Appendix A- Construction of the model

The construction of the model of Tigris and Euphrates in ancient Mesopotamia was a challenging task. Archaeological and geoarcheological surveys have not provided sufficient data for an accurate reconstruction of the irrigation system. Therefore, it was often necessary to combine data from different sources and make assumptions on certain parameters or characteristics of the canal system. In the following paragraphs the problems that needed to be resolved for the creation of the model are described. The importance of these assumptions and their effect on the conclusion of the analysis are further discussed in the discussion paragraph.

A.1 The determination of the irrigation land

A major challenge for this study was the determination of the irrigation land in the Mesopotamian valley. The determination of the irrigated land is significant because it is directly related to the water demand in each of the nodes of the irrigation system.

The main problem associated with the determination of the irrigation land is the lack of historical data that would specifically determine the cultivated areas of the valley. Instead the area of the settlements is usually determined during an archeological research. An option would be to assume a constant irrigation land, equal to the maximum of land that can be cultivated. However, this method fails to consider the differences in the cultivated area and population between different parts of the valley.

An alternative solution would be to assume that the area of the settlements is proportional to the area of the agricultural land. This assumption is based on the concept that the higher the population of a settlement the larger the cultivated area that is necessary to feed this population. Many researchers used the assumption that population is directly associated with the cultivated area. For instance, Adams (1981) claims that 1.5 of land is needed per person assuming a minimal based on the principle of “least effort”. It must be noted though that the 1.5 hectares per person do not include only cultivated land but also uncultivated land for other uses.

In Figure A.2.1 the reasoning of the concept that total settlement area is proportional to total cultivated area is shown.

Figure A. 1.1 Illustration of the concept that settlement area is proportional to cultivated area

A correlation between the total cultivated area and the total settlement area can be found using the study by Adams (1981). The total irrigation land was approximated by Adams (1981, Table 6) from the Early Uruk till the Early Dynastic period. The method that Adams used to determine the cultivated land is the formation of polygons that would include the two major groups of settlements in the northern and southern part of the valley. However, a handful of isolated sites are not included in the polygon. Nevertheless, it is considered that this relatively arbitrary method is giving a rough estimate of the cultivated area for this area.

An approximation of the total settlement area is also given by Adams (1981) Table 13. The settlements have been categorized based on their size to six categories ranging from “village” to “city”. The number of settlements that belong to each category and the average area of each category was used to calculate the total settlement area. In the following table the total irrigated area and the total settlement are shown (Adams, 1981).

Table A. 1.1 The total settlement and irrigation area

	Total Area	Area per site
Total Settlement Area (ha)	2919	11
Total Irrigated Area (ha)	438842	1714

The settlement and irrigated area per site is calculated by dividing the total cultivated or settlement area with the number of sites. Therefore, it is considered that cultivated area is steady and similar in each site. This is a major assumption made during the construction of the model. It is considered, however, that it is not introducing a significant error to the calculations. Even if some settlements are bigger than others the area of cultivated land in these sites is not necessarily higher. For example, in the cities that were administrative centers, only a small percentage of the land was cultivated. During the Ur(III) period (2100-2000 B.C) only 7% of the total area of Umma was cultivated (Rost, 2015). However, the food that was necessary to feed Umma’s population was produced either in the surrounding villages or in distant locations and it reached the city through trade. As a result, while the overall amount of food that is produced in the valley increased due to Umma’s high population the local production did not necessarily increase as well. On the other hand, while smaller villages have a lower population the main land use in this area is agriculture. Therefore, determining the irrigation land in each location based on population would introduce a higher error than if an equal agricultural land is considered in each site. For more accurate results, a more detailed research is necessary.

It must be noted that based on the calculations made by Adams (1981) the total number of settlements is 239 while in the map around 256 settlements of the Uruk period are shown excluding the sites were reduced or doubtful occupation is considered. It is not possible to Know which one of the sites in the map are not included in the calculation. Therefore, a correction is made to take into account the discrepancy between the number of settlements.

A.2 The determination of the irrigation nodes

For each of the periods more than 200 settlements existed in the Mesopotamian valley. The meticulous study and representation of all the sites will defeat the purpose of this thesis. Instead a more simplified version of the irrigation system is going to be simulated. The settlements are going to be grouped into nodes that contain more than one settlement. The grouping of the settlement is based in proximity. The settlements that are closer than 10.8 Km from each other are going to be grouped in the same node by drawing circles with a radius of 5.4 Km in the valley’s map. This method of grouping is based on the study by Rost (2015) there were secondary canals with a length of approximately 2.7 Km in each side of the river. In the following table the settlement area and cultivated of each node is shown.

Table A. 2.1 The settlement and cultivated area per Node

Node ID	# settlements	Cultivated Area per Node (ha)
1	1	1714
2	2	3428
3	4	6857
4	2	3428
5	4	6857
6	2	3428
7	4	6857
8	1	1714
9	3	5143
10	1	1714
11	6	10285
12	22	37713
13	13	22285
14	22	37713
15	12	20571
16	9	15428
17	11	18856
18	6	10285
19	4	6857
20	3	5143
21	3	5143
22	2	3428
23	11	18856
24	3	5143
25	2	3428
26	7	12000
27	23	39427
28	11	18856
29	2	3428
30	8	13714
31	9	15428
32	7	12000
33	19	32570
34	8	13714
35	4	6857
36	3	5143
37	2	3428
Sum	256	438842

It must be noted that a small area of the Mesopotamian valley is meticulously surveyed. Although an overall picture of the occupation in the Mesopotamian valley is given by Adams (1981) there are large parts of the valley that were not surveyed. Thus, these calculations are useful to determine the general characteristics of the settlements in the valley rather the exact size of each settlement in the area. These general characteristics are adequate for the level of accuracy of this research.

A.3 The determination of the water demand

The determination of the water demand was made using the calendar of Rost (2015) dairy. According to Rost (2015) research the agriculture in the Mesopotamian valley was mainly focused in winter grain cultivation. Due to the climatic conditions in the Mesopotamina valley the cultivation of summer crops in the Mesopotamian was not significant. The cultivation of winter grain such as barley was practiced from ancient times till the modern period. The barley was preferred compared to other types of grain because of its resistance to salinity and drought. The agricultural calendar of Rost (2015) was used for the determination of water demand of the barley and wheat crop during a year.

The first step of the water demand calculations is to determine either irrigation is necessary. For this reason the water losses are calculated and compared to the water available. The meteorological data from modern measurements were used.

In particular rainfall and evaporation-transpiration data are going to be used. The open water evaporation data of the Abu Dibbis reservoir from 1942-1947 were used (Buringh,1960, Table 6). According to FAO guidelines. The equation used to calculate the demand is :

$$ET_c = ET_o * K_c$$

where K_c is the crop coefficient. The water demand coefficient Kc was determined based on the stage of the plant development using FAO guidelines for crop water demand by Allen et al. (1998).

Combining the crop calendar by Rost (2015) and the water demand calculations based on FAO guidelines the monthly and yearly water demand was calculated. It must be noted that the crop calendar gives the range of time between sowing and harvesting. Therefore, the range of water demand can also be calculated on a yearly basis. The yearly water demand is significantly higher than the range given by FAO 450-650 mm/ year (Allen et al. 1998). This is due to the fact that with the modern methods of cultivation and intensive fertilization the crop is growing much faster than in ancient years. As result, the water needs of modern crops are lower than they used to be in the past.

The irrigation demand was determined by subtracting from the crop demand the rainfall per month. The precipitation mean from 1940 till 1956 was also obtained from Rost (2015).

In the following table the irrigation demand calculations are shown.

Table A. 3.1The monthly water demand for irrigatio

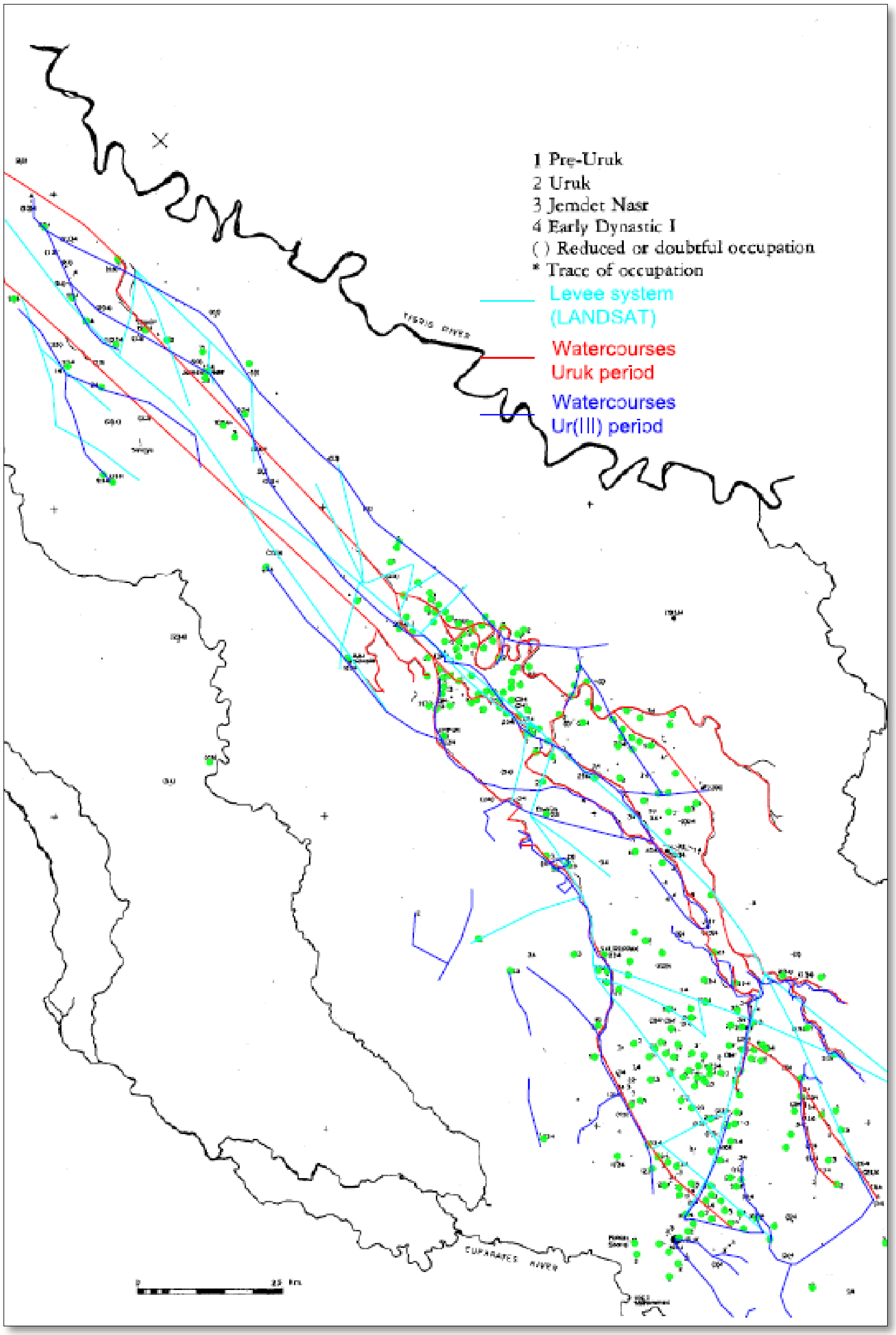
	January	February	March	April	May	June	July	August	September	October	November	December	Yearly
Open Water Evaporation (mm)	103	92	165	130	142	249	318	304	272	93	177	125	2170
Agricultural Activities				Harvest	Harvest	-	-	-	-	Sowing	Sowing		
Plant development stage	Middle	Middle	Middle	End	End	-	-	-	-	Initial	Initial	Middle	
Crop Water Demand(mm)	118.45	105.8	189.75	32.5	35.5	-	-	-	-	0	0	143.75	707-742
Rainfall (mm/month)	17.9	9.4	23	12.1	6.6	-	-	-	-	0.5	22.4	27.8	119.7
Irrigation need (mm/month)	100.55	96.4	166.75	20.4	28.9	-	-	-	-	-	-	115.95	588-623

A.4 The determination of the watercourses

The determination of the layout of the irrigation system as well as the determination of the dimensions of irrigation canals was a challenging task. For the determination of the main water courses in the area the map from Adams (1981) survey was used. The reconstruction was based on the assumption followed by Adams that near every settlement an active channel should be present.

Several settlements are not connected or are not in the proximity of the main watercourses as described in the map. In order to determine the canals that provided water to these settlements the Landsat map data and the map of the irrigation system at the Ur(III) period was used.

In the following figure the map of the settlements and main watercourses during the Uruk period by Adams (1981) is shown. In a different colour the course of the main watercourses during the Ur(III) period is shown based on the map proposed by Adams (1981) as well as the reconstruction of the river system by Steinkeller (2001). The images of the levee system based on LANDSAT data was also used to complete the rest of the map.



Modified from source: Adams (1981)

Figure A. 4.1 Map of the settlements and main watercourses in ancient Mesopotamia

Based on Figure 1 a reconstruction of the main watercourses in ancient Mesopotamia was created. In the following figure the main watercourses in ancient Mesopotamia and the nodes of the irrigation system are shown. There are some nodes that cannot be connected with the main part of the river system. Nodes 18, 29 and 41 are probably connected to smaller canals or natural streams.

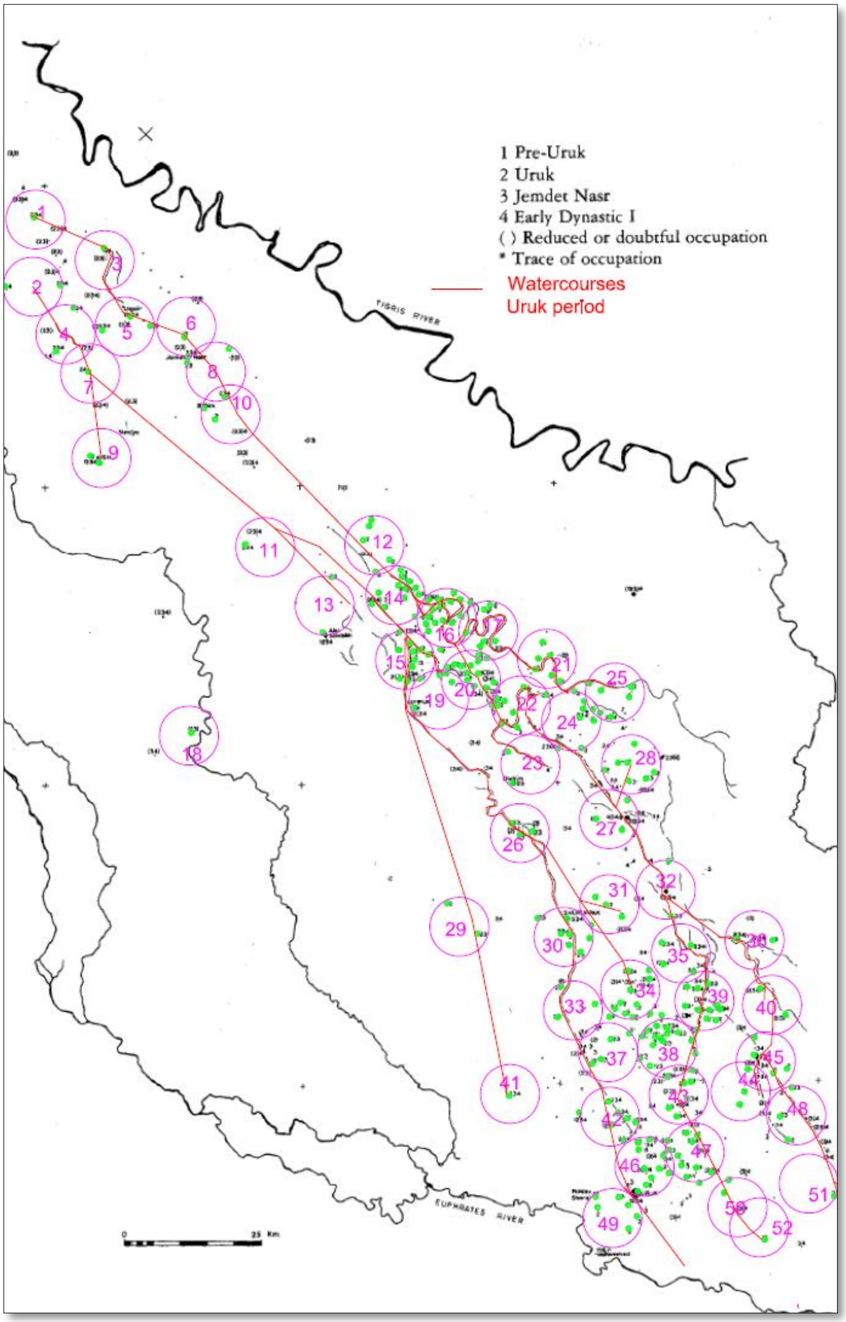


Figure A. 4.2 Map of the watercourses in ancient Mesopotamia and the settlements clustered in Nodes

Before the creation of the model, it was important to determine if Tigris and Euphrates are connected with a major canal or tributary since the boundary conditions for the two rivers will have to change if the two rivers are connected. In the map presenting the reconstruction of Euphrates and Tigris in the ancient Mesopotamia by Steinkeller (2001), a major canal connecting Tigris and Euphrates named “Iturungal” can be clearly seen. Therefore, a further research concerning the “Iturungal” canal was necessary. It must be noted that the Steinkeller reconstruction is referring to a later period than the one examined in this study.

In most of the older archeological researches such as Adams and Nissen (1972), Jacobsen (1970) the “Iturungal” canal was considered to be a branch of the Euphrates River. However, Heimpel (1990) argues that the “Iturungal” canal is in fact Tigris and not a branch of Euphrates. Furthermore, according to Rost (2015) the Iturungal was probably “a major tributary of Tigris”. Also Adams (2008) in Fig1 clearly shows that the Iturungal canal was connecting Tigris with the southern part of Mesopotamia. According to Adams (2008) however during the Ur period the canal “ultimately joined a major branch of ancient Euphrates” and “was apparantely constructed either early in the Early Dynastic I period or in the preceding Jemdet Nasr period “.

Thus, it can be concluded that during the Uruk period there was no major connection between the two rivers and the Iturungal canal was a Tigris tributary that was later canalized to allow the communication of the two rivers. It is certain that there were smaller connections between the two rivers but in this study each river is considered independent.

The software Sobek Rural was used to create a model of the river system consisting of the watercourses and the nodes that abstract water for irrigation. In Table A.X and Table A.X the Nodes of the model of Euphrates and Tigris is shown. For reasons of clarity, the initial numbering was not followed. Instead, the main branches of both rivers where separated into Nodes of the Main Branch, in which the secondary branches were connected to the main river course.

Table A. 4.1 Euphrates model

Euphrates		
Nodes	Main Branch	Connected Branches
2		Main Branch
4		Main Branch
7	Node 1 of Main Branch	Main Branch-Branch 1
9		Branch 1
11	Node 2 of Main Branch	Main Branch-Branch 2
13		Branch 2
15	Node 3 of Main Branch	Main Branch- Branch 3 & Branch 4
19		Branch 3
29		Branch 4
41		Branch 4
26	Node 4 of Main Branch	Main Branch-Branch 5
30		Main Branch
31		Main Branch
34		Main Branch
33		Main Branch
37		Main Branch
41		Main Branch
42		Main Branch
46		Main Branch
49	Last Node of Main Branch	Main Branch

Table A. 4.2 Tigris model

Tigris		
Nodes	Main Branch	Connected Branches
1		Main Branch
3		Main Branch
5		Main Branch
6		Main Branch
8		Main Branch
10		Main Branch
12		Main Branch
14		Main Branch
16	Node 1 of Main Branch	Main Branch-Branch 1
17		Branch 1
21		Branch 1
24		Branch 1
25		Branch 1
20		Main Branch
22	Node 2 of Main Branch	Main Branch -Branch 2
23		Branch 2
27	Node 3 of Main Branch	Main Branch-Branch 3
28		Branch 3
32	Node 4 of Main Branch	Main Branch-Branch 4
35		Branch 4
39		Branch 4
38		Branch 4
43		Branch 4
47		Branch 4
50		Branch 4
52		Branch 4
36	Node 5 of Main Branch	Main Branch
44		Branch 5
40		Main Branch
45		Main Branch
48		Main Branch
51	Last Node of Main Branch	Main Branch

A.5 The cross-section and slope determination problem

Finding data about the cross-section of the rivers Tigris and Euphrates was a difficult task. Most of the archeological researchers are interested in the location and capacity of the river and the irrigation canals. Also in several researches give the width and height of the levees rather than the dimension of the cross-section of the river.

An indication of the width of Euphrates River is given by Stone and Zimansky (2004) based on satellite image "The channel is clearest to the north where it is some 400 meters width and shows up as a dark bond". The above description is referring to a part of one of the major canals of Euphrates near Maskan-Shapir.

A more detailed description of Euphrates and Tigris is given by Rawlinson (1876). According to Rawlinson " The Euphrates at his junction with Khabour is 400 yards wide and 18 feet deep, at Izrah or Verdi 75 miles lower down it is 350 yards wide and of the same depth, at Hadiseh , 140 miles below Werdi it is 300 yards wide and still the same depth, at Hit 50 miles below Hadiseh, It width has increased to 350 yards but its depth has diminished to 16 feet, at Felujiah, 75 miles from Hit the depth is 20 feet but the width has diminished to 250 yards [...] The consequence is at Hillah, 90 miles below Felujiah, the stream is no more than 200 yards and 15 feet deep, at Diwaniyah, 65 miles further down it is only 160 yards wide and at Lamlun, 20 miles below Diwaniyah it is reduced to 120 yards wide with a depth no more than than 12 feet."

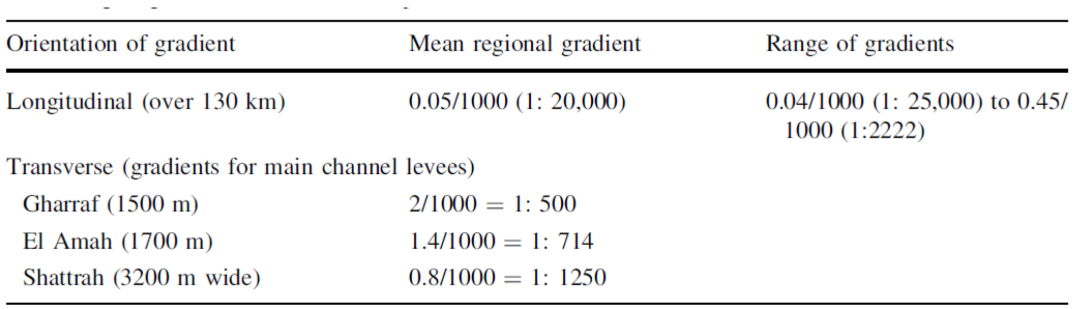
For the Tigris river it is mentioned that "The Tigris is often 250 yards wide at Diarbekr which is not a hundred miles from its source and it is navigable in the flood from the bridge of Diarbekr to Mosul, from which place it is descended at all seasons to Baghdad, and thence to the sea. Its average width below Mosul is 200 yards with an average depth which allows to ascend of light steamers unless there is an artificial obstruction. Above Mosul it rarely exceeds 150 yards and its depth is not more in places than three or four feet."

The usefulness of these data is questionable since the source is quite old and these observations have not been confirmed by more modern sources. Furthermore, the Euphrates and Tigris described in the particular case is the modern rivers and it is safe to assume that the depth and width of the rivers has significantly changed from the 3rd millenia BC. Finally, it is obvious that only the navigational part of the rivers is described. Therefore, these dimensions should be used with caution and only of they are confirmed or not contradicted by other sources.

Gasche and Tanret (1998) give a description of the present Euphrates and Tigris. According to those researchers the width for both river is round 250 m whereas the depth of Euphrates is around 5-8m and the depth of Tigris is 10-15m. This description is in accordance with Rawlinson's description about Euphrates.

Furthermore, it is stated that Euphrates has a slope of 0.1m/Km between Fallugah and Hindiyah whereas the gradient of Tigris is only 0.0065m/km. According to Wilkinson et al (2005) the slope of the Mesopotamia plain is 1:20000 as it can be seen in Table X.

Table A. 5.1 The slope of the Mesopotamian plain and the main channel levees (Wilkinson et al.,2015)



Orientation of gradient	Mean regional gradient	Range of gradients
Longitudinal (over 130 km)	0.05/1000 (1: 20,000)	0.04/1000 (1: 25,000) to 0.45/ 1000 (1:2222)
Transverse (gradients for main channel levees)		
Gharraf (1500 m)	2/1000 = 1: 500	
El Amah (1700 m)	1.4/1000 = 1: 714	
Shattrah (3200 m wide)	0.8/1000 = 1: 1250	

The mean regional gradient is going to be used in this case for both rivers when there are no data available about the slope of the river. It must be noted that the slope mentioned by Gasch and Tarnet (1998) about Tigris is extremely small. However, it should be taken into account Gasch and Tarnet are describing the part of Tigris below Baghdad that Tigris is meandering.

Table A. 5.2 The dimensions and slope of Tigris River

Tigris Section	Nodes	Width	Depth	Slope	Reference
North	1to 16	250	10 to 15m	1:150000	Gasch and Tarnet (1998) and Rawlinson (1876)
Middle	16 to 27and 16 to 25	180	10 to 15m	1:150000	Gasch and Tarnet (1998) and Rawlinson (1876)
South	28-51	180	10 to 15m	1:20000	Wilkinson et al (2015) and Rawlinson (1876)

Table A. 5.3 The dimensions and slope of Euphrates River

Euphrates section	Nodes	Width	Depth	Slope	Reference
North	2to 15	250	4.8	1:20000	Gasch and Tarnet (1998) and Wilkinson et al. (2015)
Middle	15to 26	180	5 to8	1:10000	Gasch and Tarnet (1998) and Rawlinson (1876)
South	28-51	180	5to 8	1:20000	Wilkinson et al (2015) and Rawlinson (1876)

A.6 The river flow determination problem

The determination of the flow of the rivers Tigris and Euphrates in ancient times was not possible since there are no record of water depth or flow measurements. However, an estimate of the flow of the two rivers in ancient times can be derived from recent flow data. It is necessary to carefully examine the flow data of the two rivers since the past few decades several dams have been constructed in the course of the two rivers resulting in a gradual decrease in their flow.

According to UN-ESCWA (2013) almost the total of the river flows comes from the part of the river in Syria and Turkey. As a result a flow measuring station in the Iraq border would be sufficient to describe the total flow of flow of the river. In the following Table the main dams and barrages in the Euphrates River are shown in chronological order.

Table A. 6.1 Dams and barrages in the Euphrates River in a chronological order of completion

Country	Name	Completion year
Iraq	Hindiyah	1914
Iraq	Ramadi	1948
Turkey	Keban	1974
Syria	Tabqa	1975
Iraq	Fallujah	1985
Iraq	Haditha	1987
Syria	Baath	1987
Turkey	Karakaya	1987
Turkey	Ataturk	1992
Syria	Tishreen	1999
Turkey	Karkamis	1999
Turkey	Birecik	2000

Source: Compiled by ESCWA-BGR based on Jones et al., 2008, p. 62; FAO, 2009; Beaumont, 1998; General Directorate of State Hydraulic Works in Turkey, 2009; Altinbilek, 2004, p. 21; Kaya, 1998; ACSAD and UNEP-ROWA, 2001; Ministry of Environment in Iraq et al., 2006; Ministry of Irrigation in the Syrian Arab Republic, 2012; Ministry of Water Resources in Iraq, 2012. (a)

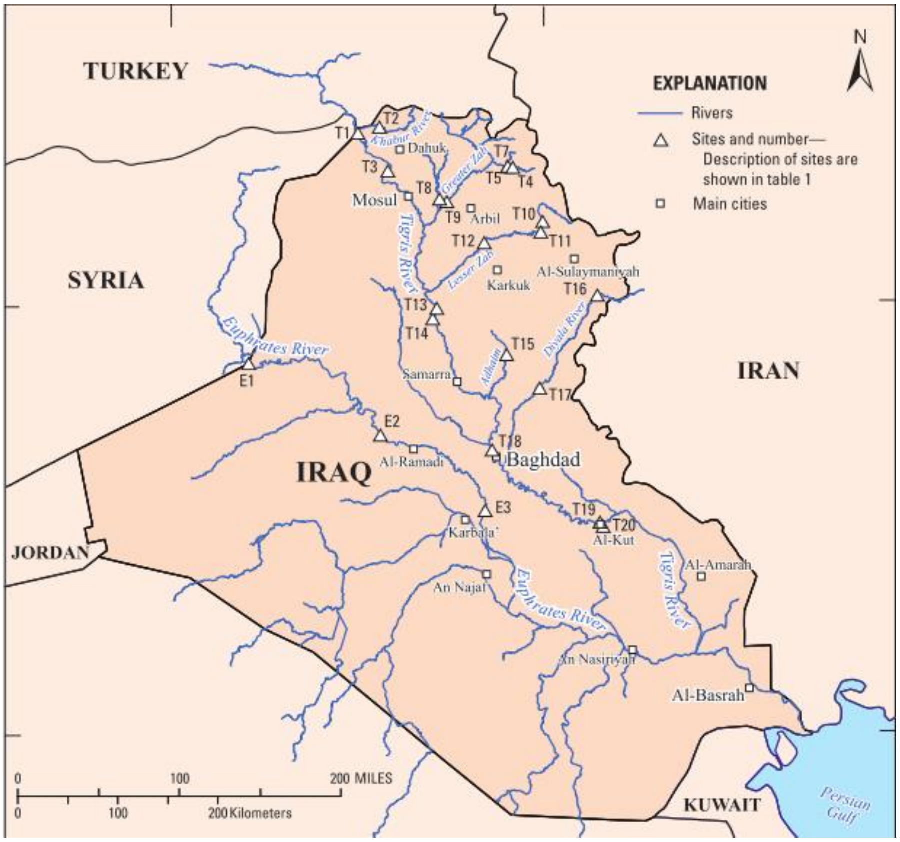
The flow of the Euphrates in the Iraqi border is only affected by the dams or barrages upstream. Therefore, the most important dams are the ones built in Turkey or Syria. The oldest dam built in Turkey in Euphrates is the Keban dam that is completed in 1974. Consequently, the most reliable flow measurement for this case are the flow measurements before 1974 in a gaging station next to the Iraqi border.

In the following Table the major dams and barrages in Tigris River are shown.

Table A. 6.2 Dams and barrages in the Tigris River in chronological order of completion

Name	Country	Completion year
Batman	Turkey	1998
Devegecidi	Turkey	1972
Cag-cag	Turkey	1968
Dicle	Turkey	1997
Goksu	Turkey	1991
Kralkizi	Turkey	1997
Al-Adheem	Iraq	1999
Derbendikhan	Iraq	1961
Dibbis (L.Zab)	Iraq	1965
Diyala	Iraq	1969
Dokan	Iraq	1959
Hamrin	Iraq	1981
Mosul	Iraq	1986
Samarra-Tharthar	Iraq	1956
Dez	Iran	1962
Karkeh	Iran	2001
Karun	Iran	1977
Marun	Iran	1998

It can be clearly seen that the oldest dam in Tigris course before the Iraqi border is the Cag-cag dam built in Turkey in 1968. Therefore the most reliable flow data are the measurements in the gaging station near the border with Turkey before 1968. The flow measurements by Saleh (2010) were used in this study. In Figure 2 the gaging stations in the Mesopotamian valley are presented.



Source: Compiled by ESCWA-BGR based on Jones et al., 2008, p. 62; FAO, 2009; Beaumont, 1998; General Directorate of State Hydraulic Works in Turkey, 2009; Altinbilek, 2004, p. 21; Kaya, 1998; ACSAD and UNEP-ROWA, 2001; Ministry of Environment in Iraq et al., 2006; Ministry of Irrigation in the Syrian Arab Republic, 2012; Ministry of Water Resources in Iraq, 2012. (a)

Figure A. 6.1 Location of the gaging stations in the Mesopotamian valley

From the figure above it can be clearly seen that Tigris has major tributaries like Greater and Lesser Zah and Diyala. Therefore, the flow of Tigris near Bagdad consists of the flow near the border with Turkey and the flow of the major tributaries.

In the following table the gauging stations that were used for the determination of the discharge of the two rivers is shown.

Table A. 6.3The gauging stations used for the deterimantion of monthly discharge

	Euphrates	**Tigris**
Station	E1	T1+T9+T12+T15+T17

In this study the data of the monthly flow measurements from 1958-1968 was used. The choice of the particular decade was based on the availability of data for the particular gauging stations and the reliability of the data.