Investigation of the evolution of the irrigation system in ancient Mesopotamia using a hydraulic model

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***Abstract*- In this study a simplified model of the rivers Tigris and Euphrates during the Uruk period (3500-3100 B.C.) was created in order to define the hydraulic behaviour of the rivers in ancient Mesopotamia. The model was used to test the effect of a number of factors on the water-level of the river system. Especially, the role of the development of settlements in the Mesopotamian valley and the way the irrigation system was operated was examined. Also, physical processes such as the avulsion of the secondary branches of the two rivers was taken into account.**

According to the results of the simulation Euphrates is much more sensitive to an increase in water demand than Tigris. However, when two branches in the upper part of the river are closed the problem of low water level in Euphrates is solved. Furthermore, the development of settlements and irrigation nodes in ancient Mesopotamia, at the lower part of the valley, has as a result a lack of sufficient water even at the early stages of societal development. On the other hand, Euphrates does not seem to be so sensitive to an increase in water demand in the upper part of the valley.

I. INTRODUCTION

An important question that often should be answered in archaeological studies is how an ancient irrigation system is managed. In particular, archaeological researchers are interested in the reasons that led to a centrally or locally administrated system. There are two approaches that can be used when trying to answer this question. According to the first approach, central control was necessary in order to meet the managerial requirements related to the system's uses. For example, the need for state control of irrigation may be rising from the lack of sufficient water level for navigation. On the other hand, some archaeological studies claim that the central control of the irrigation system is a choice of each ancient society rather than a need. In order to define which of these theories describes better the transition from a locally controlled to centrally controlled irrigation in antiquity further research is required.

Most archaeological researches are trying to answer this question by studying archaeological records and correlating the complexity of a society or the size of the irrigation system with the way it is administrated. In this study an alternative approach is going to be followed. A hydraulic model is used in order to connect the physical attributes of the irrigation system and in particular hydraulic features such as the water level, to the way it is administrated. The approach is based on the theory that there is an interconnection between landscape and ancient societies. This concept is based on the logical assumption that historical events or actions of the major stakeholders of a period cause the evolution of patterns in human society or natural attributes of the landscape. In response to these changes the interested parties either choose or are forced to act to adjust to the new conditions. Therefore, the changes in the hydraulic characteristics of an irrigation system can be used to draw important conclusions about the causes that triggered major historical events or changes in societal organisation.

The theory that the modifications of the hydraulic landscape due to human actions or natural processes is closely related to the evolution of human societies is supported by many authors. Wilkinson *et al.* (2015) claims that small scale processes related to the hydraulic landscape can have a significant effect on the formation and organization of the canal system. Also Magliocca and Ellis (2016) states that human societies and the landscape are coevolving as humans adapt to the changes of environment and in turn shape the landscape according to their needs. Furthermore, it is underlined by Wilkinson *et al.* (2015) that the farmers in ancient Mesopotamia paid attention to the 'natural tendencies' and used the natural landscape in order to construct an efficient irrigation network.

The irrigation system in ancient Mesopotamia is an example of a system that passed from local control to central administration. Based on archaeological data during the Ur(III) period (2100-2000 B.C.) the irrigation system was state controlled. There is a large number of records from this period describing the important role that state played on the operation and maintenance of the irrigation system (Rost, 2015). However, during earlier periods, irrigation seems to be mainly locally managed. It is therefore a suitable system for this investigation.

II. THE STUDY AREA

The study area of this research consists of a large part of the Mesopotamian valley from the area near the modern city of Hilla till the area near Samawah. The choice of the particular area was made because it has been surveyed by many researchers including Adams (1981). Therefore, the position of the settlements and the main water courses of the area at different chronological periods has been defined. Since aim of this study is the investigation of the evolution of the irrigation system, the map can be used to detect the changes in the settlement and canal network. The results of the model simulations are going to be used in combination with archaeological data about the ancient Mesopotamian society.

In this study the irrigation system during the Uruk period (3500-3100 B.C.) was simulated. The particular chronological period was chosen mainly because there was a sufficient amount of data to roughly reconstruct the irrigation system of the time. Furthermore, during this period the transition from a locally administrated system to a centrally controlled canal network, took place. According to Wright (1977), during the Uruk period, there was a form of an early state society compared to the less centralized "chiefdoms" out of which that states emerged. During this period major urban centres were created "within which there was a network of smaller administrative and production centres". Urbanism is associated with state formation and state administration of the system. Overall, during this period a centrally controlled decision making process can be detected and "an administration that controlled the movement of goods from production points to assembly points and thence to central points for aggregation and subsequent redistribution" (Wright, 1977).

Other researchers such as Rost (2015), Wilkinson et al. (2015) has also focused on the particular area. The data and conclusions of these studies were used not only for the construction of the model but also for the interpretation of the results. The research from Rost (2015) was used to from an overall image of the difficulties associated with the operation of the irrigation system and the measures that were taken in ancient Mesopotamia to cope with this challenges. Also, the need for central coordination in order to take large scale measures that would ensure the efficient function of the irrigation system central coordination was identified. The effectiveness of these measures was tested in this study using the hydraulic model.

Wilkinson et al. (2015) and Ertsen (2016) provided the conceptual framework of the project. In these studies, it was pointed out that Mesopotamia is a territory where the theory of human niche construction can be applied and tested since it is a typical example where the long term interaction between human and the environment can be observed.

The particular area has also been surveyed from a geoarchaeological point of view by Jotheri et al. (2016). The geoarchaeological investigation of the area is very important since it provides information about the hydraulic properties of the system that are usually neglected in a common archaeological survey. The description of the avulsion of the system in this study was also very helpful for the modelling of the physical processes that would change the shape of the river and canal network and in turn would affect the operation of the irrigation system.

III. THE CONSTRUCTION OF THE MODEL

The construction of the model was a challenging task. The basic assumptions and values that were chosen for the construction of the model can be seen in detail in Appendix A.

The model was based on a map from Adams (1981) that indicates the major watercourses and settlements during the Pre-Uruk and Uruk period (3500-3100 B.C.) The reconstruction of the water system was made using the archaeological maps from Adams, archaeological researches for later archaeological periods and maps created from remote sensing data.

In Figure 1 the irrigation system and the irrigation nodes that were modelled are presented.

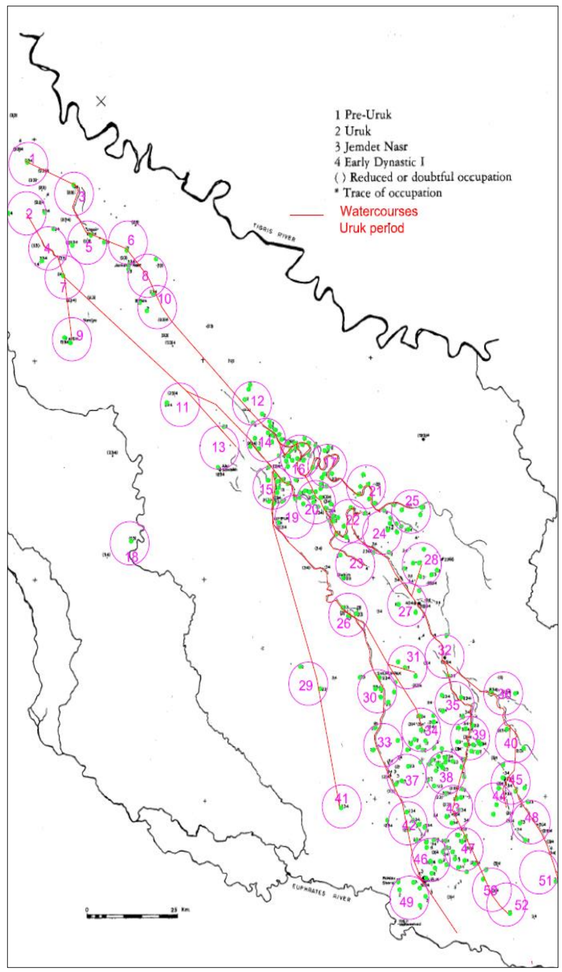

Figure 1 The river system and the irrigation nodes in ancient Mesopotamia

The study area includes the city of Uruk and smaller settlements in the upper and lower part of the river. The settlements were organised in clusters to reduce the number of nodes that would be connected to the system. The number of settlements in the lower part of the river is much higher than the upper part as the area seems to be more densely populated.

For the determination of the water demand in the river system it is considered that each settlement is connected to a certain surface of irrigation land. The irrigation land that was attributed to each settlement was defined by dividing the total cultivated area with the number of settlements.

Therefore, it is assumed that the 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 calculation. 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.

Based on Adam's (1981) map both Tigris and Euphrates have several major branches or main canals. The distinction between natural branches and canals is difficult to achieve. In Adams research they are both referred to as watercourses. In the model, a branched system of the rivers was created. The determination of the position of these branches-canals was based on the assumption that near a cluster of settlements an active watercourse must be present that would provide a sufficient amount of water for irrigation.

In addition, to the determination of the location of the main branches of the rivers Tigris and Euphrates and the irrigation nodes a number of features of the rivers was necessary to be specified in order to model the hydraulic behaviour of the river system. In particular, the following parameters were defined and inserted in the model:

1. The cross-section and slope of the rivers and branches
2. The discharge of the rivers
3. The water demand of the crops

The model was used to estimate the impact of the irrigation demand on the rivers' flow.

IV. SCENARIOS

For the determination of the behaviour of the river and the irrigation system several scenarios were tested:

<u>Scenario 1</u>

Firstly, the behaviour of the water system of the river before the construction of human settlements was tested. In Scenario 1 it is considered that there is no water demand for irrigation.

As mentioned before it is not certain either the rivers' branches are naturally created or human constructions. Aim of this scenario is not to define the behaviour of the water system before human intervention but rather to underline the effect of irrigation demand on Euphrates and Tigris.

Scenarios 2& 3

In Scenarios 2 and 3 the need for some form of coordination in order to ensure that there is sufficient amount of water for irrigation is investigated. An indication for the need for administrative control is the lack of sufficient amount of water to satisfy the water demand. Based on the results of these scenarios it can be determined if action should be taken to keep the water level in the river above a certain threshold that would allow navigation and that would satisfy the irrigation needs.

In both scenarios all branches and irrigation nodes were open. The water level in Tigris and Euphrates was calculated assuming average and minimum flow.

Scenarios 4&5

In Scenarios 4&5 the effect of human intervention at the branches in the upper part of the valley is investigated. In particular, the boundary conditions of branches 1 and 2 in both Tigris and Euphrates are changed.

It is checked either a change in the boundary conditions will reduce the problem of lack of water in the lower part of the valley. The possibility of flooding due to high water level is also considered.

Scenarios 6&7

In Scenarios 6&7 the effect of human intervention at the branches of the lower part of the valley is investigated. The boundary conditions of branches 5 and 6 were changed.

The results of this scenarios are compared with the results of scenarios 4&5. It can therefore be determined the control of which part of the rivers will effectively solve the water shortage problem.

Scenarios 8,9&10

In these scenarios the vulnerability of the upper and the lower part of Euphrates to a gradual increase in water demand is assessed. In order to represent the natural fluctuation of the river's flow, the real flow measurements of Euphrates from 1958 till 1968 were used as an input to the model.

In scenario 8 the fluctuations in the water level of Euphrates when the time series of real flow measurements is used is shown.

In Scenario 9 the maximum amount of nodes that are open in the lower part of the valley before a serious shortage of water is observed is determined.

In Scenario 10 the maximum amount of nodes that are open in the upper part of the valley before a serious shortage of water is observed is determined.

By comparing the results of Scenarios 9 and 10 the vulnerability to draught of each part of the valley is examined. Furthermore, the possible actions that could solve the water shortage problem in a local level are considered.

Scenarios 11 to 15

In this set of scenarios, the silting of the river system is investigated. The decrease of the depth of the cross-section due to sediment deposition was simulated.

The ability of each branch to carry a sufficient amount of water in the irrigation nodes despite a considerable reduction in its cross-section is tested. It can be therefore determined either a branch is going to continue to be used after a significant part of it is filled with sediment or it is going to be abandoned.

Scenario 16

In this scenario the theory supported by Jotheri et al (2016) that during a period there was only on main branch in irrigation system and the rest of the branches-canals have been abandoned due to avulsion is tested.

V. RESULTS AND DISCUSSION

The results of these scenarios were used to identify the parameters that have a significant influence on Tigris and Euphrates flow. Especially, the impact of the development of settlements and the boundary conditions of the river branches were examined. The results of the simulations can be seen in more detail in Appendix B.

An overview of the scenarios that were tested is shown in Table 1. In the first scenario the flow of the river assuming that no irrigation nodes are open was simulated. Aim of this simulation was to define the behaviour of the river system before the construction of settlements and the abstraction of water for irrigation in the Mesopotamian valley.

Based on the results of Scenario 1, when there are no irrigation nodes and minimum discharge measurements are used both Tigris and Euphrates maintain a water level above 1,5 m. In Euphrates the water depth ranges from around 6.5m in the upper part of the valley during the periods with high flow to around 1m and in the lower part of the river, during dry periods. In Tigris, the water depth ranges from 12 to 2 m at wet and dry periods respectively.

The water depth in the two rivers is within the range that it is expected based on literature. In particular, Gash and Tarnet (1998) states that the water depth of Euphrates near Bagdad ranges from 5 to 8 m while the water depth of Tigris ranges from 10 to 15m. It can be seen that the water depth of the nodes in the upper part of the study area is within these limits. It is therefore an indication that the model simulates the two rivers sufficiently well. The water depth in the river branches also gradually decreases from the upper part to the lower part. However, it remains above the necessary for navigation level, at all parts.

It must be noted that the software does not force the water depth to be confined within the depth of the canal. Thus, the water-depth only depends on the river's discharge even if a different canal depth is considered in the determination of the cross-section.

Table 1 Overview of the scenarios

			Results		
	Aim of the Simulation	***River Flow***	***Nodes Open***	***Branches Open***	***Results***
Scenario 1	Evaluate if the behavior of the river system is adequately represented by the model	Tigris and Euphrates- Minimum monthly discharge measurements	None	All	Without human presence there is enough water in both river systems
Scenario 2	Define the effect of irrigation demand on the water depth of the river system	Tigris and Euphrates-Average monthly discharge measurements	All	All	In order to ensure that there is a sufficient amount of water in the upper and lower part of the valley some kind of human intervention is necessary.
Scenario 3	Define the effect of irrigation demand on the water depth of the river system	Tigris and Euphrates- Minimum monthly discharge measurements	All	All	
Scenario 4	Define the effect of the boundary conditions at the end of the branches on the water depth of the river system	Tigris and Euphrates- Minimum monthly discharge measurements	All	Branch 1 is closed	The river Tiger is not sensitive to fluctuations of water demand. There is no sufficient water in Euphrates to satisfy the water demand for irrigation unless at least two of the upper branches of the river are closed.
Scenario 5	Define the effect of the boundary conditions at the end of the river branches on the water depth of the river system	Tigris and Euphrates- Minimum monthly discharge measurements	All	Branch 1 and branch 2 is closed	
Scenario 6	Define the effect of the boundary conditions at the end of the river branches on the water depth of the river system	Tigris and Euphrates- Minimum monthly discharge measurements	All	Branch 5 is closed	River Tiger is vulnerable to flooding when the lower branches are closed. Closing the upper branches of Euphrates solves the low water level problem more efficiently than closing the lower branches of the river.
Scenario 7	Define the effect of the boundary conditions at the end of the river branches on the water depth of the river system	Tigris and Euphrates- Minimum monthly discharge measurements	All	Branch 5 and branch 6 is closed	
Scenario 8	Investigate the behavior of the river system using real discharge data	Euphrates- Monthly discharge measurements from 1958 till 1968	All	All	Euphrates is very sensitive to an increase in water demand in the lower part of the valley. It is not sensitive to an increased water demand in the upper part of the valley as there is sufficient water to satisfy most of the irrigation needs.
Scenario 9	Investigate the vulnerability of the river system to the increase in water demand in the lower part of the valley.	Euphrates- Monthly discharge measurements from 1958 till 1968	Last 3 Nodes	All	
Scenario 10	Investigate the vulnerability of the river system to the increase in water demand in the upper part of the valley.	Euphrates- Monthly discharge measurements from 1958 till 1968	First 16 Nodes	All	
Scenario 11	Investigate the effect from the avulsion of the river branches on the water depth of the river	Euphrates- Monthly discharge measurements from 1958 till 1968	All	Branch 1-20%,80%100% closed	There is no significant difference in the flow of the main branch of Euphrates when a branch is silted up to 80%. If a branch is abandoned the Problem of low water level in the river disappears. This is an indication that it is possible that not all the river branches were active at the same period.
Scenario 12	Investigate the effect from the avulsion of the river branches on the water depth of the river	Euphrates- Monthly discharge measurements from 1958 till 1968	All	Branch 2-20%,80%100% closed	
Scenario 13	Investigate the effect from the avulsion of the river branches on the water depth of the river	Euphrates- Monthly discharge measurements from 1958 till 1968	All	Branch 3-20%,80%100% closed	
Scenario 14	Investigate the effect from the avulsion of the river branches on the water depth of the river	Euphrates- Monthly discharge measurements from 1958 till 1968	All	Branch 4-20%,80%100% closed	
Scenario 15	Investigate the effect from the avulsion of the river branches on the water depth of the river	Euphrates- Monthly discharge measurements from 1958 till 1968	All	Branch 5-20%,80%100% closed	
Scenario 16	Investigate the water depth of the river when there are no branches	Euphrates- Monthly discharge measurements from 1958 till 1968	All	No branches	If no branches are open the water level in the river increases significantly.

In Scenario 2 the water depth in Tigris and Euphrates was examined when a significant amount of water is used for irrigation. In Figure 2 the water depth in Euphrates is shown, if all irrigation nodes are open. It is obvious from the graph that the water depth in Euphrates reduces significantly during the periods that there is low water flow and high irrigation demand. Especially in the lower part of the river the water depth reaches almost zero during dry years. On the other hand, it seems that Tigris is less vulnerable to the water abstraction due to irrigation than Euphrates. Even in the "worst case" scenario when all the branches are considered to operate simultaneously and the water demand is maximum the water level does not reduce significantly. However, in the periods of maximum irrigation the water-level drops below the 2 m threshold that is considered crucial for the navigation in the river. Although the water level in the main branch of Tigris River remains at an acceptable level, the water depth in some of its branches is significantly reduced. As illustrated in the Figure 3 when all the nodes in Tigris are open, the 4th branch of the river is receiving a very small amount of water. This canal is the longest branch of the river and at later periods it was expanded in order to connect Tigris with Euphrates (Iturungal canal). A possible explanation for this behaviour is that a large number of irrigation nodes are connected to the particular canal. Therefore, the amount of water in the canal is not sufficient to both satisfy the irrigation needs and maintain water depth of 2 m.

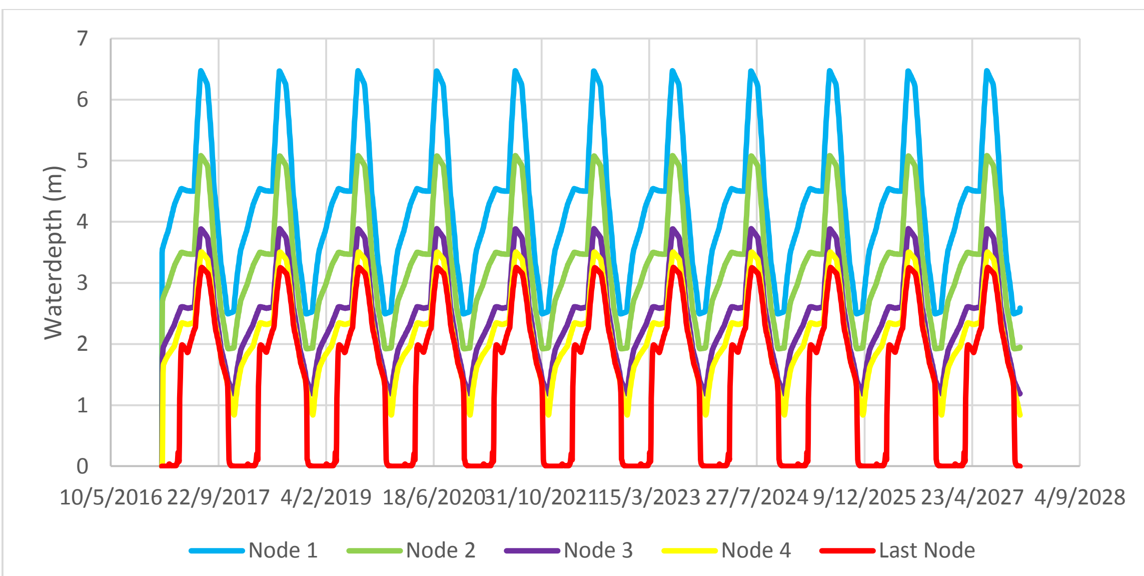

Figure 2 Waterdepth in Euphrates when all the irrigation nodes and branches are open

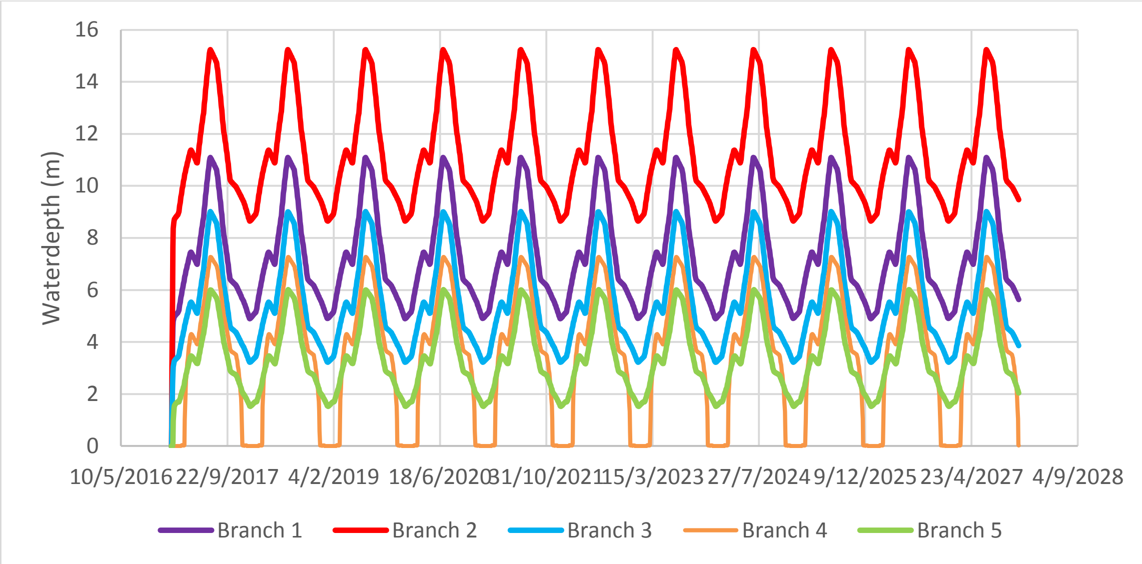

Figure 3 Waterdepth in Tigris' branches when all the irrigation nodes and branches are open

It becomes clear from these observations that a human intervention is necessary in order to ensure that a sufficient amount of water will flow through the Iturungal canal in order the navigation between the two rivers to be possible. This conclusion is confirmed from historical data of later chronological periods when the Iturungal canal was used as an important transportation artery. According to Rost (2015) there were some major constructions at the beginning of the canal that were used to regulate the flow.

In Scenario 3 average flow measurements are used in the simulation instead of the minimum monthly flow measurements of the decade. Nonetheless, in Euphrates the problem of low water depth remains. In contrast, in Tigris when the average flow is used in the simulation, the impact of the irrigation nodes on the river and the branches diminishes. Thus, it is evident, that Euphrates is much more vulnerable to variations in water depth due to irrigation.

Interesting is the effect of the irrigation demand on the flow of the branches-canals. As it can be seen from Figures B.3.3 and B.3.4 (see Appendix B) the 4th and 5th branch of Tigris and Euphrates respectively is receiving very low or no water at all when all nodes are abstracting water from the river. As a result, in order these branches to provide water to the irrigation nodes connected to them it is necessary that the branches and nodes in the upper part of the river are operated differently. A solution could be closing one of the upper branches or decreasing the cross-section of the river downstream.

In Scenarios 4-7 the effect of closing the boundary nodes of the branches in the upper and lower part of the river, were studied. From the results of this research, the importance of the determination of the boundary conditions on the river branches was detected.

It can be clearly seen from Figures B.4.1 to B.4.2 (see Appendix B) that if the 1st branch in the upper part of Euphrates is closed the water depth in its lower part remains below 2m but for a shorter period of time. On the other hand, if the 1st branch in the upper part of Tigris is closed, the water depth is increased above 3m in all parts of the river. The water depth in Tigris when only one canal is closed is higher than the water depth when there is no water abstraction for irrigation. Therefore, it can be concluded that a change on the boundary conditions of the branches can significantly diminish the water shortage problem in the valley.

When both the 1st and 2nd branch of Euphrates is closed then the water depth remains above 2 m at all nodes and the problem of low water depth in the lower part of the river disappears. It must be noted though, that in the case that both the first and second branches of Tigris and Euphrates are closed the water depth in the upper part of the valley rises significantly during high flow periods. Therefore, the danger of flooding the areas in the north is increased during these periods. It may be more efficient that one of the branches downstream is closed in order to increase the water depth at the lower part of the valley without causing a significant rise in the water depth upstream.

If the branches at the lower part of Euphrates are closed, then the water level remains around zero during the periods of maximum irrigation demand. This observation can be explained by looking at the water depth of the branches connected to the lower part of the river (Figure B.3.2.). The flow of the river is already substantially reduced before reaching the 5th branch. Consequently, by only closing the 4th or 5th canal not enough water is saved to solve the problem.

On the contrary, when the 5th branch of Tigris is closed the water depth in the main branch rises above 2 m at all nodes. Also the water depth in the upper part of the river remains around 12 m. On the other hand, when an upper canal is closed the water depth in this area is rising to 16-17 m and the possibility of flooding increases. It can be concluded then that closing canal in the lower part of the river is a better way of maintaining the water depth in Tigris than closing a canal upstream.

Overall, based on the results above, it seems that Euphrates has a major water problem when the irrigation demand is maximum and all the branches of the river area open. It is therefore necessary to close more than two of the major branches in order to ensure that enough water is available for irrigation. If two of the upper branches are closed the water level problem at Euphrates is solved and the river can be used for transportation of goods. In contrast, more than two branches in the lower part of the river need to be closed to maintain a sufficient water level for navigation in the river.

The main problem in Tigris is the high differences in water depth between the upper and the lower part of the river. If the upper branches are closed then the water depth remains above 2m in the whole length of the river but the water depth upstream is rising above 17m, probably flooding the area nearby. For Tigris the most efficient approach is closing the branches downstream. Closing just the last branch of the river is sufficient in this case.

In Scenarios 8 to 11 the vulnerability of the areas in the upper and lower part of the valley to drought is investigated. Since it is a gravity irrigation system it is likely that the lower part is more vulnerable to water scarcity. Also, the possible measures that should be taken in a local and central level to regulate water demand are examined.

Aim of these scenarios is to identify the increased need for a local and central coordination for the efficient distribution of water in the water demand nodes. This connection can be later on used to draw important conclusions about the changes in hydraulic properties of the rivers that caused major shifts in the way of management of the irrigation system. Also the influence of the changes in societal organization during the Uruk period, on the hydraulic landscape of the Mesopotamian valley is investigated.

In Scenario 9, the behavior of the river system in relation with the development of the human settlements is explored. For a more realistic approach, the flow data of the decade 1958 -1968 were used instead of a series of years of minimum flow.

According to Figure B.9.1, if only 3 irrigation nodes are open downstream, a problem of low water level appears in the lower part of the river. Based on the results of this scenario, it can be concluded that from the earliest stages of the development of settlements in the area, problems with the water level and the water availability appeared. It is evident that some kind of coordination was necessary to retain the water level above 2 m even if only a small number of settlements were present. As the number of settlements increased the periods of drought increased in duration and frequency. The need to take measures to retain the water depth at a desired level became more and more urgent. This could lead to the building major constructions that would close major canals or branches in order to maintain the water depth in the main branch at a sufficient for navigation level. Another solution could be, using Tigris as an alternative source of water. Simple constructions such as barrages could also be built to locally increase the water level. The presence of such constructions or barrages is verified by archeological records (Rost, 2015).

In Scenario 10 the vulnerability of the upper part of the valley to an increase water demand for irrigation is tested. According to the results of this scenario around 16 irrigation nodes can be opened in the upper part of the river before a serious lack of water is evident downstream. By comparing Scenario 9 and Scenario 10, it can be clearly seen that Euphrates is, as expected, much more vulnerable to the abstraction of water from the lower part of the river. It must be noted that the nodes downstream contain more settlements than the nodes in the upper part of the system. Therefore, a smaller number of nodes in the lower part of the valley corresponds to a larger abstraction of water. However, the amount of water abstracted by the 16 first nodes of the river is significantly higher than the water abstracted by the last two or three nodes.

This result shows the importance of the settlements' position for the determination of their influence in the river system. The nodes near the last node of the river seem to have a greater impact, locally, than the nodes further upstream. Thus, local control of the last nodes can limit the lack of water problem in the area but closing the upper branches would be a much more effective solution.

In Scenarios 11-15 the influence of sediment deposition on the water depth of the river system was examined. In Figure 4 the water depth in Euphrates when the cross-section of the 1st upper branch is decreased more than 80% is shown. Since the 1st branch of the river is the one receiving the higher amount of water it is expected to be the first to be affected from the sediment deposition. It is obvious from the graph that even if the largest part of the cross-section is silted the water level in the main branch of the river is not significantly affected. In particular, the frequency of low water depth incidences in the main branch of the river is not significantly reduced. However, the duration of the dry periods slightly drops. The difference in the discharge before and after the silting of the branch is important only in high flow periods. In contrast, when the branch is fully blocked by sediment deposition the water depth in the main branch rises and the incidence of low water depth in the river disappears.

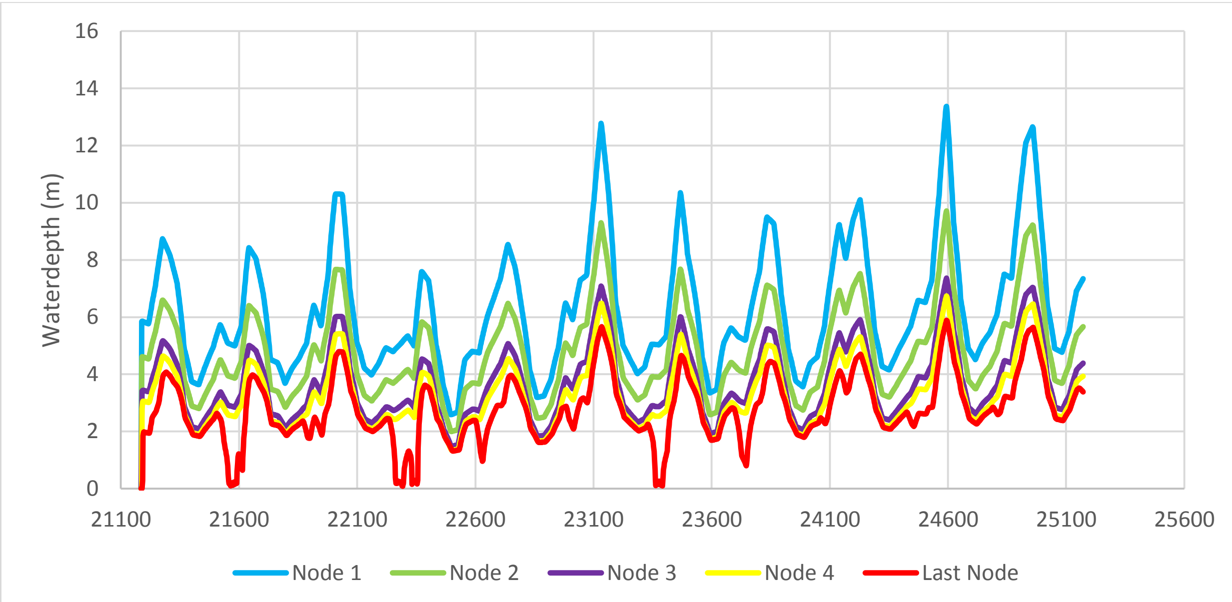

Figure 4 Waterdepth in Euphrates when the cross-section of branch 1 decreases 80%

Generally, the complete abandonment of a branch has a significant effect on the river flow. However, if the cross-section of a branch is decreased up to 80% the effect on the water depth of the main branch is limited and difficult to notice. It can therefore be concluded that it takes a long time till the deposition of sediment in the river branches has a significant effect on the river flow.

There is no evidence suggesting the simultaneous operation of all the branches of the rivers. It is possible that only one of the branches was active at a certain period. After the flow in this main branch was reduced due to silting another branch was used instead as the main transportation artery and the previous canal was simply abandoned. The possibility of having only one main branch of Euphrates at a certain period is tested in Scenario 16. In Figure 4 the water depth in Euphrates when there are no branches is shown.

It can be clearly seen that when there are no secondary branches in the river the water depth increases significantly. The water depth is no longer within the range defined by literature. This result indicates that modelling Euphrates with a number of open branches is a good representation of the river's behavior.

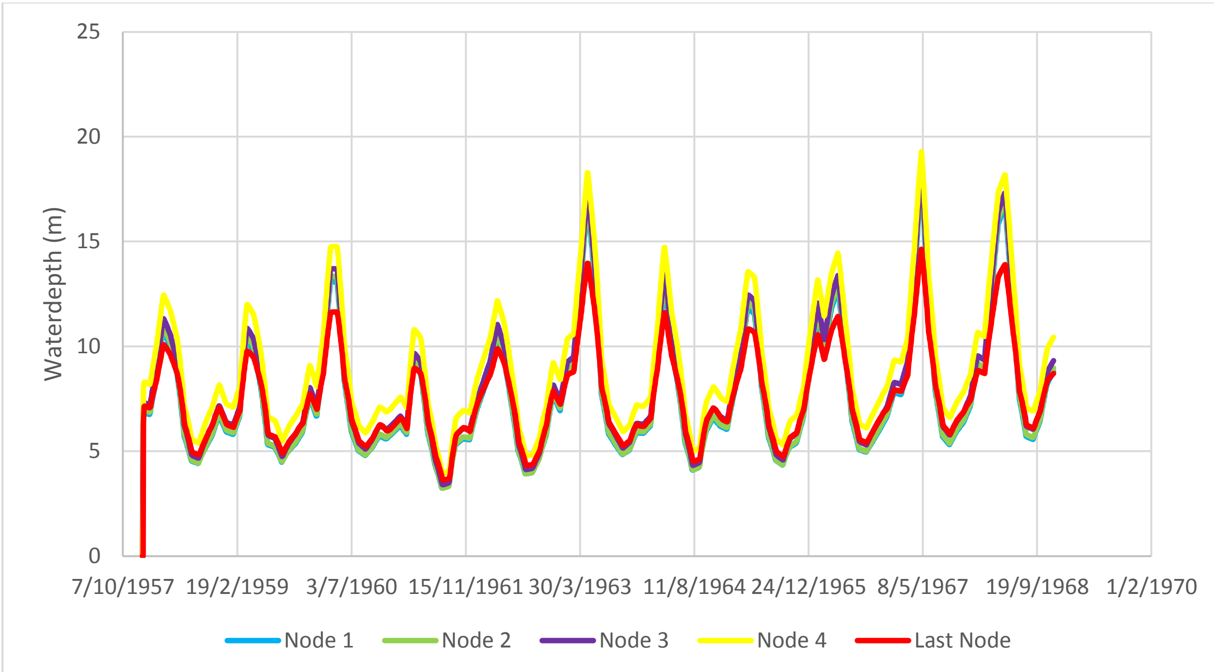

Figure 5 Waterdepth in Euphrates when there are no branches

VI. DISCUSSION

In order to estimate the accuracy of the results from the above scenarios the limitations of the model should be taken into account. During the construction of the model a number of assumptions were made due to lack of available data. For example, the clustering of the settlements into nodes was made in a rather arbitrary way. The main criterion for the clustering of the settlements was the creation of a simplified image of the irrigation system, where a limited number of nodes is connected to the river system and the spatial differences in settlement density were taken into account. Also, a number of hydraulic parameters were defined based on modern observations since historical were not available. The flow and the cross-section of the river was determined based on modern and pre-modern observations.

A more detailed determination of the settlement and cultivated area is necessary for a more accurate model of the river system since it is related to the irrigation demand in the area. The calculation of the cultivated land based on the settlement area is not an accurate representation of reality. In the large urban centers such as the city of Uruk only a small percentage of the area near the settlements was actually used for agriculture. The population of the big cities was mainly sustained from goods arriving to the city form agricultural areas.

The determination of the actual river course and branches during the Uruk period is necessary. The river course proposed by Jotheri et al. (2016) differs significantly from the representation of the river system as it was reconstructed based on Adams (1981) research and was used in this model. However, a change in the overall length of the river does not affect significantly the conclusions from the hydraulic behavior of the river system. The presence or not of the branches is, however, important for the modelling results and must be investigated further.

In addition, there is no indication that all the river branches existed during the same chronological period. Based on the research of Jotheri et al. 2016 there is one main branch of Euphrates and Tigris. According to this research the course of the rivers continuously changed as the silted branches of the river were abandoned and replaced by new.

Furthermore, it is possible that different boundary conditions, than the ones tested in this study, are the actual hydraulic conditions in the end of the branches. For example, some branches may end up in a swamp or reservoir. The effect of such a scenario in the flow of each of this branches should be tested.

The modelling limitations of the sediment deposition scenarios should be considered when evaluating the results of Scenarios 11-15. The sediment deposition process was simulated by changing the depth of the cross-section of the canals. However, this method does not accurately represent the decrease of the capacity of the canal since the model does not confide the water depth to the depth of the cross-section.

It must be noted though that the model is only a simplified representation of the irrigation system in ancient Mesopotamia. Aim of this study is to describe the trends and tendencies in the water flow of the river system rather than describe accurately the behavior of Tigris and Euphrates. In order to overcome the uncertainties associated with the modelling of the irrigation system further research is necessary.

An important role of the model is to indicate the significance of certain hydraulic parameters for an accurate description of the river system. For example, the importance of the boundary conditions in the end of the river branches was underlined by this analysis. A change in the boundary conditions of the branches seems to have a detrimental effect on the flow conditions of the river. Based on the results of this study the water depth of Tigris and Euphrates is more sensitive to the closing or opening the boundary nodes of the branches than a sharp rise in irrigation demand.

Overall, the results of the scenario's simulations should be used with caution. On the other hand, the trends in the behavior of the system that emerged from this analysis can be used for a more accurate representation of the rivers.

VII. CONCLUSIONS

In this study a simplified model of the rivers Tigris and Euphrates during the Uruk period (3500-3100 B.C.) was created to define the hydraulic behavior of the rivers in ancient Mesopotamia. Several scenarios were tested in order to identify the relationship between the water depth in the main branches of the river and the development of settlements in the Mesopotamia valley. Also, the effect of closing one or more branches due to human intervention or natural processes was investigated.

Based on the results of the simulations the following conclusions can be reached:

- Tigris is less vulnerable to the abstraction of water for irrigation than Euphrates. However, if the upper branches of the river are closed then the danger of flooding increases.
- For Euphrates, closing a branch in the upper part of the river solves the problem of low water level in the lower part of the river.

- The lower part of the river Euphrates is more vulnerable to an increase in water demand for irrigation than the upper part. Even if only 3 irrigation nodes in that part of the valley are open a problem in the river water level appears.

The lack of sufficient water for irrigation in the lower part of the Mesopotamian valley and the vulnerability of the area to water abstraction creates a need for coordination between the settlements in the lower part of Euphrates in order to solve the water scarcity problems. These conditions can cause the emergence of a centrally controlled society where the behavior of the members is regulated from some form of authority.

However, the options of a local administration to address the problem are limited. Almost all the irrigation nodes in the area should be closed in order to maintain the water depth above 2 m which is the minimum for navigation. Also, even if the last two branches of the river are closed the problem remains. Therefore, the measurements that could be applied in a local level cannot effectively solve the problem.

An option to deal with the lack of sufficient water for irrigation is the formation of a political connection between the upper and lower part of the valley. The lower part of the river is more densely populated and the major urban centers of the period are located in this area. It can therefore be assumed that the center of power in ancient Mesopotamia is located in the southern part of the valley. The political power of the lower part could be used to regulate the water abstraction or branch-canals operation in the north. According to this research, these actions would effectively solve the low water level problem.

An alternative solution, would be the production of the food necessary to sustain the valley's population in the north of Mesopotamia. The products can then be transported through the river system to the lower part of the valley. In this case, the water abstraction in the south should be minimized in order to keep the water level above a threshold necessary for navigation.

In Euphrates the lack of water and the necessity for control of the upper part of the river could trigger the change in the management of the irrigation system. On the other hand, in Tigris the irrigation demand is less crucial. Despite the fact that a large number of irrigation nodes are connected to Tigris the water depth is not significantly influenced from the water abstraction for irrigation. The main problem in Tigris is the large difference between the water depth in the upper and lower part of the river. If the branches or irrigation nodes in Tigris are closed the water depth in the upper part of the river rises significantly and the area becomes more vulnerable to flooding.

Overall, the trends in the behavior of the system that emerged from this analysis can be used to draw important conclusions about the reasons that led to changes in the way of operation and management of the irrigation system in ancient Mesopotamia. However, for a more accurate representation of the river system a more detailed model is necessary.

VIII. RECOMMENDATIONS

The model in this research is a simplified representation of the irrigation system in ancient Mesopotamia. Aim of this research is to prove that a hydraulic model is useful tool for historical research. However, additional research and a more detailed model is necessary to accurately represent the connection between the societal and organizational changes in ancient Mesopotamia and the landscape of the valley.

In particular, a more accurate representation of the irrigation system is necessary:

- The land of the settlements and the way each settlement is connected to the river system should be defined.
- The determination of the boundary conditions of the branches-canals is important.
- The sediment deposition and avulsion of the river should also be more accurately described and modelled.
- possibility that only one main branch in the river at a certain chronological period as stated by Jotheri et al. (2016) should be further examined.

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