage. Verification of the calibrated Manning's n is achieved by using one set of data that is set number 5.

The scope of the simulation is to find the maximum flow that can safely pass through the Tigris River reach between Kut and Amarah barrages under current condition, with the actual cross-sections, and under modified critical cross-sections into trapezoidal cuts for $3300m^3/s$ discharge, which is the maximum flood wave observed downstream Kut Barrage in 1988.

Different scenarios applied to the model by increasing the discharge at the upstream of the reach to find out the current capacity for the Tigris River within the study reach and critical discharges that can cause the inundation. Each scenario will contain two cases, one of them with maximum lateral inflow and the other one with zero lateral inflow. In all scenarios, the outflow from the intakes will be at their minimum as possible to identify the critical discharge in the main reach after the intakes. The identification of the flow that can pass safely between Kut and Amarah barrages is directly connected to minimum freeboard resulting from the simulations in the surveyed available cross-sections. It is assumed that flow passes safely when a minimum freeboard is higher than $0.5m$.

After computing the current capacity and defining the cross-sections causing chocking to the flow, modifications are conducted in three steps to find out the maximum discharge carrying capacity after each made modification. In each step simulation runs are conducted to evaluate the flow conditions along the reach. The first step is to modify cross sections by removing growing islands and sidebars. In the second step, cross-sections with high flow velocities more than $1m/sec$, are modified. Finally, in the third step, modifications to cross-sections are conducted to increase the capacity of reach of the river to accommodate a discharge of $3300m^3/s$.

7. RESULTS AND DISCUSSION

7.1 Calibration and Verification

Through many trial runs of the HEC-RAS simulation model, it was found that the differences between observed and computed water surface profile can be decreased if the reach is separated into two parts having different values of Manning's n coefficient. The first part is the first 105 kilometers extended from Kut Barrage to Al Garbi City. The second is the remaining 145 kilometers extended from Al Garbi City to Amarah Barrage.

Table 3 shows the obtained RMSE when using different values of Manning's n coefficients during the calibration process along the reach between Kut and Amarah Barrages. The process was conducted by using the four sets of data at the three gaging stations. These four sets of data represent the data with a flow varied between 3000 and $533m^3/s$ discharged from Kut Barrage. The lowest RMSE of 0.095 was obtained when using Manning's n coefficient of 0.026, 0.03 for the Kut- Ali Al Garbi and Ali Al Garbi- Amarah reaches respectively, and 0.03 for the flood plain of the whole reach under study.



Table 3. RMSE test of the calibration results.

Part of the channel	Manning's n		RMSE			
			Data set number			
	Kut- Ali Al Garbi	Ali Al Garbi- Amarah	1	2	3	4
Main	0.026	0.03	0.90	0.58	0.40	0.096
Flood plain	0.04					
Main	0.027	0.03	0.95	0.64	0.46	0.155
Flood plain	0.04					
Main	0.026	0.03	0.80	0.53	0.39	0.095
Flood plain	0.03					
Main	0.026	0.29	0.76	0.57	0.41	0.122
Flood plain	0.03					
Main	0.028	0.03	0.91	0.68	0.52	0.21
Flood plain	0.03					
Main	0.025	0.03	0.84	0.56	0.41	0.096
Flood plain	0.03					
Main	0.026	0.031	0.83	0.54	0.4	0.097
Flood plain	0.03					

It is clear that the most recent observation among the sets of data, which is set number four, has the lowest RMSE and the simulated water surface elevations closely match that observed compared to other sets of data. This is referred to the date of surveying the cross-section and the date of recording each set of data. The cross-sections used in the simulation model were surveyed at a date closer to that of recording the data of set number four. In the other words, the geometric data surveyed during 2012, which was used in model, are more representative to the condition of the cross sections when taking the water level measurements during 2013 that other dates.

The calibrated Manning's values were verified using one set of data that is set number 5. **Table 4**, shows the water surface profile for verification process. **Table 4** presents a comparison between the observed water surface profile of set number 9 and that simulated by using the calibrated Manning's coefficients. The results of the verification process showed good agreement between observed and computed water surfaces with RMSE of 0.19,

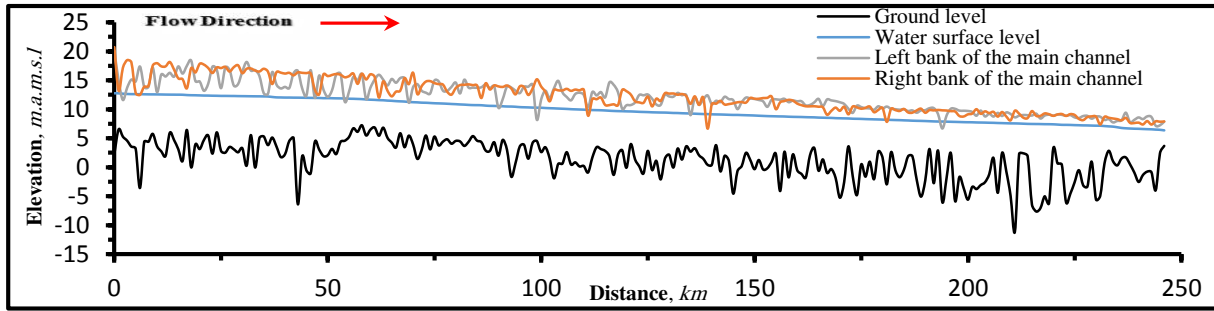


Figure 3. Water surface elevations at a discharge of 400m³/s, case one.

Table 4. Comparison between observed and simulated and water surface profiles during verification of the calibrated Manning’s coefficients.

Station <i>km</i>	Discharge <i>m³/s</i>	Water surface elevation, <i>m.a.m.s.l.</i>	
		Simulated	Observed
0+ 00	355	12.4	12.7
105+ 050	290	9.4	9.5
251+ 100	145	7.4	7.4

7.2 Current Capacity of the Reach

Estimating the discharge capacity of the reach of Tigris River under study was conducted by increasing an assumed discharge at Kut Barrage and different scenarios for the lateral inflow and outflow until the critical discharges are reached that can cause the inundation.

It was found be that discharges below 400m³/s are completely accommodated by the main channel of the reach. At discharges more than 400m³/s the water surface elevations reach the flood plain at different locations. This result was obtained for the two cases of lateral inflow and outflow. In first case, no lateral inflows while the second case there is lateral inflow. **Fig. 3** and **Fig. 4**. show the water surface elevations along the reach at a discharge of 400m³/s for the first and second case, respectively. It is clear that the water surface elevations reached the flood plain of the reach at different locations.

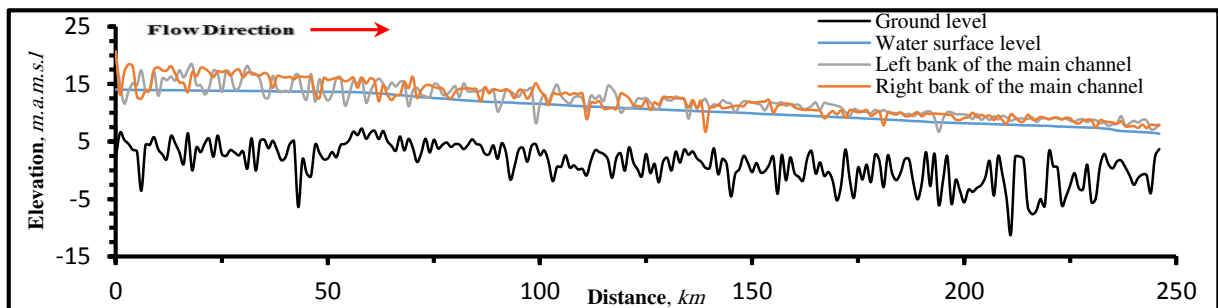


Figure 4. Water surface elevations at a discharge of 400m³/s, case two.



By increasing the flow out of Kut Barrage to a discharge of $1800\text{m}^3/\text{s}$, all water levels are kept below 1m than the levels of the left and right levees of the reach of Tigris River. This value of discharge is considered as a critical discharge before inundation occurred at which at least 1m of freeboard is ensured along the river reach. This result was the reach by analysis two cases of assumed lateral inflows and outflows along the reach of the river. In case one, all of the lateral inflows were assumed to be zero.

Fig. 5 and **Fig. 6** show the water surface elevations along the reach at a discharge of $1800\text{m}^3/\text{s}$ for the first and second case, respectively, which show that the water surface elevations are kept at least 1m below the elevations of the levees of the reach of the river. While the analysis of the second case showed that the freeboard will be less than 1m from station $30+150$ to station $91+000$. At station $60+150$ it is just 5cm freeboard.

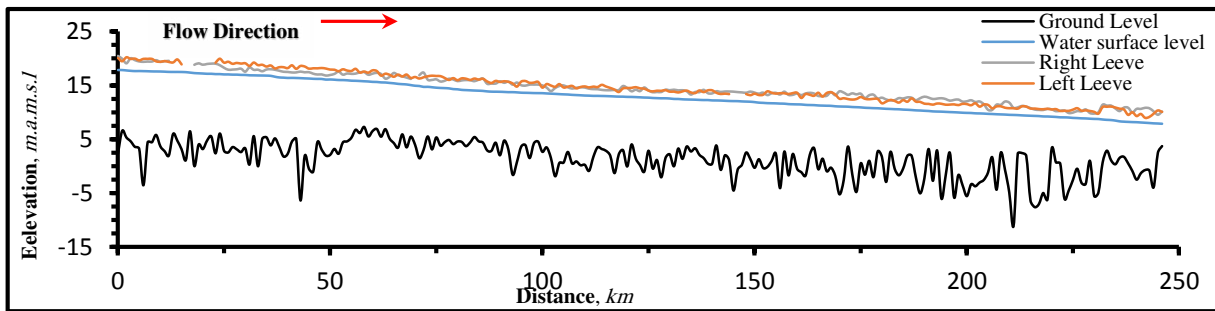


Figure 5. Water surface elevations at a discharge of $1800\text{m}^3/\text{s}$, case one.

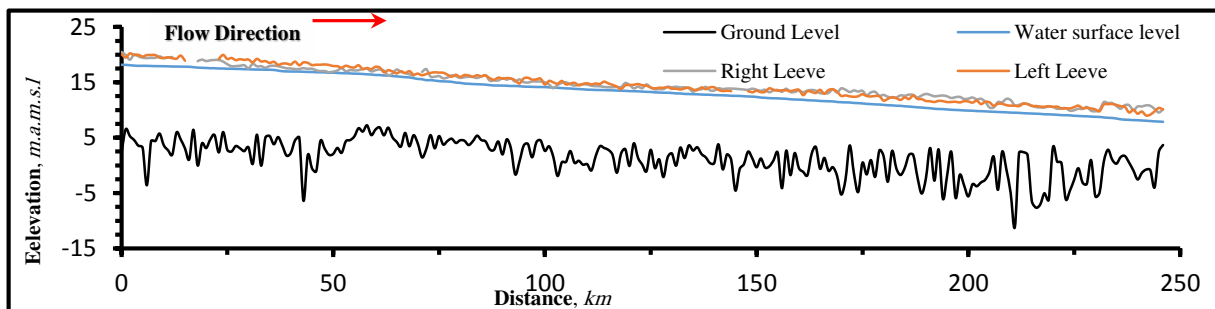


Figure 6. Water surface elevations at a discharge of $1800\text{m}^3/\text{s}$, case two.

$1700\text{m}^3/\text{s}$ can be safely discharged through the Kut barrage with fully lateral inflow, at this discharge the water surface elevations along the reach are kept at least 1m below the elevations of the levees.

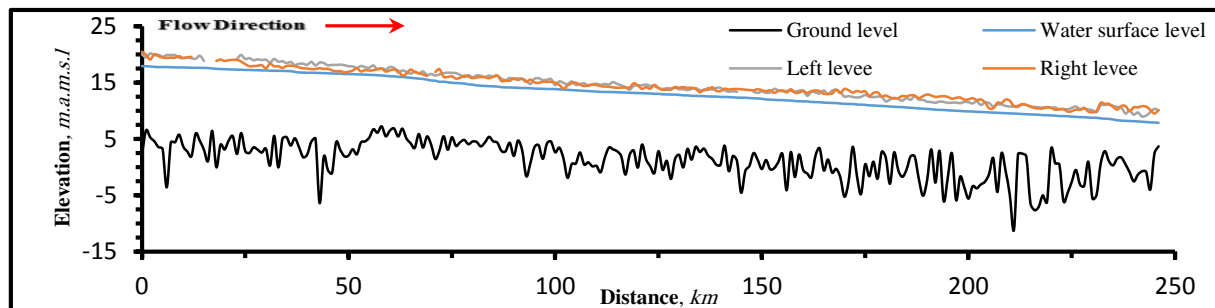


Figure 7. Water surface elevations at a discharge of $1700\text{m}^3/\text{s}$, case two.



When the discharge downstream Kut Barrage is increased to $2000\text{m}^3/\text{s}$ with no lateral inflow, it was found that the freeboard will be less than 1m below the levees in many locations downstream of Kut Barrage as shown by **Fig. 8**.

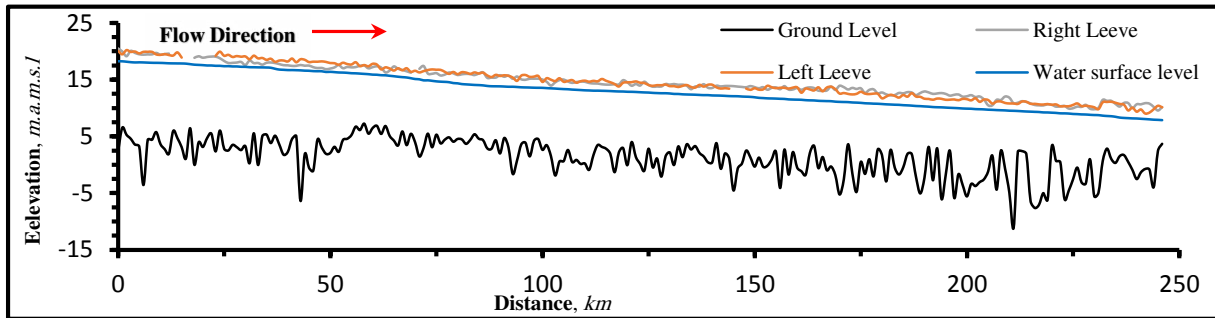


Figure 8. Water surface elevations at a discharge of $2000\text{m}^3/\text{s}$.

Model runs were conducted with the value of the flood discharge of $3300\text{m}^3/\text{s}$ that was recorded during 1988 at the Kut Barrage. It must be noted that this discharge passed safely through the reach of Tigris River at that time. **Fig. 9** and **Fig. 10** show the water surface elevations along the reach at a discharge of $3300\text{m}^3/\text{s}$ for the two cases, respectively. It is clear that under the current conditions of the cross-section, the reach of Tigris River can't accommodate the flood discharge of 1988. The elevations of the water surface obtained with conditions of lateral inflow and outflows of case one are higher than the levees of the river reach. The elevations of the water surface obtained for case two have much higher extent than that of case one. This is an indication that the change in the hydrograph of the river and the reduction in the flow caused deterioration of the river capacity due to deposition of large amount of sediment for the period from 1988 and 2012.

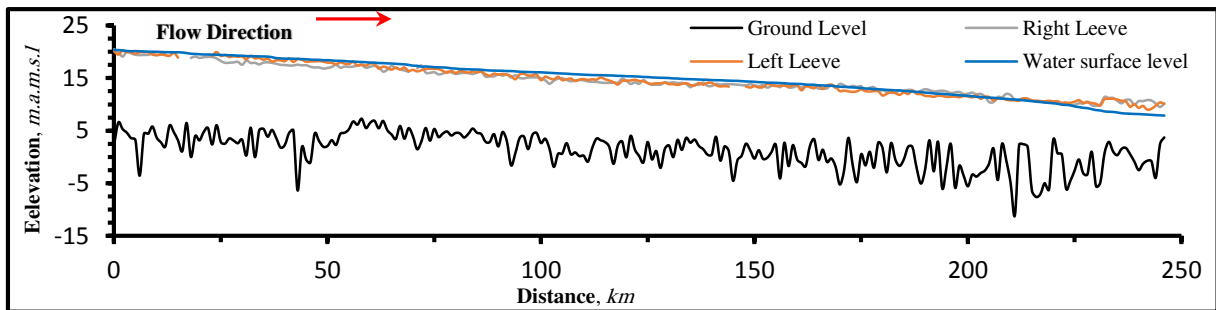


Figure 9. Water surface elevations at a discharge of $3300\text{m}^3/\text{s}$, case one.

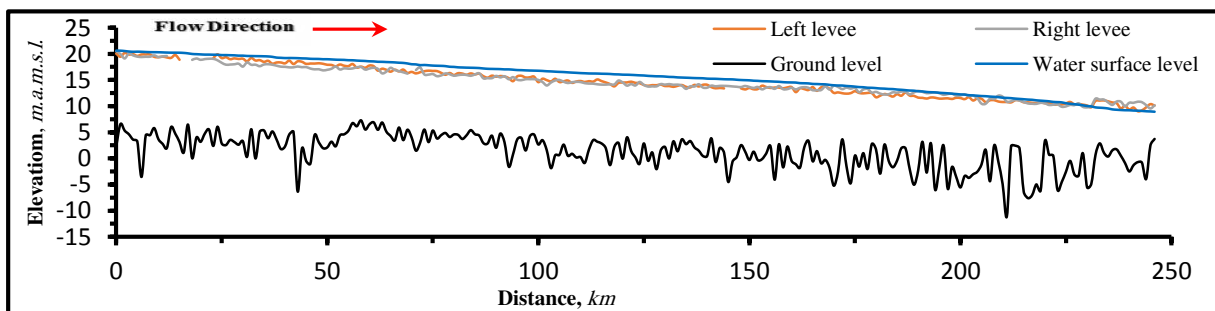


Figure 10. Water surface elevations at a discharge of $3300\text{m}^3/\text{s}$, case two.

7.3 Modification of Cross-sections of the Reach

It was shown previously that the current capacity of the reach of Tigris River between Kut

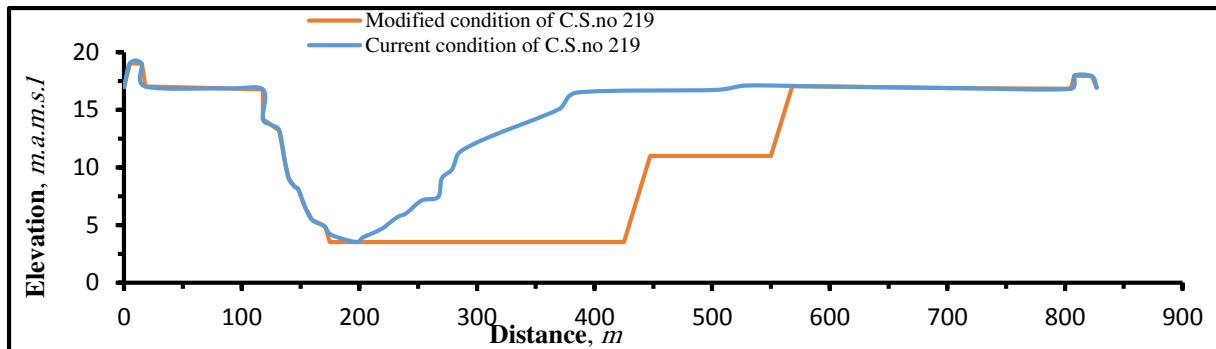


Figure 11. Modified cross-section number 245, station 1+000.

and Amarah Barrages is limited to $1800m^3/s$ when there are no lateral inflows or $1700m^3/s$ when there are lateral inflows along this reach. These flow discharges form nearly half of the flood discharge of 1988. More than thirty years of low flow within the reach with the lack of periodic maintenance are the main cause of deterioration of the capacity of this reach of Tigris River. Therefore, it is a very important issue that should be given utmost attention to recovering the capacity of the river to accommodate expected flood discharges. The strategy to recover the capacity of the river reach is to identify islands and sidebars along the reach and modify the cross-sections at their locations. Then specifying cross-section causing choking to the flow and modify these cross-sections one by one.

The cross-section of 12 islands and 2 sidebars along the reach of Tigris River between Kut and Amarah Barrages were modified by reshaping into trapezoidal cross-sections. **Fig 11** shows a sample modified cross-section number 245 at an island located at station 1+000.

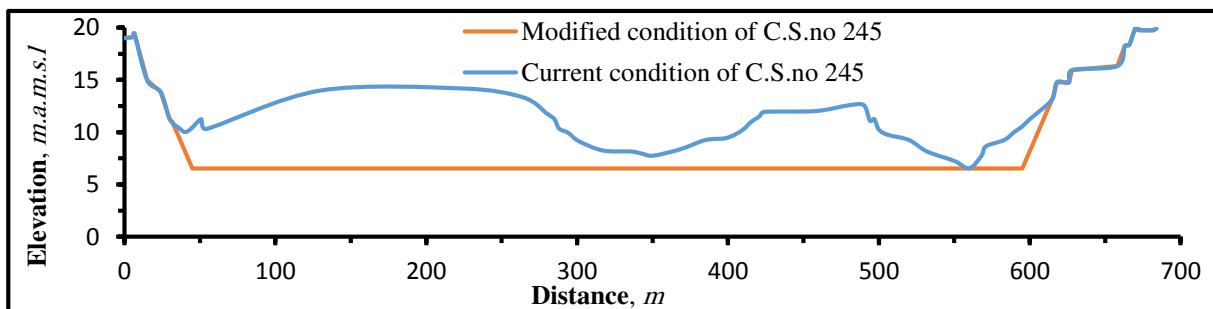


Figure 12. Modified cross-section number 219, station 27+150.

Fifty-eight cross-sections were specified as cross-section causing choking to the flow along the reach of Tigris River between Kut and Amarah Barrages. These cross-sections of the river were expanded and reshaped into trapezoidal cross-sections. **Fig. 12** shows a sample modified cross-section number 219 located at station 27+150.

Results of the model runs with modified cross-sections showed that the water levels along the reach are lowered by an average of 20cm in addition to that 20cm when modifying the cross-sections at the islands and sidebars so that the achieved lowering in water level is 40cm compared to current conditions of the cross-section.



A flow of $2100m^3/s$ can be now safely discharged at Kut Barrage without any lateral inflow and $1900m^3/s$ with lateral inflow from the tributaries. **Fig. 13** and **Fig. 14** show the water levels along the reach of Tigris River after modifying the cross-sections for a discharge of $2100m^3/s$ without any lateral inflow and $1900m^3/s$ with lateral inflow, respectively. All water levels along the reach are kept at 1m below the level of levees.

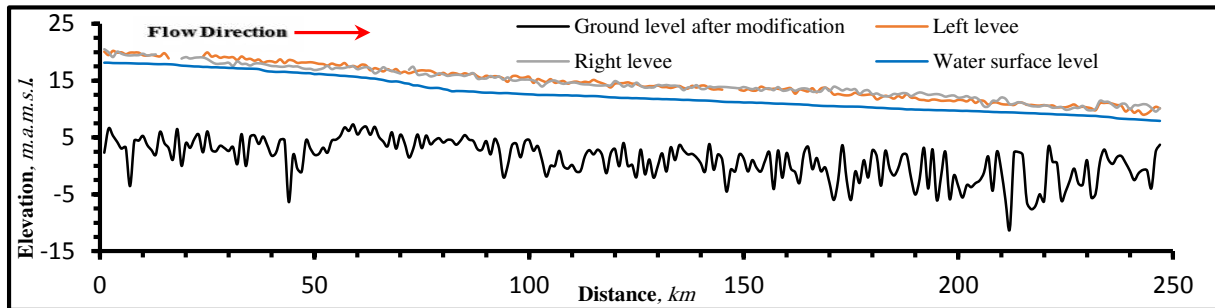


Figure 13. Water levels along the reach of Tigris River after expanding 58 cross-sections at the locations of choking for a discharge of $2100m^3/s$, without any lateral inflow.

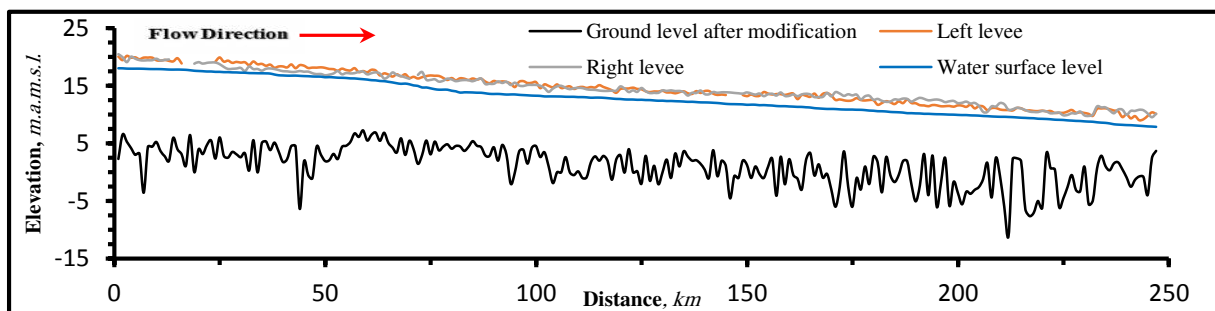


Figure 14. Water levels along the reach of Tigris River after expanding 58 cross-sections at the locations of choking for a discharge of $1900m^3/s$, with lateral inflow.

With the above modification of the cross-section the flood discharge of $3300m^3/s$ during 1988 cannot be reached. Additional cross-section needs to be modified. These cross-sections were selected based on the model runs with a discharge of $3300m^3/s$. The cross-section at which the water level reaches or be above the levels of the levees of the reach. Additional 111 cross-sections were selected to be modified. These cross-sections were modified by reshaping into trapezoidal cross-sections.

Results of the model runs with modified cross-sections showed that the reach can safely pass the flood of $3300m^3/s$ without any lateral inflow and $3000m^3/s$ with lateral inflow from the tributaries. **Fig. 15** and **Fig. 16** show the water levels along the reach of Tigris River after modifying the cross-sections for a discharge of $3300m^3/s$ without any lateral inflow and $3000m^3/s$ with lateral inflow, respectively. All water levels along the reach are kept at 1m below the level of levees.

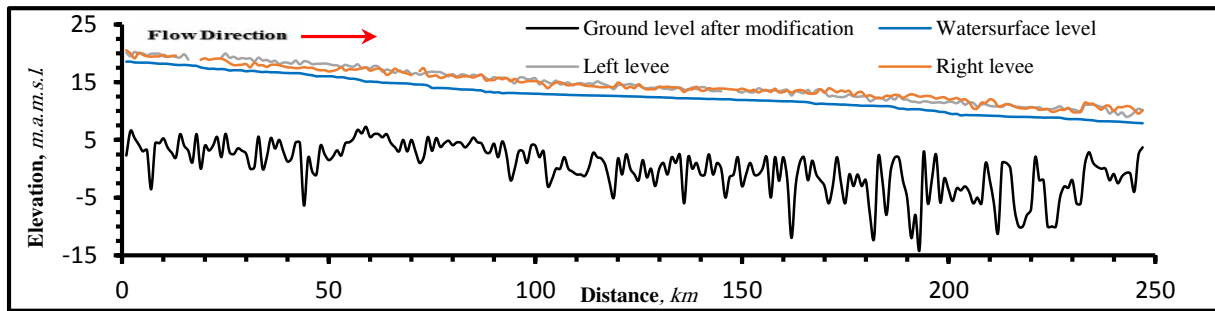


Figure 15. Water levels along the reach after removing 12 islands, 2 sidebars and 169 expanded cross-sections for the discharge $3300\text{m}^3/\text{s}$ with fully inflow discharges, without any lateral inflow.

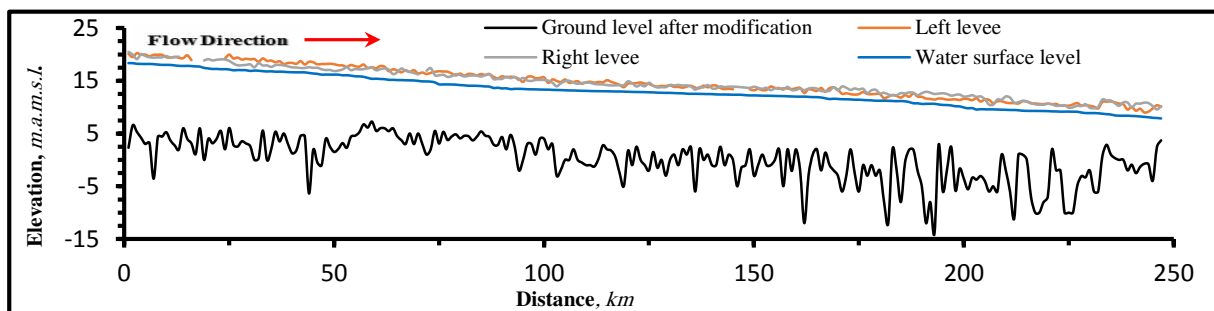


Figure 16. Water levels along the reach after removing 12 islands, 2 sidebars and 169 expanded cross-sections for the discharge $3000\text{m}^3/\text{s}$ with fully inflow discharges, with lateral inflow.

8. CONCLUSIONS

- Under the current conditions of the river reach, the water surface elevations will reach the flood plain of the reach at different locations at discharges more than $400\text{m}^3/\text{s}$.
- The discharge capacity of the Tigris River between Kut and Amarah Barrages was significantly changed compared to its capacity of 1988. The reach can now safely accommodate $1700\text{m}^3/\text{s}$ discharged at the Kut barrage with lateral inflow and $1800\text{m}^3/\text{s}$ when there are no lateral inflows while it was $3300\text{m}^3/\text{s}$ during 1988.
- In case of removing 12 islands and 2 sidebars within the studied reach, the water surface level will reduce by an average of 20cm and flow of $1900\text{m}^3/\text{s}$ can be discharged safely at Kut Barrage without any lateral inflow and $1800\text{m}^3/\text{s}$ with lateral inflow from the tributaries. With cost of 95 billion IQD .
- In case of expand fifty eight narrow cross-sections in addition to removing the islands and sidebars, the water level will declined by an average of 20cm in addition to that 20cm when modifying the cross-sections at the islands and sidebars the reach can safely pass $2100\text{m}^3/\text{s}$ discharged at Kut Barrage without lateral inflow and $1900\text{m}^3/\text{s}$ with lateral inflow from the tributaries. With cost of 223 billion IQD .
- In case of reshaping additional 111 cross-sections along the reach, the discharge capacity can be safely increased to $3300\text{m}^3/\text{s}$ without any lateral inflow and $3000\text{m}^3/\text{s}$ with lateral inflow from the tributaries. With cost of 741 billion IQD .

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