Civil engineering department: Water Resources Management MSc Thesis

Title: Hydro-Archeological Modelling of Neo-Assyrian Watercourses

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Abstract

This thesis is the first attempt in modeling Sennacherib's (Neo-Assyrian king) colossal watercourse networks, with its main goal to uncover their hypothetical functionalities and operation, regarding irrigation needs and harvest yield production. Their total length surpasses 150 Km and was completed in four stages, with lack of data forcing stage two's exclusion. The stages modeled are separated in a Local and Regional system, the latter is assumed to connect the Zagros mountains foothills and Bandawai area with the capital of the era (early 6th century BCE) Nineveh, through a mix of artificial channels, canalized rivers, and streams. Two models were used AquaCrop and Sobek, with the former for crop and latter for flow simulations. Two feeder channel widths (1- 2 m), along with three inflow *("Wet"- "Reference"- "Dry")* and control *(Absent, Maximum, Limited)* choices are modeled with Sobek, adding up to 14 hydraulic scenarios. Noteworthy is that "Dry" year agriculture requires irrigation throughout the hole region and both seasons (Spring-Autumn), with results presenting around 60% gains in harvest amounts when control is applied for the Regional System. Although navigation feasibility was not thoroughly explored, "Reference" (and consequently "Wet") year inflows show water depths rising to or higher than the accepted. Concluding a decisive answer to the "archeological debate" of Sennacherib's motivation for construction of such massive infrastructure is impossible with present data (Environment, canal, social) available. Circumstances favoring control and therefore planned rural irrigation (rather than capital-centered) for Nineveh's hinterlands are analyzed and discussed. Lastly a few interventions seen as valuable for further modeling studies were suggest towards the members of the LoNAP team as a contribution to their upcoming field survey.

Acknowledgments

First, I would like to thank my supervisor Dr. Maurits Ertsen for his patience, clear points throughout our discussions, and guidance over the hurdles of completing a master thesis. Dr. Ronald van Nooyen for his valuable help in handling and solving issues related with the flow modeling software (Sobek). Although our collaboration with Dr. Herve' Reculeau was for a short period, without his additions of crop-data and discussions the crop simulation part of this thesis would have been unfeasible. Last but certainly not least I would like to make my gratitude known, towards Dr. Daniele Morandi Bonacossi and Alberto Savioli (Surveyor and GIS expert), members of the Land of Nineveh Archaeological Project, from the Department of Humanities and Cultural Heritage (DIUM), University of Udine (Italy). Dr. Daniele Morandi Bonacossi for his valuable article contributions as well as detrimental feedback provided during the modeling process. While Alberto Savioli for his inputs and our discussions related to deciphering canal data, as they were a catalyst in finalizing canal features for this thesis.

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1: INTRODUCTION

BRIEF HISTORIC BACKGROUND

The region of ancient Mesopotamia encompassed valleys and floodplains between the rivers Tigris and Euphrates, situated in modern Iraq and parts of North-East Syria. Assyrians emerged around 2000 BCE from the northern Tigris floodplain, forming a base around their capital city of Ashur, while also expanding westward during the Middle Assyrian era (1400-1200 BCE) (Figure 1). Nearby conquered lands were assimilated into "The Land of Ashur", extending almost until the north-south Euphrates arm, transforming the small city-state of Ashur to a growing regional power (Wilkinson, Ur, Wilkinson, & Altaweel, 2005). From 1300-900 BCE, Middle Assyrian and early Neo-Assyrian periods, the empire went through multiple phases and degrees of land contraction, apart from minor conquest victories by Tiglath-pileser I (1114-1076 BCE) (Wilkinson et al., 2005). The 9th century BCE saw expansion of Assyria with several Aramaean states and other communities. Despite periods of decay (mostly in early 8th century BCE), Assyria managed to conquer land and acquire client states in western Syria and the Levant. From 745 BCE, the empire extended its borders westward throughout the Levant reaching Egypt, and eastward to the Iranian state of Elam. The collapse of the Assyrian empire came between 630 – 609 BCE, with Medes and Babylonians sacking Nineveh in 612 BCE (the capital at the time), while internal conflicts and climate (especially droughts) are assumed to contribute to the collapse (Sinha et al., 2019; Wilkinson et al., 2005).

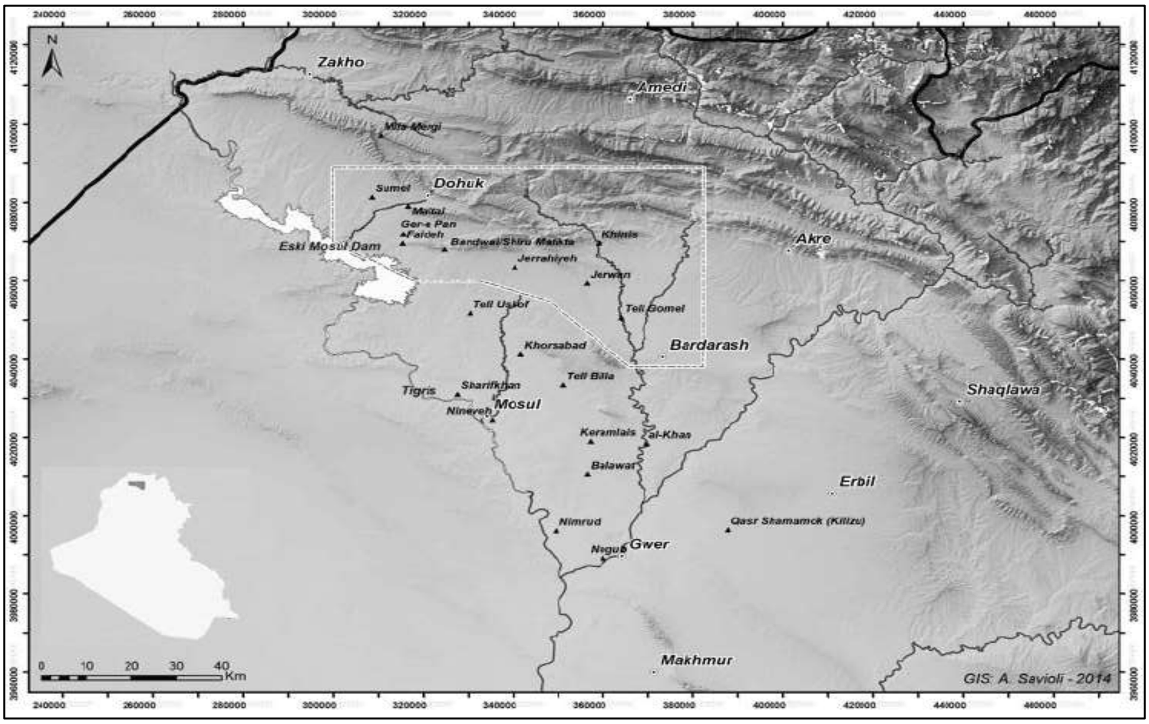

Figure 1 The heartland of the Assyrian empire (Morandi Bonacossi, 2019)

The Neo-Assyrian period shows an intensification of Middle Assyrian settled areas, rearrangement of natural hydrology, plus administrative and agricultural changes. During the 8th – 7th centuries BCE, a movement of the empire's core northward takes place, by appointing Dur-Sharrukin and later Nineveh as the political capitals, by kings Sargon II and Sennacherib, respectively. Assyria reached their largest recorded territory by an empire in the Near-East region, while their core migrated north creating the "Assyrian Triangle" between the cities of Nineveh, Khorsabad, Arbela and Nimrud (Morandi Bonacossi, 2019). Administrative changes in the empire went hand in hand with deportation of a subjugated state's population, which was common practice after successful invasion campaigns. As much as lowering threats of rebellion, this also made labor available, for example for expanding irrigated farming.

Much of Assyria's empire building, including the resettlement programs, took place through intensification of settlements and agriculture, by exploiting hitherto marginal or unsettled lands and using irrigation systems to support them (Morandi Bonacossi, 2018). Examples of large-scale canals are the Nimrud, Arbela, Kilizu and Nineveh systems connecting each city to its hinterlands. The Nimrud system originates near the confluence of the Khazir and Upper Zab rivers, with its course incorporating subterranean reaches, fed partially by shafts directed to Negub. Erbil was fed by a subterranean canal from Bastora Chai river, while its nearby area of Qasr Shamamok (Kilizu) also tapped in the upstream Upper Zab conveying water towards the area along with its natural wadis (UR, 2019).

Nineveh's system, which is the focus of this MSc thesis, connects the city with north-eastern and northern hinterlands, by the Khinis and Bandawai canals, respectively (Figure 2). Khinis runs through its homonymous area, crossing Jerwan, where numerous offtakes and remains of an impressive aqueduct using approximately 400,000 bricks has been discovered, before it drains in the Khosr river – ultimately reaching Nineveh. The Bandawai also originating from its eponymous village, is characterized as a cross-watershed canal due to large excavations (15-20 m) required to guide it towards Tell Uskof and massive spoil banks resulting from years of maintenance. Another cross-watershed canal (Uskof) discharges in a tributary of the Khosr river near the town of Tell Uskof, joining other flows directed to the capital by the Khosr (Morandi Bonacossi, 2019).

GOAL OF THIS THESIS

This thesis attempts to reconstruct the canal network connecting Nineveh, capital of the era, to its northeastern hinterlands. Such reconstruction supports further discussions on what the canals could have made possible in terms of agriculture and bringing water to the capital of Nineveh, as well as a first assessment of transport capabilities. These canals are attributed to Sennacherib, a Neo-Assyrian king rising to power in 704 BCE. Upgrading hydraulic and road infrastructure, along with rearranging regional populations within his domain, are some of his most notable accomplishments. Administratively, he increased populations in provincial centers, also prompting a denser network of rural settlements, relying on deporting record amounts of people (0.5 million) and symbolically imprinting his dominance with reliefs, such as those found on regional or more local hydraulic systems (Morandi Bonacossi, 2018). During Sennacherib's reign, Nineveh grew from 200 to 750 ha, with royal elites having available a lavish palace, impressive public buildings, stunning court art and the king's exotic gardens. Also noteworthy is that sewers systems were identified in Nineveh's palace and some of the larger housing buildings (George, 2015).

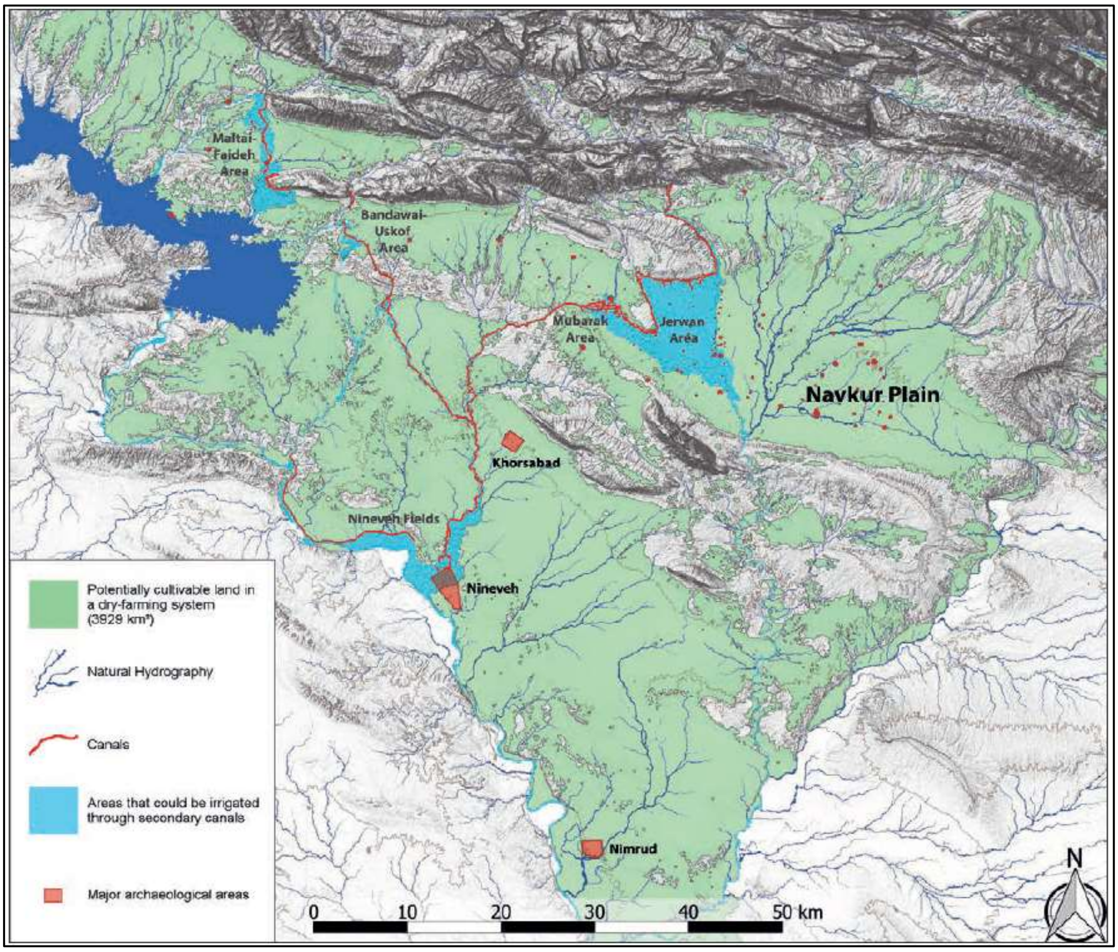

Figure 2 The Nineveh canals (Morandi Bonacossi, 2019)

THE NINEVEH CANAL SYSTEM

The canal system has not been built all at once – four phases can be distinguished spanning 14 years, with this thesis dealing with three of these. Description and data on the canals are obtained through the Udine Land of Nineveh Archeological Project (LoNAP),(Ur, 2005) and Erbil Plain Archaeological Survey (EPAS), both uncovering important aspects of Neo-Assyrian hydraulic infrastructure. These hydraulic features, along the seemingly planned infilling of land niches made possible by large scale irrigation systems supporting intensification in rural settlements, propelled a rise in urban demographics and prosperity of political and regional capitals.

1. The first stage of canal building started shortly before 702 BCE, with the Kisiri canal extracting water from the Khosr river, potentially watering Nineveh's fields and royal gardens, while also crossing irrigation ditches on its route. The canal continues until it splits shortly before the city into a channel leading towards the Tigris floodplain and another to Nineveh's walls.

2. The Musri system, the second stage, was mentioned in the king's inscriptions dated at 694 BCE, as he enlarged several springs at the foot of Mount Musri (present day Jebel Ba'shiqah), created reservoirs, and diverted flow towards the Khosr. Other than observing two of the four large visible springs reaching the Khosr through natural canals, its route is almost impossible to identify, largely due to lack of ground observations and damaged channels proving quite hard to date.

3. The third stage consists of multiple canals such as the Maltai and Faida, situated north of the capital. Maltai connects the basins of Dohuk and Faida as a cross watershed channel likely fed by spring(s) and the river Dohuk, with limited data on offtakes (one) and cross sections (none). Faida is spring fed and surrounds the west side of the Jebel Al-Qosh hill near the end of Maltai canal. Moving south deriving from the Bandawai village, the cross-watershed canal flows in Nineveh's direction, while only one offtake route is known. The canal continues into the Uskof canal, topographically and morphologically similar to Bandawai, ultimately leading to a tributary of Khosr near the town of Uskof. As with Bandawai, the route is identified, but no offtakes are known for this reach. The Taibisu channel shows extreme linearity and width, not following the natural contours – these observations disconnect it from Neo-Assyrian canals.

4. The fourth stage refers to the Khinis canal, originating at the village of the same name, sharing a large drainage basing (525 Km^2) with the river Atrush. It took water from the river Gomel (Atrush continuation), thanks to a weir and collected the water of several springs along its course, as it proceeds towards the top end of the Navkur plain. Before it reaches the Mubarak area, five aqueducts are observed, with the fourth (the Jerwan aqueduct) being the largest with an estimated 400,000 limestone ashlars used. The Jerwan and Mubarak areas have 16 offtakes (7 and 9 each), all leading in the Sheikhan plain fields. After the Mubarak complex, the canal pours in a tributary of the Khosr, which ultimately guided water to the capital.

A detailed description of the three types of cross-sections for Khinis along with the other canal is provided in the methodology, while length and average slopes of the canals are shown in Table 1 below (Morandi Bonacossi, 2019; Ur, 2005). Worth noting is that the Faida has more detailed available data on slopes near its offtakes, further explained in the Methodology section.

Table 1 Canal features of Length in Km and slope 10-3 m/m by (Ur, 2005).

Stages	Canals	Length (km)	Gradient (10^{-3} m/m)
1	Kisiri	13.4	0.95
2	Musri	-	-
3	Maltai	4.2	4
	Faida	9.7	1.6
	Bandawai	5	0.8-1
	Uskof	4.4	1.2
	Tarbisu	23.1	0.6
4	Khinis	55	0.9

POSSIBLE USES OF THE CANAL SYSTEM

The Assyrian mainland was defined by the triangle formed between modern cities of Qal'at Sherqat (Assur), Mosul (Nineveh), Khorsabad (Dur-Sharrukin) and Erbil (Arbela). Annual precipitation occurs predominantly during the cool season (November-April), composing 90 - 95% of the yearly amount, due to Mediterranean cyclonic systems. Rain amounts range from 600 to 1000 mm for the north and west, dropping to around 200 -300 mm for the southern and eastern parts of the region. Currently the majority of Assyrian mainland is safely situated above the isohyets defining the "zone of uncertainty", characterized by annual isohyets of 200-300 mm, high annual variability 40-60% and unpredictable success of rain-fed cereal agriculture, due to limited water availability. Dry years can force the rise of this zone northward deeming much of the mainland unfavorable for cultivation, while wetter years move it south providing high yields (Sinha et al., 2019).

In a recent paper, (Sinha et al., 2019) sheds some light on the hydro-climatic history of the region between 950-550 BCE, through a comparison with more recent periods. Stable isotopes ($\delta_{18}O$) and ($\delta_{13}C$) measurements gathered from Kuna Ba Cave in northern Iraq, located around 300 km southeast of the modern city of Mosul (Nineveh), near the city of Sulaymaniyah provide indications of peak wet conditions for nearly two centuries (925-725 BCE), leading to a 15-30% increase in cool season rainfall compared to the 1980-2007 period. A so-called Assyrian mega-drought would have taken place in the 675-550 BCE period (exhibiting the largest increase in $\delta^{18}O$,

$\delta^{13}C$ over 125 years of aridity), matching the period of imperial collapse 660-600 BCE. These years are deemed comparable to the drought years of 1990-91 and 2007-08, responsible for significant cereal crop failure and livestock decease spread across northern Iraq and Syria (Sinha et al., 2019).

Agriculture in semi-arid areas is directly limited by water availability and soil fertility. In a more general context, cropping options depend on climate, natural environment and cultural features, such as cultivating technology and land use patterns (Morandi Bonacossi, 2019). Little is known about Neo-Assyrian agricultural practices from records, but a preference of wheat over barley as well as the existence of vegetables and potentially orchards seem to have existed. Due to the lack of detailed data, crop analysis has been performed using Middle Assyrian practices on crop choices, sowing rate and yields provided mainly, through the assistance of Herve Reculeau Professor in the Oriental Institute at the University of Chicago (Reculeau, 2011).

An intriguing question sprouting is whether Sennacherib's hydraulic accomplishments provided meaningful changes in the agricultural economy of Nineveh's region. Did the canals allow shifting focus from extensive dry farming to intensive, and high yields, diminishing weather related uncertainty, when supported by irrigation? Two main opinions exist on this issue.

1. Julian Reade insists these canals would have failed to elevate the level of agriculture productivity significantly in Nineveh's rural surroundings (Morandi Bonacossi, 2019).
2. Ariel Bagg did not dismiss the regional economic benefits of the king's project, assisted by a preliminary assessment of these from the LoNAP team (Morandi Bonacossi, 2019).

Through fieldwork and computer simulations based on ASTER digital elevation models, LoNAP presents significant land surfaces available for easy irrigation, extending far beyond Nineveh's northwestern and northeastern fields, in close proximity to many of the canals, including Jerwan, Tell Mubarak, Bandawai, Faideh and Maltai areas. The dense settlements on the Navkur plains, especially in Jerwan and Tell Mubarak, strengthen assumptions of artificial watercourses, accompanied by a 65% increase in the number of identified cites and their settled area by 73%, through a pattern closely relatable to other core region planned settlements, such as Erbil. As such, the intensively cultivatable surface land in the LoNAP study area reaches 164 km^2, much greater than 56 km^2 in Nineveh's direct surroundings. These lands could have been the motivation for stages 3 and 4, to reduce harvest uncertainty and increase yields, which suggests a methodical promotion of the piedmont belt of the Zagros mountains as a staple food supplier for the capital (Morandi Bonacossi, 2018).

Then, to add to this image of possible intensive use, discovery of quay walls on the Gomel river suggest natural watercourses were also used in transportation of goods and people. This brings up the question of potential use of canals in addition to rivers as means to achieve frictionless transport towards the major cities of Nineveh and Nimrud (Morandi Bonacossi, 2019).

THIS THESIS

With the above in mind, this thesis project explores functional capabilities of Sennacherib's stage 1, 3 and 4 canals, with data made available through the LoNAP project and Jason Ur's satellite image analysis for stage 1 Kisiri (Ur, 2005). Sobek, a one-dimension numerical open channel flow model provided by Deltares, is used to simulate canals and their behavior during different operational and flow conditions. Additionally, AquaCrop, an agriculture model from the Food and Agriculture Organization, is utilized to assess production yields under varying water availability. Relying on available data (canals, hydrology, agriculture), this study's goal is to present the hydraulic/production capabilities of regional and local systems within the Nineveh system, potentially aiding in deciphering the economic impact and consequently motives of the Assyrian king's hydraulic accomplishments.

2: METHODOLOGY

This section aims to provide an overview of the thought process and modelling tools, utilized to access Regional and Local system's hydraulic capabilities as well as their consequences on harvest yields. A brief description of *Environmental Parameters, Crop and Flow Modelling* will take place in the homonymous paragraphs, while a detailed version is provided in the **Supplementary document: Methodology**.

ENVIRONMENTAL PARAMETERS

Weather characteristics for early 6th century BCE Neo-Assyrian mainland such as precipitation and temperature are assumed to roughly equate with the 1979-2010 datasets of the region, according to (Sinha et al., 2019). These are obtained through the National Oceanic and Atmospheric Administration (NOAA), while three sets of daily values (rainfall and temperature) are defined representing fields in the vicinity of Nineveh, Navkur and Faida. Nineveh's time-series was used to identify the wettest

1980 (494 mm) and driest 1999 (128,5 mm) years based on annual precipitation amounts in millimeters.

Soils are based on the 1960 study from Iraq's Ministry of Agriculture (Buringh, 1960), supplying general characteristics such as soil categorization and average depth range. Two distinct soil types are assumed for Nineveh and Navkur-Faida fields, the former is categorized as loamy with a depth of 3 m, while the later as silt loam and a 2,25 m depth. Salinity amounts of these soils are deemed insignificant, while groundwater levels are low and seen as uninfluential towards water exchange with the upper soil (Buringh, 1960).

CROP MODELLING

Two-row Barley is the crop of choice for this study, although mentions of wheat as the dominant crop are presented in (Morandi Bonacossi, 2019). The lack of Neo-Assyrian evidence for planting periods, sowing and yield rates force the use of Middle Assyrian estimations for these parameters. Widely accepted sowing rates in their original units qu/iku range from 30-35 (Mari-Middle Assyrian), while qu and iku conversions to kg and hectares respectively are a more controversial topic (Reculeau, 2011, 2018).After consulting Hervé Reculeau Professor in the Oriental Institute at the University of Chicago specializing in Middle Assyrian period, choices regarding metrological conversions planting dates, sowing and yield rates are defined. With 30 qu/iku as sowing rate, qu = 0,5 kg and iku = 0,42 ha resulting in 35,71 kg/ha, maximum seed to yield rate of 1:10, and lastly planting dates during Autumn and Spring (7th November-March) seasons.

AquaCrop is the modelling tool used in determining timing and amount of irrigation events throughout the growing season (otherwise referred as Irrigation Schedule), in addition to estimating dry harvest yields. Two years are chosen to conduct simulations representing wet-dry periods (1980-1999), while both Spring and Autumn seasons are modelled. These simulations are run for all pairs of weather-soil characteristics attributed to the above-mentioned fields (Nineveh, Navkur and Faida). Continuous irrigation is ruled out do its extremely low flow per day and high labor requirements, while a 30 mm per hectare and event delivery amount is chosen after investigating three low end choices of 20-30-40 mm. Calibration of yield to the maximum yield (1:10) is performed for Nineveh's lands during wet Autumn season. An important output of these simulation runs is irrigation event timing, which is converted to available days to complete one event described thoroughly in the **Supplementary document: Methodology**. These are utilized in evaluating the flow simulating software's (Sobek) performance, by producing water coverage percentages reaching fields (compared to intended 30 mm amount) within available time. Lastly AquaCrop is used in estimating dry harvest yields for the different fields, years and hydraulic condition scenarios, the latter is described in the paragraph below.

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Table 2 Dry harvest yields in kg/ha for a 30 mm, Net water requirement delivery and rainfed growing season. Along with the available time to irrigate in days for each field, year, and growing season.

Wet year						Dry year			
	Deliver pre event (mm)	***30***	***Net Requirment***	***Rainfed***	***Available days to Irrigate***	***30***	***Rainfed***	***Net Requirment***	***Available days to Irrigate***
Nineveh fields	**Spring**	203	207	146	4.5	203	DEAD	203	4
	Autumn	355	358	DEAD	4.5	366	DEAD	367	4
Navkur fields	**Spring**	218	219	203	5	216	DEAD	216	4
	Autumn	350	364	354	9	367	DEAD	367	4.5
Faida fields	**Spring**	218	219	192	5	218	DEAD	219	4
	Autumn	366	377	346	10	336	DEAD	376	5.5

FLOW MODELLING

Canal systems are separated in Regional and Local, representing their potential in irrigation along with individually defined reaches, as shown in Figure 3.

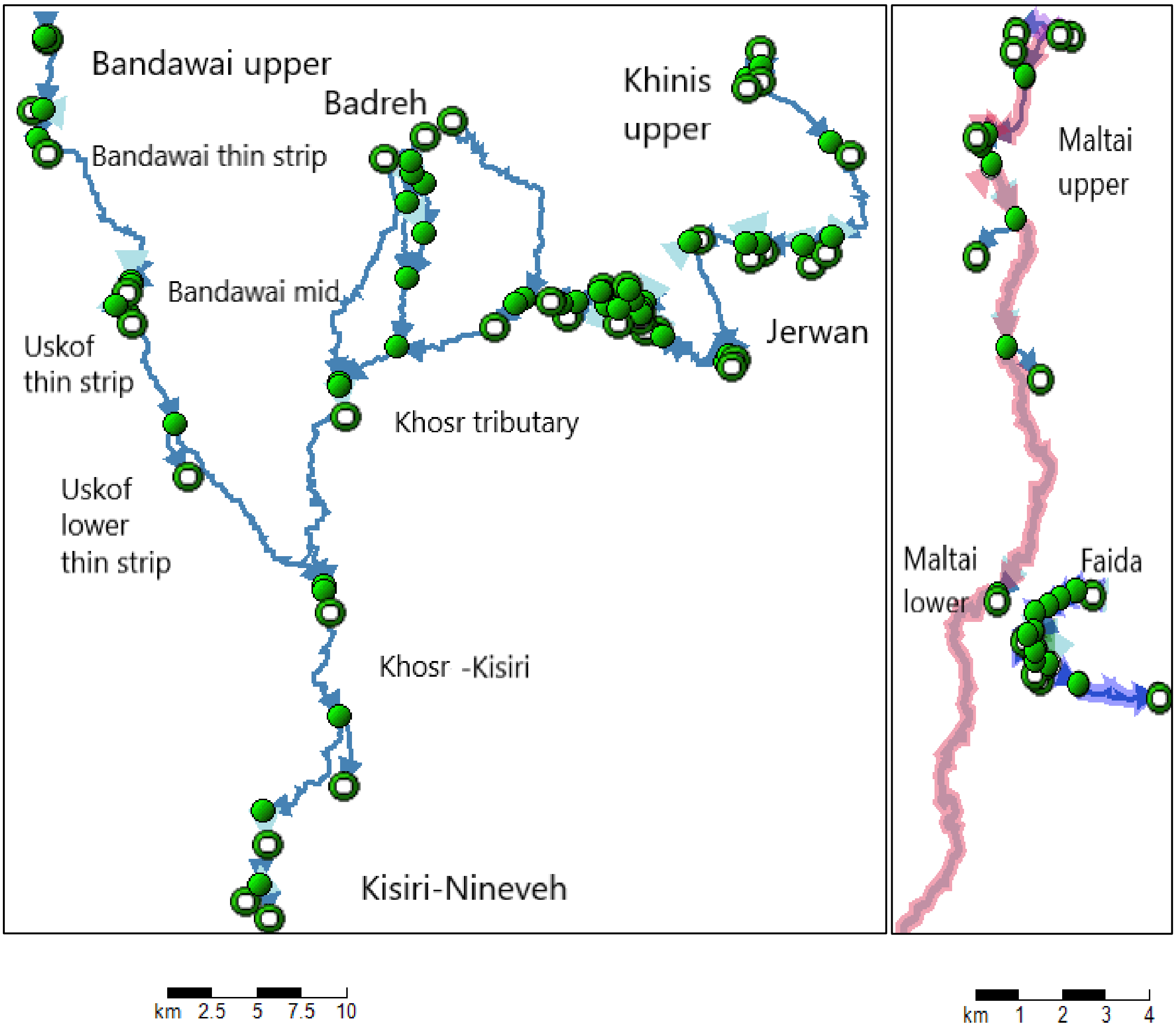

***Figure 3** The Regional canal system is shown in the left while the Local is displayed on the right, green dots that are hollow represent canal origins or outputs (offtakes) while full green dots junctions between canals.*

Sobek's core canal features are slopes, cross-sections, and bed roughness.

- Slopes in the Maltai and Regional system's main stretches are identical to Table 1, while Faida has a more detailed slope profile near its offtakes with a mean of 0,77 m/Km.

- Cross-section types used for the Regional system are roughly of trapezoidal shape, while three variations of their bottom width and maximum water depth: (4,8 X 1,6), (6 X 1,6), (14,5 X 2,5) in meters. Local system's cross-sections are based on the three discovered in the Faida canal with (3,8 X 0,5), (4,2 X 0,5), (3,3 X 0,5) in meters. Regarding offtakes two choices were simulated 1- and 2-meter bottom widths in a rectangular shape, while water depths of 1 and 0,5 m for Regional and Local systems.

- Roughness of bed material is classified according to the data provided by the LoNAP team, and quantified consulting (Arcement & Schneider, 1989; Dr. Xing Fang, Department of Civil Engineering, 2000). Faida is cut through natural bedrock, while Maltai upper region is considered as earthwork. The Regional system is mostly classified as earthworks, with canalized River section for Uskof lower, Khosr tributary and Khosr thin strip. Additionally, Bandawai upper and the upper part of the Khinis reaches are considered as cut through natural bedrock. Lastly both system's offtakes are assumed as earthworks.

Scenarios are produced based on three water inflow and control choices and two offtake widths mentioned above. Inflow is defined as Wet-Reference-Dry, while control Absent-Maximum-Limited summing up to 14 scenarios for both offtake widths.

Control is enforced through operating gates positioned a few meters in secondary canals, while weirs are placed downstream the junction between offtake-main reach, at about 20 m. *Maximum control* refers to a weir placed downstream each offtake (junction), while *Absent* has no form of control. For *Limited control*, offtakes further than 5 Km form a (Archeologically identified) settlement do not receive a weir aiding their access towards more water.

Wet inflow conditions are used to calibrate under Absent control, while Reference serves this role for the remaining two control alternatives. Therefore, response of the systems is evaluated on Reference and Dry inflow under Absent control and Dry for Maximum-Limited control. Summary of both systems inflows are shown in Table 3.

The evaluation takes place by processing the modelled flow towards offtake destination within a specified canal stretch, which is converted in a percentage of the required delivery through the available time to Irrigate. Lastly these percentage coverages for Irrigation schedules are reinput to AquaCrop resulting in dry harvest yield estimates under 14 hydraulic scenarios and 10 fields near 10 defined canal reaches (Figure 3).

Concluding, a simple evaluation of transport capacity is made through a weight balance of a loaded raft against displaced water (utilizing water density = 1000 kg/m^3). Assuming a raft with width, length, and height of 3 X 10 X 0,5 meters, with a loaded raft's total weight of 9 tons resulting in 0,3 m of raft submerged in water. Also adding a 0,1 m safety water depth leaves us with a 0,4 m water depth required for navigation.

Table 3 Summary of Inflows per System, Control and Offtake width scenarios.

	Control		**Absent**		**Heavy**		**Limited**	
Offtake width	***System***	*Input flow Wet year*	*Reference Input flow*	*Input flow Dry year*	*Reference Input flow*	*Input flow Dry year*	*Reference Input flow*	*Input flow Dry year*
1m	*Regional*	*44.01*	*22.005*	*11.0025*	*18.05*	*9.025*	*20.755*	*10.3775*
	Local	*5.45*	*2.725*	*1.3625*	*2.6*	*1.3*	*2.6*	*1.3*
2 m	*Regional*	*41.9*	*20.95*	*10.475*	*17.75*	*8.875*	*20*	*10*
	Local	*5.3*	*2.65*	*1.325*	*2.65*	*1.325*	*2.65*	*1.325*

Table 4 Defined Canal stretches along with their total offtakes modelled, offtakes added and Irrigable hectares.

Canals	**Offtakes**	**Offtakes added**	**Irrigable hectares**
Maltai_upper	4	3	1495
Faida	4	0	1183
Bandawai_upper	1	0	90.86
Bandawai_up_thin_strip	1	1	187
Bandawai_mid	1	1	376
Uskof_upper	1	1	392
Uskof_lower	1	1	393
Khinis	3	3	549
Jerwan	16	0	10430
Koshr_tributary	3	3	675
Kisiri_Nineveh	3	0	5264
Khosr_thin_strip	2	2	316
Maltai_low	1	1	160
Badreh-Jerahiyeh	7	7	5011
Regional	39	19	23683.86
Local	9	4	2838

3: RESULTS

REFERENCE YIELDS FROM AQUACROP

AquaCrop initial results of dry harvest yield in Kg per hectare for Nineveh, Navkur and Faida across both growing seasons and years, are shown in Table 5. Its two last columns depict yield when applying delivery amounts deemed possible through Sobek, for AquaCrop's defined Irrigation Schedules (for each field and season). Resulting in less yield (ranging from 90-75 % of the maximum yield) even when coverage is met, leading to differences in dry yield per hectare ranging from 2- 22 Kg/ha for Spring and Autumn, respectively. This occurs because of Nineveh's Wet/Reference and Dry year (in all fields) requiring the first irrigation event's completion within one day. This is not possible 1 day is lower than Table 2 shortest Available days to irrigate for all fields and ends up causing the discrepancy observed in the last two columns compared to ideal 30 mm Events.

Table 5 Dry Harvest yield presented for four water delivery choices: Rainfed, Net requirement, ideal 30 mm per event and 100% coverage applied to Irrigation Schedules.

Modelled yield (kg/ha)		**Wet year**			**Dry year**			**Irrigation Schedule 100%**	
	Irrigation Delivery	***30 (mm) ideal Events***	***Rainfed***	***Net Requirement***	***30 (mm) ideal Events***	***Rainfed***	***Net Requirement***	***Wet***	***Dry***
Nineveh fields	**Spring**	203	146	207	203	0	203	203	203
	Autumn	355	0	358	366	0	367	336	344
Navkur fields	**Spring**	218	203	219	216	0	216	218	216
	Autumn	350	354	364	367	0	367	350	345
Faida fields	**Spring**	218	192	219	218	0	219	218	225
	Autumn	366	346	377	336	0	376	366	321

COVERAGE PERCENTAGES

Results of Coverage percentages for areas with the more interesting bar charts will be displayed through Figures 4-7, with their differences described below for each area, while the remaining figures are shown in the ANNEX. Figure's legends indicate the ***Absent, Maximum*** and ***Limited*** control scenarios as ***A, B*** and ***C***, presenting Reference (only for scenario ***A***), Dry years and Spring-Autumn seasons for each of them. ***B*** and ***C*** Reference seasons are met (calibrated) with at least 100% coverage and therefore not displayed, the same occurs for ***A*** Wet inflow seasons.

Local systems

These systems include the Maltai and Faida canals with the prior split in two areas upper and lower (Figures 1 and 2 in ANNEX).

*Maltai upper **A** Reference (Ref) Spring and Autumn* coverages are about 50 and 80%, and are roughly equal between the 1 and 2 m offtake widths scenarios. During Dry years, ***B*** and ***C*** scenarios dominate, reaching 45%, while ***A*** barely surpasses 10%.

Faida coverages follow a remarkably similar pattern as Maltai upper, with slightly higher coverages in Dry year seasons under ***A, B*** and ***C*** control scenarios. In ***A*** *Ref* Autumn, coverage surpasses 100%, while in Spring an increase of 12% compared to Maltai upper is observed. Differences for the 2 m offtake widths run are a decrease in **A** *Ref* seasons by around 12%, a drop in the ***A*** *Dry seasons* of 5%, and a rather high rise to 98% coverage in ***C*** *Dry* seasons.

Maltai lower coverage is met under all scenarios, except *Dry* ***A*** seasons, while a 10% increase in them is observed for the 2 m scenario.

Regional system

The ***Khinis until Khosr*** area (Figures 4 and 5) consists of the Khinis, Jerwan, and Badreh-Jerahiyah stretches and the Khosr tributary draining in the Khosr river. All areas have their ***A*** *Ref* Autumn coverage met in both 1 and 2 m widths situations.

Coverage for *Khinis* ***A*** *Ref* Spring is over 100% for 1 m offtakes, and drops to 65% for 2 m offtake widths. 1 m ***A*** *Dry year* seasons have slightly higher (4-7%) coverage than ***B, C*** scenarios, while for 2 m offtakes, this effect strengthens, reaching 16-18% higher values for ***A***.

Jerwan's ***A*** *Ref* Spring coverage remains at 72% for 1 and 2 m widths. Noteworthy is that Dry year seasons ***B, C*** control scenarios provide almost double coverage compared to **A** in both 1 and 2 m offtake width alternatives. Dry year differences between 1-2 m widths for each control scenario are negligible, as they are around 1-2%.

Khosr tributary's ***A*** *Ref* Spring coverage follows the Autumn pattern, surpassing 100% for both 1 and 2 m widths. ***A*** Dry Spring-Autumn coverage is slightly higher amongst control choices in both width scenarios, with a 6-7% increase observed for 2 m widths. Dry Autumn coverage is slightly higher (6%) compared to Spring under ***B, C*** scenarios for both width options, while ***B, C*** differences between widths are minimal at 2-3%.

The *Badreh-Jerahiyah* area ***A*** *Ref* Spring coverage percentage is 75%, with a 2% increase for 2 m width, while the ***A*** scenario performs the worst under Dry year seasons for both width alternatives. Dry year ***B*** and ***C*** are roughly equal in the 1 m run, but for 2 m, ***C*** slightly surpasses ***B*** by 5 and 6% for Spring-Autumn, respectively.

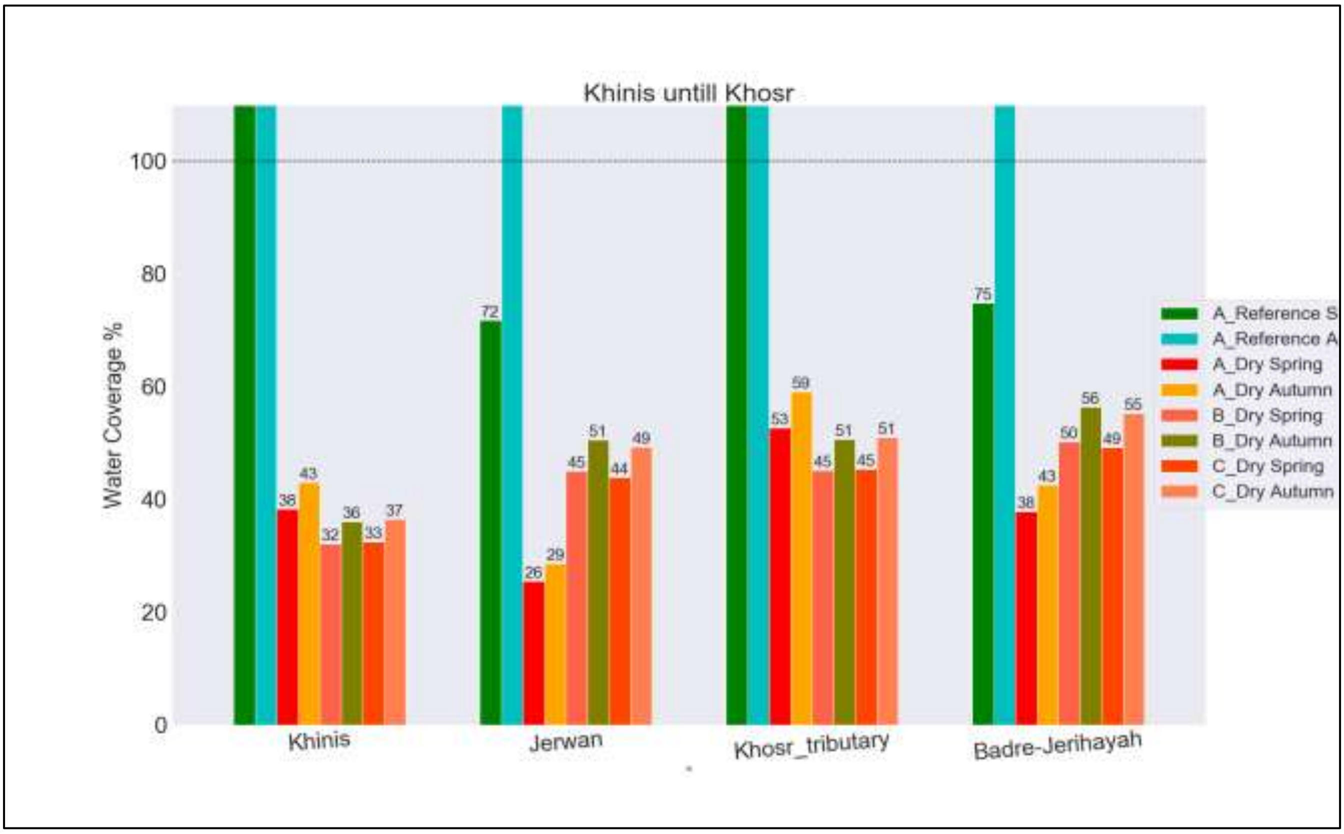

Figure 4 Sobek 1m offtake width water coverage % results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact value.

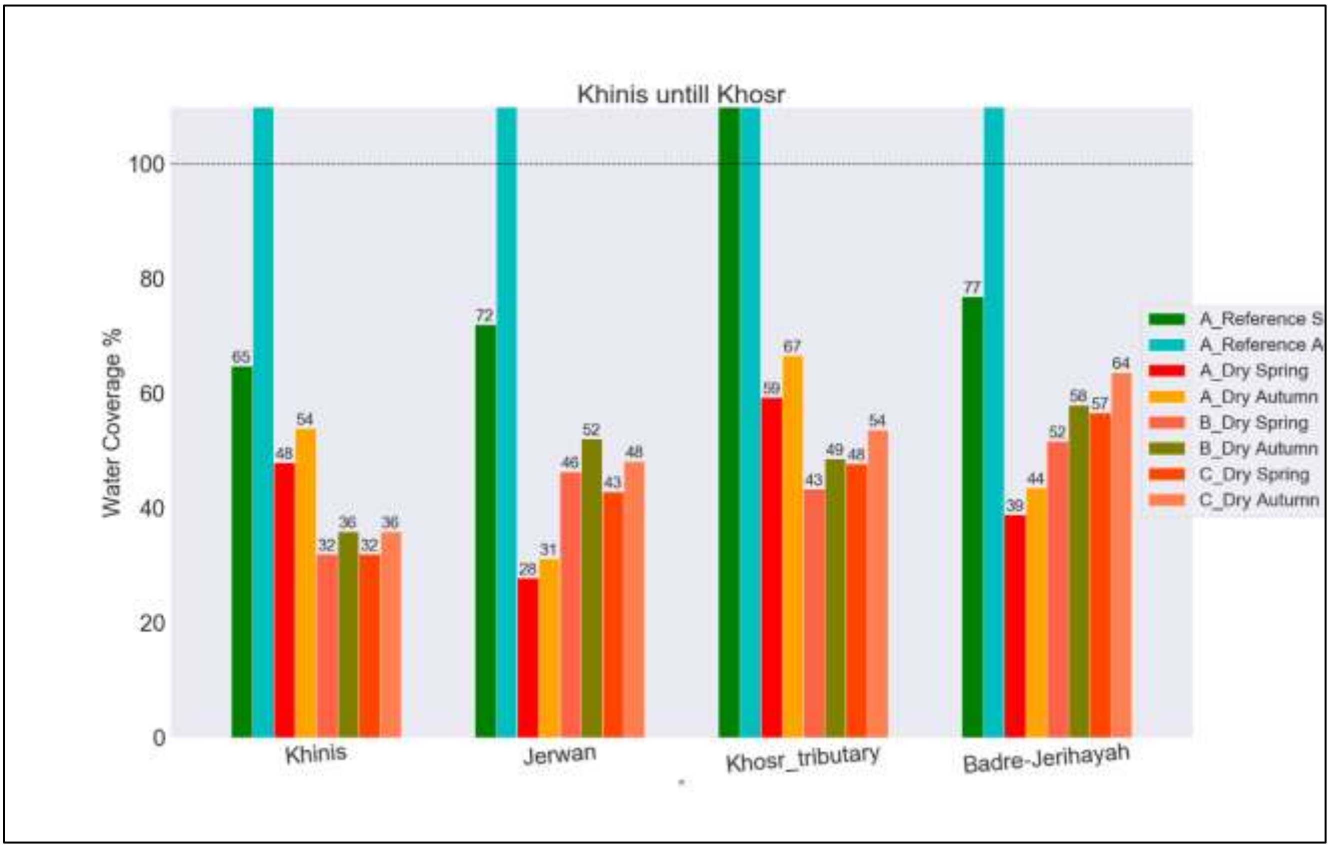

Figure 5 Sobek 2m offtake width water coverage % results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact value.

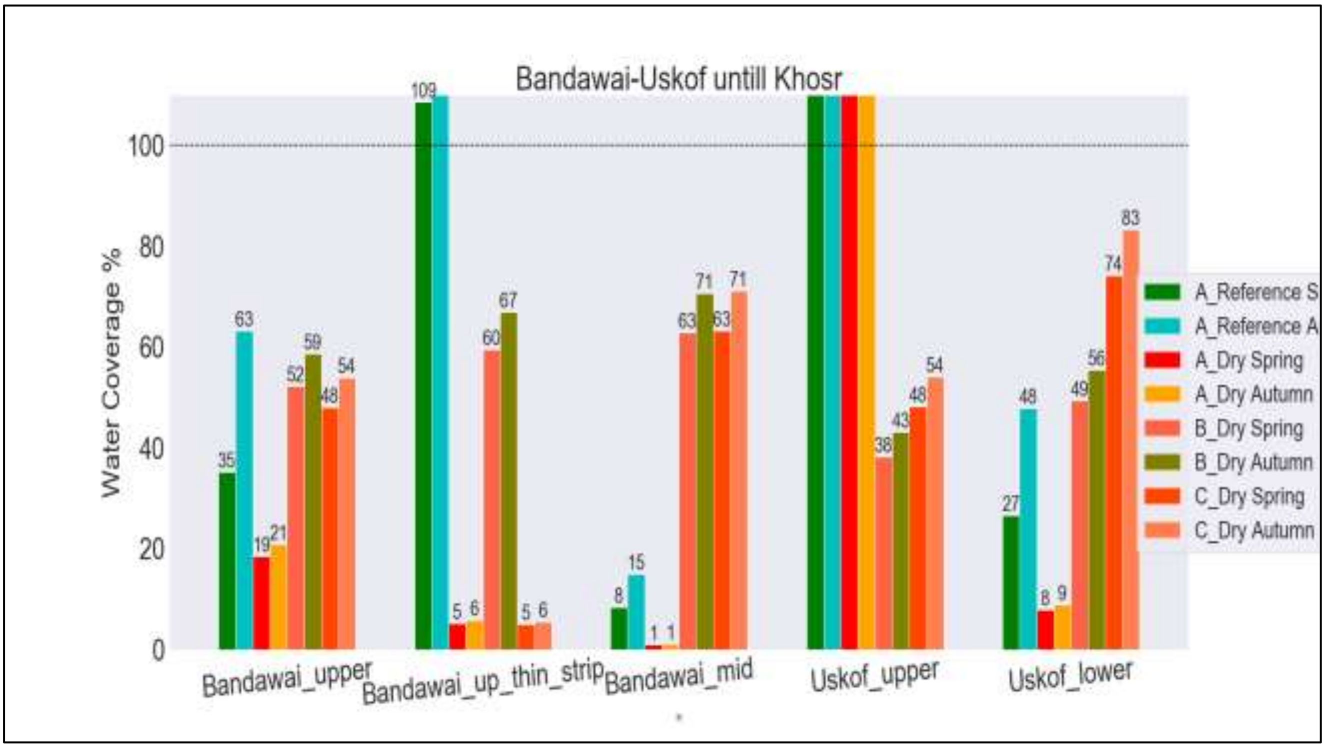

Figure 6 2m Sobek water coverage % results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C(Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

The ***Bandawai-Uskof until Khosr*** stretch (Figures 6 and 7) includes the Bandawai and Uskof canals, with the latter ultimately adding its flow to the Khosr river.

Bandawai upper's A Reference season coverage are fully met with 1 m widths, but suffer greatly in 2 m, dropping to 35 and 63% for Spring and Autumn, respectively. ***A*** Dry Spring-Autumn coverage is about half of ***B, C*** scenarios for both widths, while for ***B, C*** in 2 m, a decrease of around 10% is observed compared to 1 m.

Coverages for the *Bandawai thin strip's* ***A*** Ref seasons are met in both width scenarios, while ***C*** and ***A*** Dry season have extremely low coverage percentages, dropping about 6-7% for 2 m. ***B*** Dry year coverages marginally increase for 2 m.

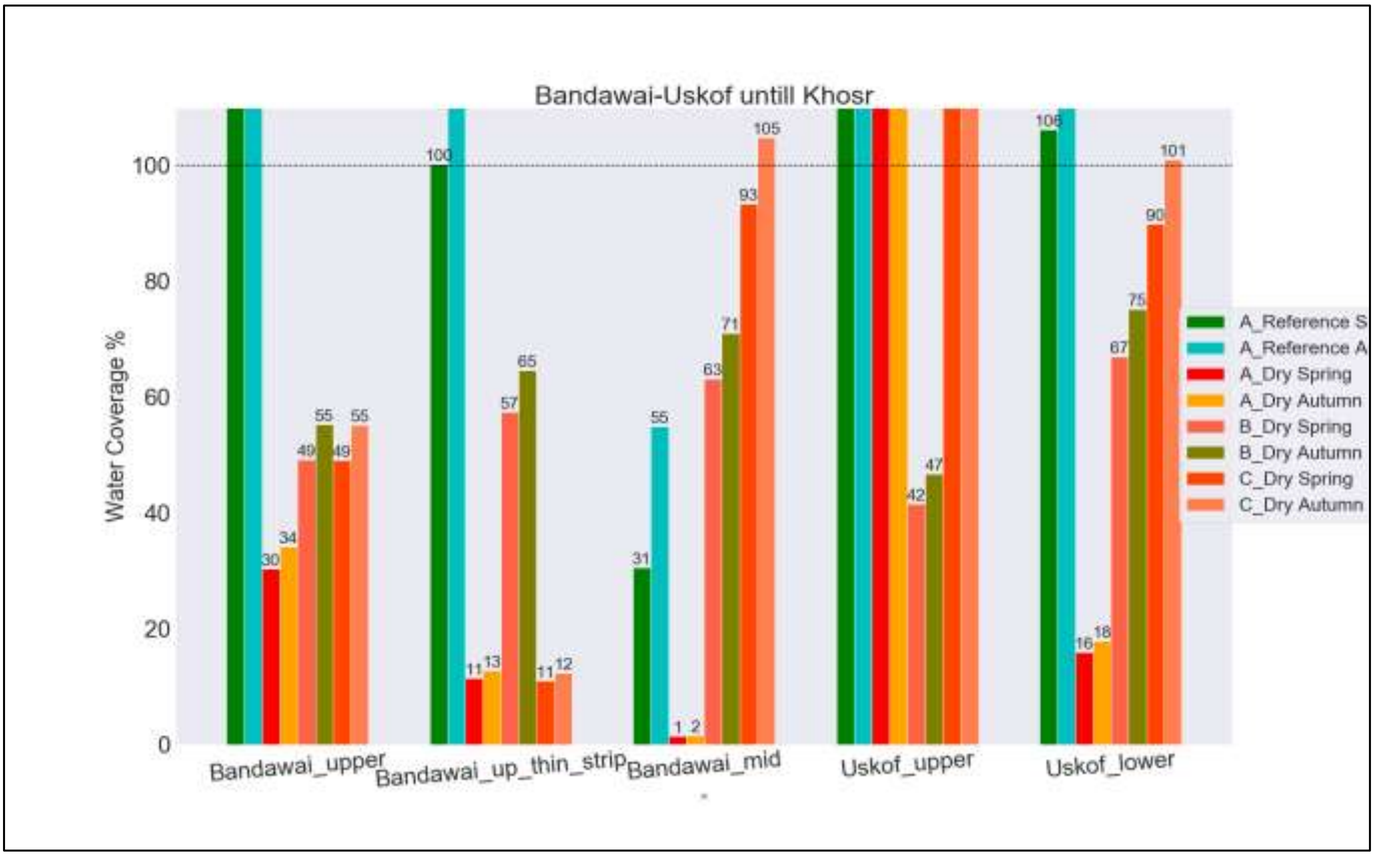

Figure 7 Sobek 1m offtake width water coverage % results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact value.

The *Bandawai middle* stretch struggles during 1 m ***A*** *Re*f seasons, barely passing 50% in Autumn, while for 2 m, coverages drop down to 8 and 15% for Spring-Autumn. A Dry year coverage is virtually non-existent for both widths, ranging around 1-2%. 1 m ***C*** Dry year runs outperform ***B*** with around 30%, while for 2 m widths they are identical at 63-71%.

The *Uskof upper* area modelled with 1 m widths exhibits an interesting outcome: all but ***B*** scenario Dry year coverages are met. However, for 2 m, the ***C*** and ***B*** Dry seasons are largely unmet, with the prior dropping to 48-54% (Spring-Autumn) and latter to 38-43%.

The *Uskof lower* stretch has the Ref seasons coverages met with a 1 m width, but struggles to 30 and 50% during 2 m. ***A*** Dry season coverage are quite low and drop under 10% for 2 m widths. 1 m ***C*** outperforms ***B*** by 90-67% to 100-75% during Dry year Spring-Autumn, while for 2 m, **C** is still higher – although both control scenarios see a decrease of 10-20% for their coverage.

The ***Khosr until Nineveh*** (Figures 3 and 4 of ANNEX) stretch consists of the Khosr thin strip plus the Kisiri and Nineveh fields, which for A control scenarios have their coverages met under both Ref-Dry year and 1,2 m widths.

The *Khosr thin strip* modelled with 1 m widths presents its lowest coverage at 71% for ***B*** Dry Spring, while for 2 m widths, ***C*** Dry Spring shows 71%. The Autumn Dry year coverages are practically met for both widths.

The *Kisiri-Nineveh* area shows the lowest coverage for ***B*** Dry Spring for both width choices with 64 and 62% respectively, while the other coverages are above 85%, ensuring a reasonable harvest.

DRY YIELD HARVEST

Intriguing results are displayed in Figures 8-13, with comments on each area's harvests and differences with the 2 m width runs. Similar to water coverages, harvests of ***B*** and ***C*** Ref year seasons are considered optimal, similar to ***A*** Wet inflow seasons.

Local systems (Figures 8 and 9)

The *Maltai upper* 1 m has ***A*** Ref year harvests are equal or roughly equal to the maximum for Spring and Autumn, while in Dry years, there is no harvest. ***C*** Dry year harvests are marginally better than ***B***. In 2 m runs, ***A*** Ref Autumn show maximum harvests, while ***B, C*** are marginally higher.

In ***A*** Ref years, *Faida* reaches optimal yields for both widths, while both widths Dry years are abysmally low (0-36 kg/ha). ***B, C*** Dry years show roughly equal yields, while 2 m offtake width ***C*** Dry Spring yield is almost double compared to its 1m counterpart.

Maltai low's ***A*** Ref Autumn reaches optimal yields, while Spring trails slightly. ***A*** Dry Spring has extremely low yields for both width scenarios. A low 14 Kg/ha increase is observed for ***A*** Dry Autumn when comparing 1 and 2 m widths. Both ***B*** and ***C*** Dry Spring-Autumn scenarios have maximum harvests in Kg/ha values.

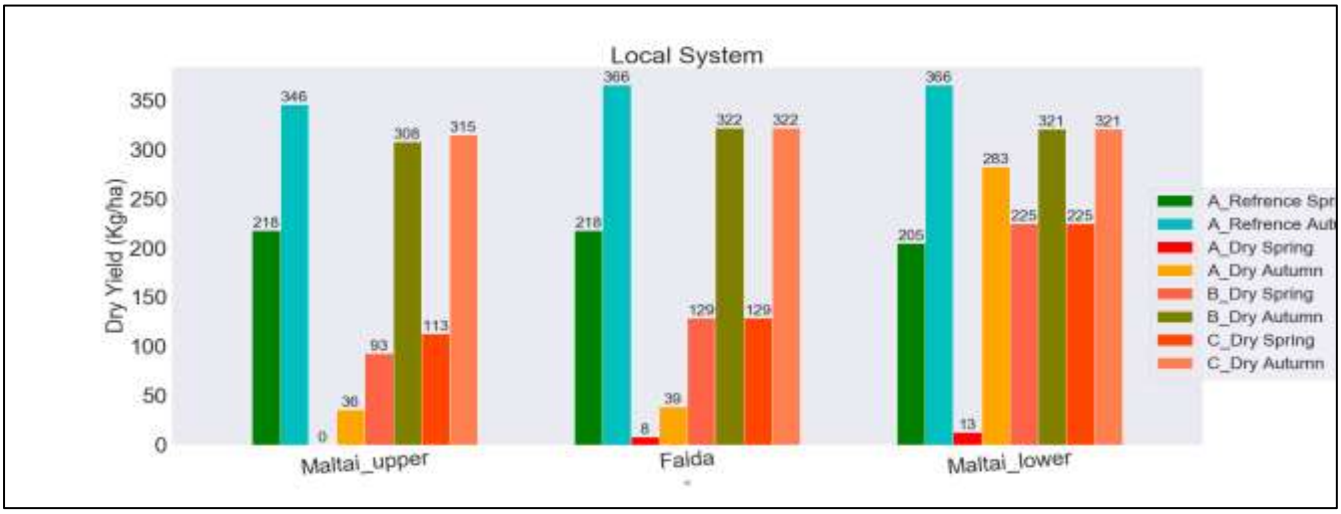

Figure 8 AquaCrop 1m offtake width dry harvest yield results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

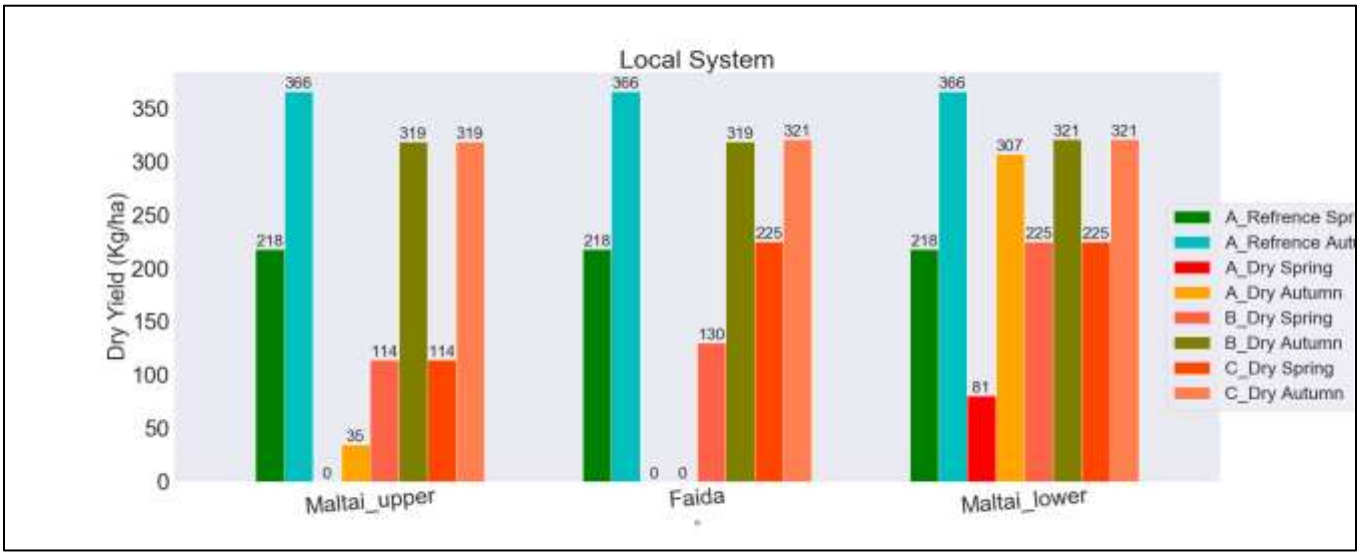

Figure 9 AquaCrop dry harvest yield results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

Khinis until Khosr (Figures 10 and 11)

Khinis 1 m ***A*** Ref seasons are at optimal yield rates, while ***A*** Dry year harvests are quite near. Spring is trailing by 19 and Autumn by 10 Kg/ha. Spring yields suffer in control scenarios ***B*** and ***C***, compared to ***A***, with 45 kg/ha, but less so in Autumn with 14 Kg/ha. For 2 m widths, ***A*** Dry year yields increase slightly (6 and 9 Kg/ha Spring-

Autumn), while ***B*** surpasses ***C*** by 39 Kg/ha during Spring, with Autumn yields remaining unaffected.

Jerwan obtains maximum yields in both 1 and 2 m width settings for ***A*** Ref seasons. ***A*** Dry year Spring yields trail ***B*** and ***C*** by around 82 Kg/ha using 1m widths, and around 77 Kg/ha with 2 m. Dry year Autumn sees a slight (~ 3 Kg/ha) increase for ***B*** for 2 m, with ***C*** and ***A*** remaining roughly equal.

Khosr tributary ***A*** Ref seasons reach maximum harvest per hectare. Dry year ***A*** Spring-Autumn practically reach optimal values in both 1 and 2 m widths too. For both offtake widths ***B, C*** Dry Autumn seasons lack just 6 kg/ha from the optimal yield, while during Spring they are both around 13-17 Kg/ha lower than ***A.*** Differences between 1 and 2 m scenarios are minimal.

Badreh-Jerahiyah A Ref seasons produce maximum yields in Kg/ha, while A Dry year Spring-Autumn yields trail with 13-14 Kg/ha respectively under 1 m offtake widths. For 2 m widths, only ***C*** Dry Autumn yields drop with 6 Kg/ha.

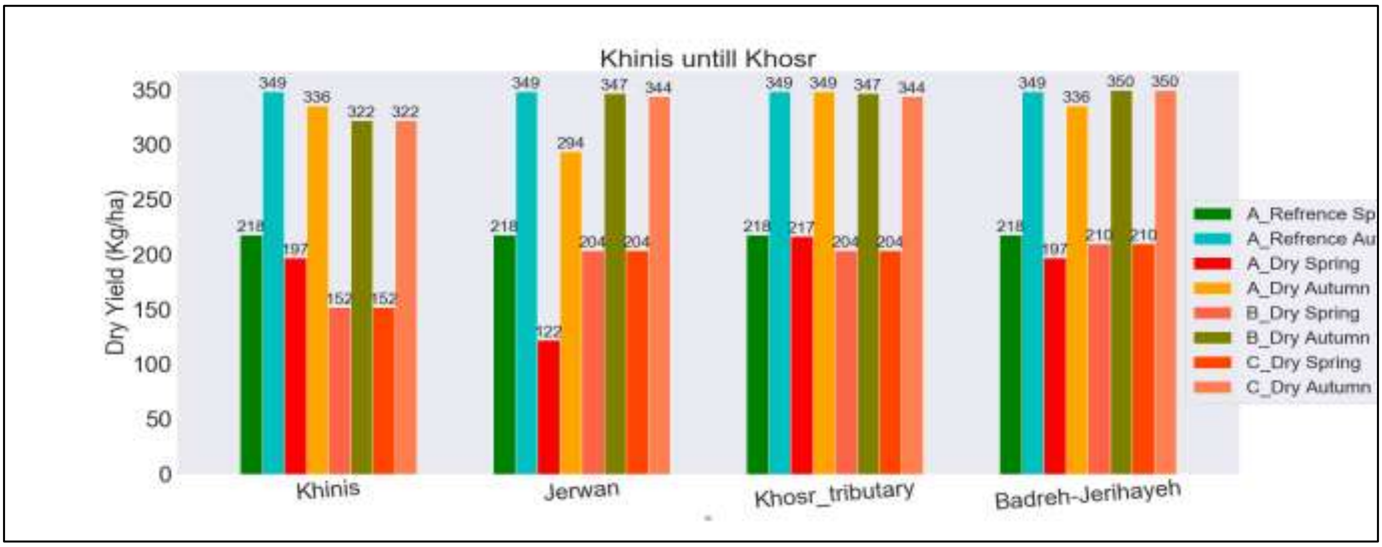

Figure 10 AquaCrop 1m offtake width dry harvest yield results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

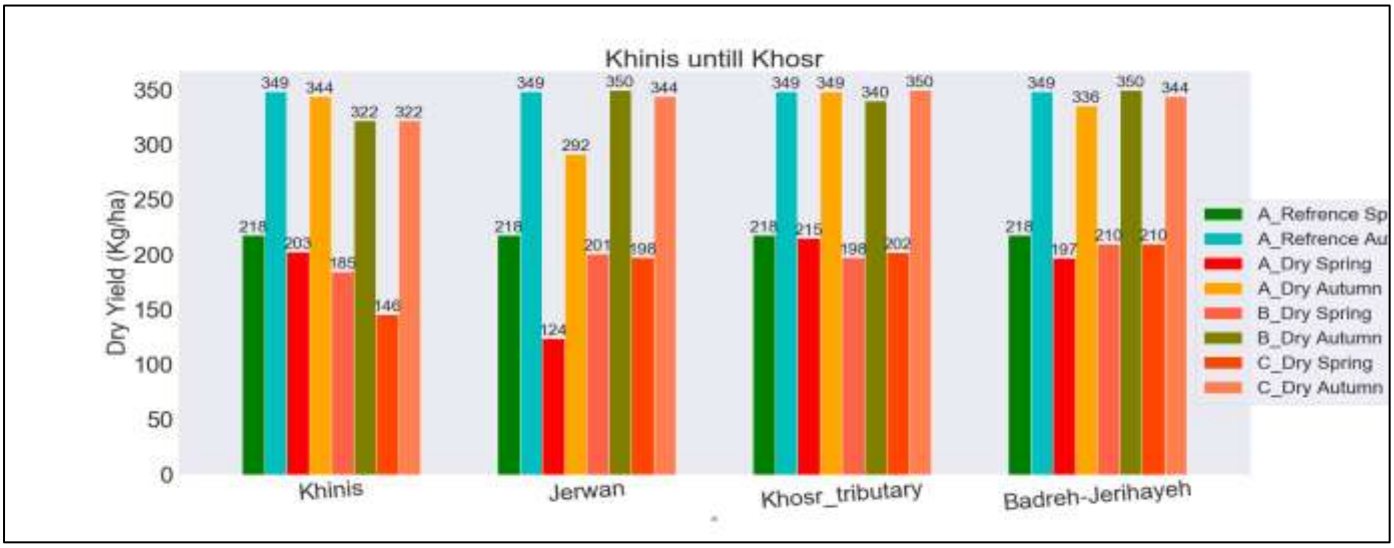

Figure 11 2m AquaCrop dry harvest yield results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

Bandawai-Uskof until Khosr (Figures 12 and 13)

For 1 m widths, ***A*** Ref seasons reach maximum harvests for all areas, while for 2 m, Bandawai mid Spring yields drop with 10 Kg/ha, with the rest remaining at maximum.

Banda upper's Dry year ***A*** trails ***B*** and ***C*** by around 68 Kg/ha during Spring, while in Autumn this is 32 Kg/ha as shown in Figure 11. For 2 m widths, ***A*** Dry years drop to 50 and 91 Kg/ha (Spring-Autumn), where ***B*** Dry seasons reach maximum harvests, followed with marginal or no changes in ***C*** Dry Autumn-Spring.

Bandawai thin strip yields, as observed in Figure 11, are only in the ***B*** Dry season near maximum harvest, while the rest (***A, C***) show terrible yields ranging from 13 to 22 Kg/ha. For 2 m scenarios, the ***A*** and ***C*** yields drop to zero, as plants die before harvest.

Both *Bandawai middle* width scenarios produce no harvest during ***A*** Dry year, while for 1 m, ***B*** and ***C*** are nearly optimal for both seasons. Using 2 m widths results in a relatively large drop during ***B*** Dry Spring with 22 Kg/ha, a marginal drop in ***B*** Dry Autumn and a rise for ***C*** Dry Autumn.

Uskof upper's 1 m width ***A, C*** Dry Spring-Autumn yields are near the maximum, while ***B*** shows a 10 Kg/ha drop in Spring and 5 Kg/ha in Autumn. The 2 m results slightly change, like 4 Kg/ha in Dry Autumn and a 12 Kg/ha drop in ***C*** Dry Spring.

The *Uskof low* ***A*** control scenario in the Dry year results in almost non-existent yields for both 1 and 2 m widths, with the latter shown a small increase. ***B, C*** Dry seasons are practically at maximum, while for 2 m widths a small drop is observed in ***B*** Dry Spring of about 7 Kg/ha.

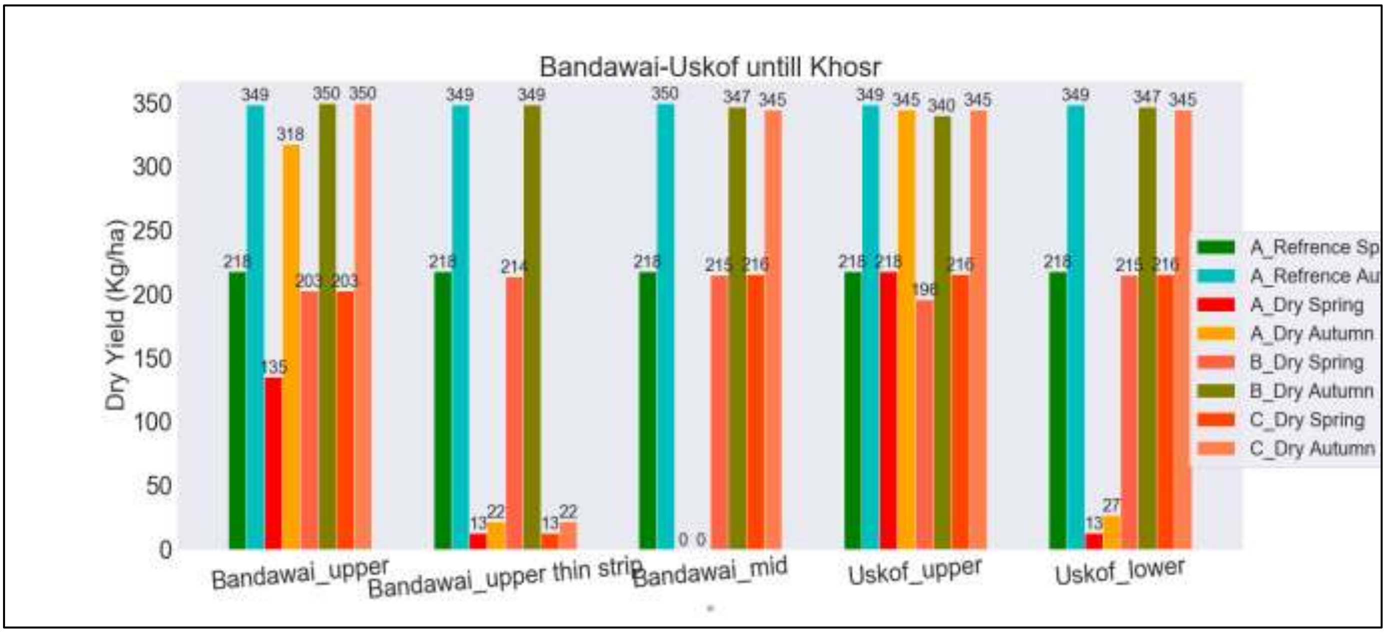

Figure 12 AquaCrop 1m offtake width dry harvest yield results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

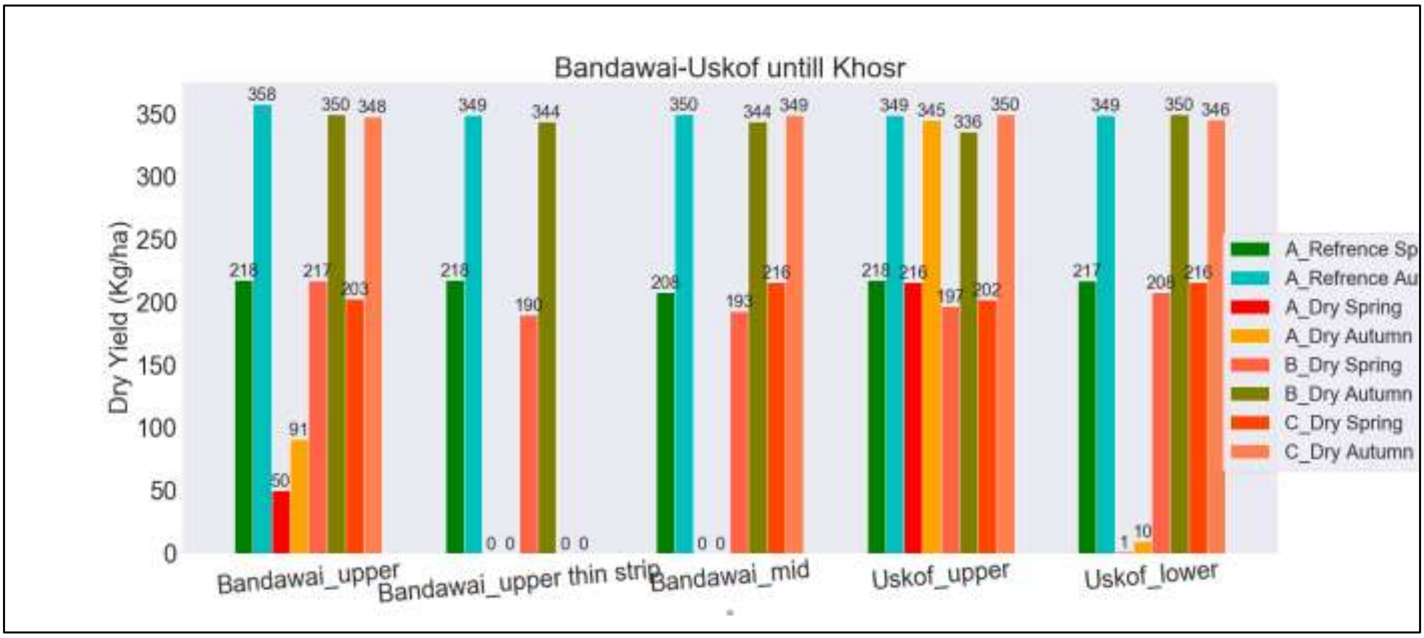

Figure 13 2m AquaCrop dry harvest yield results per canal reach and, Control scenarios A (Reference-Dry, Spring-Autumn), B (Dry, Spring-Autumn) and C (Dry, Spring-Autumn) indicated on the x axis, while numbers on top of the bars indicate the exact values.

Khosr until Nineveh

The *Khosr thin strip* scenarios produce harvests extremely close to optimal under Ref-Dry years and ***A, B, C*** control scenarios as shown in Figures 6, 7 of the ANNEX. Differences between 1 and 2 m widths are almost absent.

Kisiri-Nineveh features an identical yield pattern with the Khosr thin strip, except for ***B*** Dry Spring, which is 10-12 Kg/ha lower compared to the other scenarios under both 1and 2 m widths.

TOTAL MASS IN KILO TONS OF HARVEST

For each system, under Reference-Dry years, and for all three control scenarios ***A, B*** and ***C***, the total dry yield for the irrigated areas is presented in Tables 6 and 7. These tables are explained to expose percentage gains/drawbacks in yields between offtake widths (Table 6) and control scenarios (Table 7).

Table 6 Dry yield in kilo tons for 1 and 2 m offtake widths, Spring-Autumn under Reference, and Dry inflow conditions, and percent differences between 1 and 2 m widths.

	Offtak Widths	1m		2m		1 vs 2 m	%
	System	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*
Absent Weirs	***A_Reference Spring Yield***	1.82	37.79	1.86	37.59	2.2	0.53
	A_Reference Autumn Yield	3.06	60.63	3.12	60.8	1.96	0.28
	A_Dry Spring Yield	0.06	22.4	0.23	20.48	283.33	8.57
	A_Dry Autumn Yield	1.02	40.54	0.97	35.83	4.9	11.62
Maximum Weirs	***B_Dry Spring Yield***	1.27	35.01	1.33	34.75	4.72	0.74
	B_Dry Autumn Yield	2.7	59.94	2.72	59.71	0.74	0.38
Limited Weirs	***C_Dry Spring Yield***	1.33	31.85	1.6	31.1	20.3	2.35
	C_Dry Autumn Yield	2.72	53.93	2.73	53.68	0.37	0.46

The *Regional* system is mostly unaffected by a change in offtake widths, as seen in Table 6, with just a small increase observed for 1 m width **Absent** control's Dry year harvests by 8,6% and 11,6% during Spring-Autumn, respectively.

The *Local* systems also experience minor changes in general, except for ***A*** and ***C*** Dry Spring runs, that show a large increase when 2 m widths are used, almost 300% and 20 % for each. These results suggest that offtake widths primarily influence scenar-ios with **Absent** and (secondarily) **Limited** control.

As Table 7 shows, Reference year seasons show practically no influence of control over final harvest amounts for both systems. During Dry Spring, ***B-C*** scenarios, crop production differences are small for *Regional* around 9-10% favoring ***B*** (1-2 m widths). For the same scenarios, *Local* shows a 20% increase for ***C*** with 2 m widths and marginal changes for 1 m width. Likewise, Dry Autumn *Regional* Maximum con-trol shows the same 10% increase, while the *Local* systems remain practically the same (less than 1% changes).

When comparing ***A*** Dry year seasons with ***B***, an extreme rise in harvest is observed for the *Local* system, ranging from 167 to 2015% and 180 to 478% for Spring-Autumn and 1,2 m widths. The *Regional* system also gains greatly from applying Maximum control during Dry seasons, with Spring-Autumn ranging from 48-56% and 66-69% for 1-2 m widths, respectively.

Mild contrasts between control scenarios provide evidence that the Reference year is roughly uninfluenced by control. During Dry year seasons, it is the **Maximum** control that favors production immensely for the *Local* system and quite *largely* for the Regional (by almost 70%).

Table 7 Dry yield in kilo tons for 1 and 2 m offtake widths, Spring-Autumn under Reference, and Dry inflow conditions, and percent differences between Control scenarios A-(B/C), A-B and B-C.

Offtak Widths	1m		2m	
Control/System	*Local*	*Regional*	*Local*	*Regional*
A_Reference Spring Yield	1.82	37.79	1.86	37.59
A_Reference Autumn Yield	3.06	60.63	3.12	60.8
A_Dry Spring Yield	0.06	22.4	0.23	20.48
A_Dry Autumn Yield	1.02	40.54	0.97	35.83
B_Dry Spring Yield	1.27	35.01	1.33	34.75
B_Dry Autumn Yield	2.7	59.94	2.72	59.71
C_Dry Spring Yield	1.33	31.85	1.6	31.1
C_Dry Autumn Yield	2.72	53.93	2.73	53.68
Percent Differences				
A vs B-C Reference Spring	1.98	0.01	0.21	0.52
A vs B-C Reference Autumn	1.83	0.24	0.12	0.04
B vs C Dry Spring	4.72	9.03	20.3	10.5
B vs C Dry Autumn	0.74	10.03	0.37	10.1
A-B Dry Spring	2016.7	56.29	478.26	69.68
A-B Dry Autumn	164.71	47.85	180.41	66.65

4: DISCUSSION

In this paragraph the results that were presented above in section 3 will be compared, to see to what extent some general observations can be drawn. First, several observations concerning yields, distribution patterns and control settings are made –

as these appear as closely related. Then, in a shorter paragraph, some initial observations on navigation options are made. After observing some limitations of the current study, options for further studies are identified.

WATER DISTRIBUTION AND CONTROL

A first interesting modelling outcome are the harvest differences of ***rainfed versus irrigated*** fields. Dry years require irrigation for both Spring and Autumn for all areas to produce harvest strongly implying that irrigation would be an incredibly wise choice for supporting Dry years for all areas. Irrigation would boost Faida's production even in wetter years. During Wet/Reference years, the Faida fields benefit by around 20-26 Kg/ha (Autumn-Spring) from irrigation. The differences that appear indicate the Nineveh area's serious need of irrigation in both Reference and Dry seasons. The Navkur area, however, is the only area that appears relatively unaffected by seasonal effects, with Spring favoring irrigation by 15 and Autumn rain-fed by 4 Kg/ha.

Another general issue that can be observed are distribution differences between ***upstream and downstream*** areas. Take the stretch from Khinis until the Khosr river, with Khinis presenting its maximum Dry year yields for *Absent* control. Jerwan, however, lying just downstream, shows its best harvest performance for *Maximum* and *Limited* control scenarios. This modelling result is probably at least partly due to the Khinis offtakes being spread out (added to service fields), while Jerwan's archeologically identified ones are heavily clustered (the Mubarak complex, pointing towards control needed to ensure sufficient water allocation). Secondly, because the Khinis canal has a water accessibility (location) advantage, plus the largest inflowing basin draining in it, it will have higher flow inputs.

The Mubarak complex consists of a split into two routes both containing offtakes, that rejoin the main course further downstream. An interesting observation is that forcing flow towards the secondary route requires a weir in its primary course to manage flows of Dry or dryer than Wet years. Khosr's tributary reach is marginally affected by different control strategies, largely due to the Badreh-Jerahiyah stretch draining in it. Badreh-Jerahiyah consists of three isolated canals with their harvests suffering slightly during Dry year ***A*** and showing little to marginal improvement by applying control.

To continue on the upstream-downstream effects, ***control settings*** are important, as for example observed in the Bandawai upper region. The Bandawai thin strip performs abysmally in *A* and *C* Dry years, as for both the main course weir enabling greater water extraction capabilities is removed, downgrading it. The Bandawai middle stretch shows zero harvest under Dry year *Absent* control, as it's located on one side of a split (in the main route) with its lower slope attracting less flow- unfortunately for it. In scenarios *B* and *C,* a weir is used on the secondary route to push flow towards the "main route", along with its typical weir (20 m after the offtake-main reach junction). This suggests that a weir (or a gated offtake) on the favored (secondary) course's reach, dictating the flow distribution, would be highly beneficial to the water managers of Assyrian times. Uskof upper is situated on the favored route of the former "split" and hence shows much less change in terms of control impacting harvests. Uskof lower under *A* Dry year seasons experiences the consequences of being the furthest downstream offtake in the stretch by receiving extremely low flows, pointing out the gains in harvest security when installing weirs. Noteworthy is that up until this point the Bandawai-Uskof canals are mainly thought as conveying infrastructure, while irrigation is thought as a possibility. This thesis assumed offtakes servicing the cultivable land near the canals, to estimate the regions harvest capabilities.

The Khosr thin strip displays no variance in harvested amounts per hectare under the three control scenarios. The Kisiri-Nineveh fields are similar to Khosr's thin strip, as they appear to be largely uninfluenced by control – only the *B* Dry Spring chips on the optimal kg/ha.

Both Local system canals suggest being sensitive to control settings, except for the lower end of Maltai exhibiting relatively decent A Dry Spring and high Autumn yields in kg/ha. Regarding the upper part of Maltai, its difficulty to produce yield without control is based on its immensely high slope (4 m/Km), not allowing sufficient water depths for irrigation unless weirs are in place. For Faida, a similar situation occurs, even though a much lower slope is identified (1.6-0.77 m/Km). Here, due to offtakes being clustered and Dry year flow through the main course being very low, realizing sufficient water depth for irrigation requires at least some weirs.

In a more general outlook, an ***inversely proportional relation*** between offtake width and control applied in terms of effect on yields is observed in both local and regional systems. The Regional system shows practically no harvest change from 1 to 2 m widths, except for *Absent* control. The Local has a huge difference in *A* Dry Spring, but this diminishes greatly when increasing control, further supporting the relation stated above.

For Reference years or wetter, control does generally not improve yields, although irrigation is highly beneficial for Nineveh's fields in Spring and necessary in Autumn. In Faida's fields, a smaller but not negligible gain in Kg/ha is observed when irrigating in wet seasons, while for Navkur lands no improvement is observed.

To conclude this overview in terms of yields, during a Dry year, all areas require irrigation for the barley crop to survive and produce harvest. This is emphasized very strongly in the Local systems, where *Maximum* control application gains the system around 1250% in Spring and 170% in Autumn in terms of yields. With Limited control applied and three weirs removed, the former gain drops by a maximum of 20% in scenarios with 2m width in Spring, showing that three less weirs (with associated maintenance responsibilities) can have a non-negligible influence on barley yields. A similar pattern is observed for the Regional system with a mean across Spring, Autumn and widths adding almost a 60% surplus of harvest. When considering the system's total irrigable area, this results in around 13-19 Kilotons difference in Spring and Autumn, respectively. Two other factors strongly influencing the viability of control applications in these systems are *dry year frequency* and (daily, monthly) *inflow variability*. As noted in (Sinha et al., 2019) droughts in the region seem to appear in cycles of 2-3 consecutive years. Considering a time horizon of 10 years for this discussion will raise three estimated scenarios:

- 1 drought cycle per 10 years: planning would take place for reference-wet years favoring no control application or suggesting prediction of dry years/cycles for control enforcement. This estimation of a drought cycle commencing could take place through empirical assessments such as river or stream water depths and possibly even the visible amounts of snow in the Zagros mountains (FALES, 1989).
- Less than 1 drought cycle in 10 years: hardly any stress towards water accessibility is noticed and therefore control applications would seem unlikely.
- Multiple drought 1 cycles in 10 years would imply planning for dry years would be standard, perhaps combined with predicting wet years were control is not needed. This favors the enforcement of control over the system for proper operation.

With large inflow fluctuations, such as pulse inputs of high flow followed by multiple timestep low flows (compared to pulse inflow timestep duration), a storage-based system seems more beneficial. Storing water until irrigation is required and sustaining an intended water depth, strongly connects with the usage weirs and gates to regulate water allocation. Low inflow fluctuations would be quite like the modeled systems behavior.

A distinction between permeant and more temporary (flushable) weirs may need to be made. As implied by their names, the former will require more frequent maintenance and annual labor to sustain it but could provide higher resilience towards high flows. The latter are intended to break and "flush" downstream when high flow appear, as such their construction is cheaper maybe and less labor demanding over the longer term.

- Permanent weirs would benefit the systems more under higher (than 1 cycle in 10 years) dry year frequencies and large inflow variability conditions. This thesis used them in flow modelling, and results suggest their usefulness in dry years, although stable inflows were chosen.

- Temporary "Flushable" weirs are more convenient for 1 drought cycle occurrence in 10 years and less than one. They could be applied to mitigate losses in harvest, and once their useful period (dry) ends they self-dispose. An issue regarding this type of weir may come under large inflow fluctuations in drought year, potentially leading to failure of the weirs under "high inflows".

An important feature in building the inflow scenarios in this study was irrigable land demand. These assumptions were by default quite uncertain. One should not be misled by their labeled names ("Wet"- "Reference"- "Dry"), as the simulation period of the 7th century BCE falls with the 125 year "Assyrian Megadrought". Hence the actual Reference inflows of the era could be closer to "Dry", while "Wet" could be a rare phenomenon, changing the perspective on "controlled irrigation" and its necessity. Years with lower inflows than "Reference" gain from weirs and gates, while equal or lower than "Dry" greatly benefit or absolutely need them.

When evaluating labor (expressed in weir/gate maintenance and operation) versus benefits (harvest), the ***C*** setting for the Regional system uses 12 weirs less and requires 2 to 3 (1-2 m width) fewer gate operations, but dry yields only drop by 10% across both seasons and widths. This suggests that less or better-chosen control applications can provide almost equal harvest gains, while saving valuable resources in building materials and labor occupied for maintenance and operation. Worth mentioning is that years dryer than Reference and wetter than Dry will also benefit from control installations, as they provide greater flexibility in water allocation leading to higher reliability for harvests.

Lastly an important aspect regarding control, concerns how for irrigable areas defined the sum of all offtakes discharge in the area was used when calculating coverage percentage. In case individual offtakes require a specific discharge, the use of weirs and gates seems much more attractive and probable.

OBSERVATIONS ON NAVIGATION

Navigation capabilities depend on water depth of a given canal segment, as mentioned in the Methodology. A water depth of at least 0,4 m is assumed to be required to support the assumed raft (with 3 X 10 X 0,5 m width-length-height). In Reference years with *Absent* control, both offtake width scenarios cover this requirement, while in the Khinis area this condition is also met for *B* and *C* in 1 and 2 m runs. Jerwan drops below 0,4 m for *B* 1 m within the Mubarak complex for about 700 m during the first two days of irrigation, surpassing it shortly after that. The Khosr tributary stretch water depth is acceptable for transport with 1 m *B* and *C* scenarios, but Badreh-Jerahiyah fails the needed water depths. Bandawai and Uskof are non-navigable only for the 2 m *B* control scenario, while the Khosr-Kisiri stretch supports transport throughout all control scenarios. Dry year 2 m offtake width runs do not satisfy water depth needs for any control scenario and canal stretch, except the Khosr-Kisiri. Dry 1 m width year runs completely fail for *B*, while *C* is only met for Khosr-Kisiri. *Absent* control has satisfied transport needs for all areas, except the Badreh-Jerahiyah canals. This suggests that transport within the Regional system seems possible for Reference inflows. Contrary to Reference settings, Dry years are more susceptible to control than offtake width change, with only *A* providing navigable water depths throughout the system.

LIMITATIONS OF THIS PROJECT

Limitations of the above modelling results can be defined in the three categories *Canal, Environment* and *Social* data, that have been used (and often had to be set) to complete the flow and crop models (in Sobek and AquaCrop, respectively).

Canal cross-section, bed-roughness, slope, and offtake features are catalysts in determining the systems capabilities. With various reaches using approximations or data from other reaches (provided resemblances were reasonable), there is a clear issue of the effect that large discrepancies between modelled and actual properties may have on the segments' or systems' hydraulic behavior. As mentioned in the *Methodology*, three cross-sections are archaeologically identified for each system, while most slopes and bed-roughness values are (rough) estimations based on satellite imagery and bed material classifications. Faida is the canal described with most detail, showing a small drop in slope near offtakes, which if applied to other canals could reduce the calibrated control needs defined through the Reference year for a canal stretch or entire system. Bed roughness heavily impacts how effortlessly water flows downstream, with higher values leading to higher water depths for the same flow values – but pushing more water through the offtakes leaving less water downstream. Number and location of offtakes influence discharge amounts they need to convey, with sparsely located offtakes benefiting greatly from control, while clustered ones can cope better in the absence of canal control. The added offtakes were spread out with the idea to cover land needs, but less distance between offtakes combined with a slope reduction in the vicinity would change control requirements - especially for gates, as more meticulous operation would be necessary to service all offtakes in the vicinity.

Environmental assumptions as weather patterns, fields soil profile and runoff coefficients (determining possible inflows to canals from wadis or rivers) greatly influence AquaCrop and Sobek's results and choices. Weather patterns consist of daily precipitation, temperature, sunlight hours, and evaporation, amongst others. Noteworthy is that evaporation is neglected in Sobek. As evaporation may primarily increase inflows required, it could make sense to incorporate it. On the other hand, a higher certainty regarding inflow data would be needed first. Rain and temperature remain the most important parameters and were assumed to relate with current weather measurements (1979-2010) according to (Sinha et al., 2019). Changes in assumed timing and amount of rainfall may lead to alterations in irrigation schedule requirements, while temperatures variations can delay inhibit or even boost harvests. Soil profile information is crucial in determining how effectively water delivery (irrigation or rainfall) accommodates the field's needs. Large differences in soil profile therefore can lead to required irrigation schedule changes, as water may be drained faster or kept at the crop's reach for a longer period.

Socially defined agriculture norms/habits such as growing seasons (planting dates), sowing rates, metrological conversions (qu/iku to Kg/ha) and available labor for operation-maintenance and harvest gathering also play an important role in final harvest amounts. These parameters are deeply tied with historical and archeological findings, highly scarce for this combination of region and era, resulting in use of prior data (Middle Assyrian) with their associated uncertainties. Runoff coefficients determining possible flows in wadis, rivers, and streams, are vaguely estimated and may differ considerably, in stability and amounts. If evidence for this is provided, then a more storage-based system could become a more attractive possibility, leaving room for a more sophisticated and frequent control operation.

SUGGESTIONS FOR FURTHER STUDIES

Options for Further research is summed up in the three points below. While field surveys and further archeological data processing is still ongoing, along with many canal stretches remaining to be explored.

The LoNAP team is currently (May 2021) continuing its study and field survey (when possible due to pandemic restrictions) on the land behind Nineveh. Additional field surveys in for example the Faida canal area, where recent satellite image processing revealed 10 additional offtakes potentially existing to service the fields below, would be extremely useful to provide additional detail. Investigation of the spring near the Khinis canal origin is planned for the near future, providing a greater insight in inflow possibilities. Additional field surveys uncovering cross-sections, more detailed slopes and bed-roughness may provide alternative boundary conditions for defining potential inflows.

Concerning ways to deliver water to fields, shadufs (a water raising technique), may be taken into account. According to Bagg (2017), royal inscriptions and reliefs point out Sennacherib's interest in amongst other water lifting devices. Additionally, Yannopoulos et al. (2015) provide evidence for water raising technologies, present from the Middle Assyrian era stretching until Persian times (1200-200 BCE). Within the examples presented, the safest assumption would be the existence of the shaduf, a device based on and evolving from hand-carried buckets. These devices would provide greater flexibility (extracting water on demand), especially when irrigating thin strips along canals without extensive secondary canal networks and control applications. Navigation in dryer years may also benefit, as weirs in main routes decrease.

Different crop simulations, such as for grapes(vineyards), fruit-trees (orchards) or even rice paddies would add additional options to study how the agricultural areas could have been supported by the canals. In this thesis, a single crop barley was modelled, which is highly unlikely to be the case, as the Neo-Assyrian empire has documented wheat, flax, vineyards, orchards and even to a limited extent rice cultivation. Morandi Bonacossi (2019) stresses imperial documents mentioning the king's desire for wine, also indicated by the increase in the Iron Age archaeobotanical record of grape pips (Riehl, 2009), strengthening the argument that vineyards were cultivated during Neo-Assyrian times. Including patches of land with different crops will introduce varying irrigation schedules, a more realistic insight on water demand. These extra summer crops would also possibly require more sophisticated network planning and control approaches to satisfy multiple crop water demands, with regards for timing and amounts.

As stated above a new expedition targeted at the Khinis-Jerwan area canals is set to take place in the near future. Considering a more practical contribution to the LoNAP team's field survey and future follow-up modeling studies, this thesis will *suggest interventions* focused on refining canal -system data. Intending to achieve improved simulations of hydraulic behavior, their consequences on harvest amounts and navigation capabilities. Below 6 interventions are proposed, sorted by their modeling importance:

I. Bed-material classification: a finer classification will produce a better estimation of bed-roughness, vastly important for conveyable discharge through a cross-section relative to water depth.

II. Slope refinement: a more detailed estimation near offtake areas, similar to Faida and on secondary canals themselves. Identified divergence from slopes assumed in this study could produce differences in hydraulic behavior and control necessity.

III. Cross-sections: more estimations of top-bot widths and intended/maximum water depths along Khinis-Jerwan and especially with the Mubarak complex two routes. As for slopes large variance from assumed cross-sections could affect the Khinis-Jerwan canal area hydraulic response.

IV. Streams: locations (identifiable) that appear to pour in the canals, along with a rough estimation of their cross-section, will assist in improved assumptions of potential inflows locations and amounts.

V. Maintenance and weirs: evidence of regular maintenance of canal proves useful in bed-roughness assumptions, while although quite difficult to come by reminisce or evidence of weirs greatly affect control assumptions. Prime locations to discover them would lie near offtakes and especially heavy clustered ones (Mubarak complex).

VI. Khosr tributary: a more specific stream-wadi to explore if still feasible. In which a rough estimation of its cross-section (differences with assumed), as well as the investigation of a weir separating the Mubarak complex and Khosr tributary. Potentially providing more details assisting in creating more realistic control scenarios.

5: CONCLUSIONS

Acknowledging the limitations observed above, it is clear that more control of flows in and from the system does not automatically result in better results in terms of water availability or yield. Canal water coverage and dry yield amounts fair better during *Absent* control for reaches far up- and downstream. The Khosr-Kisiri stretch is excluded from this behavior, as it represents the far downstream part of the Regional system. As such, it shows uninfluenced harvests due to being able to incorporate unusable/leftover flows from (irrigation) upstream, while increased control hinders its coverage performance for dry years. Furthermore, offtake widths in both local and regional systems exhibit a diminishing affect in harvests, when responding to heavier control applied.

Barley is a rather forgiving crop (regarding water needs and temperature impact) which may downplay the importance of irrigation and controlled irrigation. Modelling more susceptible crops like grapes will most likely reveal higher yield benefits for heavier control applications.

Dry years greatly benefit from more control installed, allowing to extract more water and yield from the system. Converting higher coverages to more harvests, irrigation acts as an insurance policy for low flow years. This comes with the drawback that navigation is deemed impossible for many canals during irrigation for Dry year inflows. In a Reference or wetter year, transport of grains or materials is viewed as highly possible, additionally reinforcing economic trade through the region.

Main route weirs can show varying importance for the system, depending on offtake location, proximity to others in the area and special cases like split of the main course.

> Regarding offtakes, clustered ones show a higher degree of flexibility in weir installations, coping better under *Limited* control, while spread out offtakes (primarily added artificially) show the same response with the absence of weirs. Two examples are clear illustrations: Jerwan with its clustered offtake area and the Bandawai thin strip with offtakes spread out. The Jerwan complex shows no decrease in harvests even though 5 weirs are removed for scenario *C,* whereas Bandawai shows a decrease to almost none (or at least extraordinarily low) harvests.
>
> Two splits are observed in the Regional system, the first in the Jerwan area and the second in the Bandawai middle area. Both utilize split weirs relatively unrelated to offtakes, which provide flow management for each route dictating water quantities through them. Even in Reference inflow years, as (the lowest canal coverage is observed for Bandawai middle for (receiving almost none when split weir removed) *A* Ref Spring and Autumn, stressing their importance to the system.

Finally, let us return to the highly debated archeological question at the heart of this thesis: were Sennacherib's hydraulic accomplishments primarily motivated by the Neo-Assyrian empire's benefits in the larger hinterlands (in terms of harvest and/or transport) or by the direct benefits of Nineveh and its gardens extensive water needs. No single answer can be provided with the results of this thesis, given the uncertainty in data and the many options to model and perceive the water systems, but it is clear that Dry or dryer than Reference inflows would greatly increase the importance of irrigation as well as controlled irrigation. The thesis also suggests that irrigation will have been quite likely to increase yields throughout the canal area.

Further detailing key parameters such as suggested interventions (mentioned in the last paragraph of the Discussion), drought cycle frequency, magnitude of low flow years (within the system's operation period), and to lesser extent flow variability will provide a more certain evaluation of yield improving and transport capabilities of the impressive canals. This will allow a better-founded judgment of these systems available options for the Neo-Assyrian king Sennacherib to use and possibly his original motivation in constructing such colossal water systems.

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ANNEX

The ANNEX is provided in a separate document, accompanying the thesis.