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The fluidity of empire: hydraulics of neo-assyrian canal systems in relation to their possible uses

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Abstract

The Neo-Assyrian empire offers a clear example of the key relationship between imperial power and water management. Irrigated landscapes under the direct impulse of the Assyrian state were important during its imperial heydays of the late 9th to 7th centuries BC. In the very heartland of the empire (the “Assur-Nineveh-Arbela Triangle” this imperialization of the landscape was the most dramatic, with large canals, aqueducts, and dams redirecting water flows toward the urban areas. Our hydraulic analysis of the canal network connecting Nineveh to its northeastern hinterlands explores how large-scale imperial investments generated imperialized landscapes that marked a substantial divergence from the preexisting conditions in terms of shape and sizes of canal infrastructure. One key question is whether Sennacherib’s hydraulic accomplishments provided meaningful changes to the agricultural economy of the region surrounding Nineveh, especially whether the canals allowed shifting the focus from extensive dry farming to intensive irrigation farming. Our hydraulic modelling shows that Assyrian water controllers and users would benefit from irrigation on the fields upstream of Nineveh. However, they would not benefit automatically from more control of flows in and from the system. Our results do not provide a single, definitive answer, given the uncertainty in data and the many options to model and understand the water systems, but especially for inflows below reference levels, the importance of controlled irrigation is evident. This suggests that irrigation will have been very likely to increase yields throughout the canal area.

Keywords Neo-Assyrian Empire · Modelling · Irrigation · Scenarios

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Introduction

The Neo-Assyrian empire in the early 1st millennium BC offers an interesting case-study for the relationship between imperial power and water management. While its traditional core around modern Mosul was long a zone of primary dry farming, it was developed into an irrigated landscape under the direct impulse of the Assyrian state, especially during its imperial heydays of the late 9th to seventh centuries BC. This development was part of a carefully planned strategy of agrarian development and population resettlement that affected the whole imperial territory and its various landscapes: conquered regions in the periphery were partly deprived of their inhabitants, who were resettled across the empire and especially in its core areas of present-day eastern Syria and northern Iraq (Oded 1979). There, they were settled in a ruralized landscape of evenly-spaced small villages (Altaweel 2008, Morandi Bonacossi 2000 and 2018a, Wilkinson et al. 2005, Ur 2010; for southeastern Turkey see Parker (2001)). These villages were primarily dependent on dry farming and pastoralism, but when surface water was available, such as along the Lower Habur, irrigation systems of different sizes supported a demographic boom in a region too arid for dry farming (Ergenzinger and Kühne 1991; Morandi Bonacossi 2000; 2018a).

It is, however, in the very heartland of the empire (the "Assur-Nineveh-Arbela Triangle" (Radner 2011)), where the Assyrian capitals were located, that this imperialization of the landscape was the most dramatic. In the hinterland of the newly built or expanded capitals (Kalhu, Dur-Sharruken, Nineveh), Assyrian kings commissioned large canals, aqueducts, and dams, which redirected (surface) water flows from the hilly piedmont of the Zagros mountains toward the urban areas (Bagg 2000, 2017; Ur 2005). These canals were not used only to provision the imperial urban centers, however. An earlier reassessment

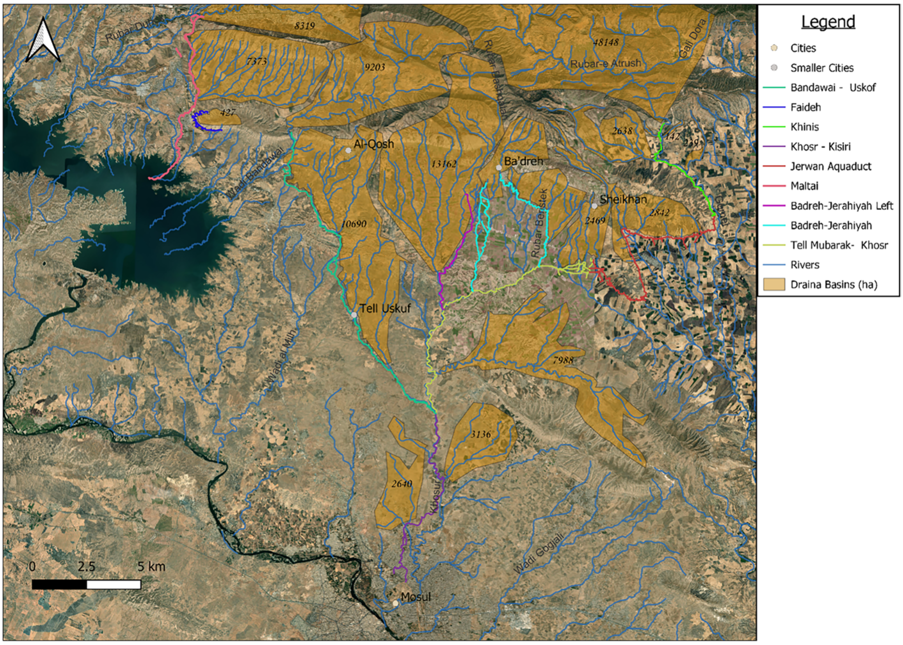

Fig. 1 The project area of the Land of Nineveh Archaeological Project

based on satellite imagery (Ur 2005) suggested off-takes existing along the canals–which in turn suggested local use of water (possibly) for irrigation at a distance from the capitals. Thanks to new initiatives like the Udine Land of Nineveh Archeological Project (LoNAP; see Fig. 1) and the Harvard Erbil Plain Archaeological Survey (EPAS), important aspects of this Neo-Assyrian hydraulic infrastructure have been uncovered in recent years.

Much of this Assyria's empire-building-in-the-making was based on exploiting new lands and partly using irrigation systems to support them (Morandi Bonacossi 2018a; 2018b). Examples of such large-scale canals are the Nimrud (ancient Kalhu), Arbela/Erbil, Kilizu, and Nineveh systems connecting each city to its hinterlands. The Nimrud system originates near the confluence of the *Khazir* and *Upper Zab* rivers, feeding from the former and possibly supplemented by the latter. Arbela was fed by a subterranean canal from the *Bastora Chai* river, while the nearby plain between Qasr Shamamok (Kilizu) and Nimrud was irrigated by a series of canals that tapped in the *Upper Zab* and its tributaries, conveying water towards the area along with its natural wadis (Ur 2018).

The most dramatic of these new hydraulic structures, however, is the Nineveh system attributed to Sennacherib, a Neo-Assyrian king rising to power in 705 BCE. The system connects the city to its northeastern and northern hinterlands, by the *Khinis* and *Bandawai* canals respectively (Morandi Bonacossi 2018b). The *Khinis* canal feeds off the River Gomel from a narrow mountain range, runs through its homonymous area, crossing *Jerwan*, where numerous off-takes and remains of an impressive aqueduct using approximately 400,000 limestone ashlars have been discovered, before it drains into the *Khosr* river–ultimately reaching Nineveh. The *Bandawai* canal, who fed off the homonymous stream near the village with same name, is a cross-watershed canal with large excavations (width of the canal bed 20–30 m, overall canal width 110–135 m) to guide it towards Tell Uskof, as well as massive spoil banks resulting from excavation and years of maintenance.

Upgrading hydraulic and road infrastructure, along with rearranging regional populations within his domain, are some of Sennacherib's most notable accomplishments. Administratively, he increased populations in provincial centers, also prompting a denser network of rural settlements, relying on deporting record numbers 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 2018a; Morandi Bonacossi and Qasim 2022). During his reign, Nineveh grew from 200 to 750 ha, with royal elites having a lavish palace, impressive public buildings, stunning court art and exotic gardens (see Frahm 2017).

Assyrian imperial irrigation efforts were top-down projects that were continuously in the making and as such unfinished (compare with Darwin 2012). Northern Mesopotamia would have experienced between 200 and 400 mm of rainfall per annum, with variability both across the region in any given year, and from year to year at any given place, within that range (Ur 2010). In 2022, in the Khatara region north of Nineveh, the entire area experienced a complete crop failure due to insufficient rainfall. This variability in rainfall would have generated varying surface flows, which made the creation of irrigation systems not straightforward as water distribution arrangements would have to be able to deal with this variable surface inflows. To what extent springs that would have fed water courses would be affected by variability in rainfall remains unclear, but some variability in spring flows is to be expected. As such, we need to consider that continuous negotiations between water availability and water needs shaped the way the Assyrians dealt with canals, crops, and farming activities. The archaeological record provides us with the remains of these efforts, which partially allow us to reconstruct how the systems were used and as such contributed to the performance of imperial power.

Our hydraulic analysis of the canal network connecting Nineveh to its northeastern hinterlands allows further exploration of how large-scale imperial investments generated imperialized landscapes that marked a substantial divergence from the preexisting conditions in terms of shape and sizes of canal infrastructure (Morandi Bonacossi 2018a; 2018b). The very existence of the canals and the massive investments they represent are proof enough that the Assyrian state had good reasons to build them, be it bringing water to the urban centers, irrigating agrarian land along the canals, facilitating the transportation of agricultural produce from those lands to the cities—or a combination of all three. One key question is whether Sennacherib's hydraulic accomplishments provided meaningful changes to the agricultural economy of the region surrounding Nineveh, especially whether the canals allowed shifting the focus from extensive dry farming to intensive irrigation farming. Whether this would have generated noticeable higher yields needs to be determined, but irrigation could also have kept yields stable in dry years and as such may have helped buffering climatic uncertainty.

Two main opinions exist on this issue. David Oates (1968) and Julian Reade (1978) have insisted that Assyrian canals would have failed to elevate the level of agriculture productivity significantly in Nineveh's rural surroundings and stressed their ideological function–which would mainly bring water to Nineveh for ornamental functions like watering the imperial gardens. On the other hand, Ariel Bagg (2000, 2017), Jason Ur (2005), and Daniele Morandi Bonacossi (2018b) have emphasized the agrarian function of the *Khinis* and *Bandawai* systems. One could argue that bringing regional economic benefits through the king's project would serve ideological functions as well.

The present study aims to understand to what extent irrigation strategies could strengthen agricultural production with the aim of protecting the Assyrian staple-crop economy from harvest failures determined by anomalously low rainfall and establishing a solid local economy based in the immediate hinterland of Nineveh. After a short presentation of the Nineveh canal system as it can be reconstructed from the archaeological and epigraphic record, we describe our methodology in some detail. After discussing the results, we offer some conclusions and suggestions for future research.

Table 1 Sennacherib's (704 BCE) stage 1, 3 and 4 canals (92 km of canals)

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 (0.77)
	Bandawai	5	0.8–1
	Uskof	4.4	1.2
	Tarbisu	23.1	0.6
4	Khinis	55	0.9

The Nineveh canal system

Four phases of construction of the Nineveh canal system can be distinguished over 15 years (703-688 BCE), with Sennacherib's famous "Bavian inscription" (688 BCE) dealing with three of them (Table 1). The first stage of canal building started shortly before 702 BCE, with the *Kisiri* canal extracting water from the *Khosr* river, potentially watering the royal gardens, while also feeding irrigation through secondary channels on its route. The canal continues its course until it splits shortly before the city into a channel leading towards the Tigris floodplain and another going through the walls of Nineveh. The entrance point of the *Kisiri* canal in the city, which was originally protected by a now lost iron grating, has been recently brought to light by archaeological excavation (Marchetti 2022). The second stage of Sennacherib's canal building, known as the *Musri* system, is mentioned in the king's octagonal prism found in Nineveh, a foundation record dated from 694 BCE describing King Sennacherib's achievements. In the inscription the king records that he enlarged several karstic springs, 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 that are quite hard to date.

The third stage consisted of a series of canals that are not connected to the Nineveh system as such, such as the *Maltai* and *Faida*, situated north of the capital (Morandi Bonacossi 2018b, *contra* Reade 1976). *Maltai* connects the basins of Dohuk and *Faida* as a cross watershed channel. The *Maltai* canal system was fed by the River Duhok and a large karstic spring ('Ain Qassara), while the *Faida* canal, which surrounds the west side of the Chiya Daka hill range near the end of the *Maltai* canal, received its water from a series of karst springs. So far only one off-take could be identified in the field along the *Bandawai* canal. Long stretches of the *Faida* canal were excavated by LoNAP, which allowed measuring cross sections. The cut is rectangular in section and varies in width between 3 m and 3.80 m. In the canal's upper course, in several stretches erosion has exposed canal cross-sections with widths up to 4.20 m. The relative variability of the canal's width suggests that Assyrian hydraulic engineers adjusted it according to the topography. Moving south from Bandawai village, the cross-watershed canal flows in the direction of Nineveh, with only one off-take identified so far, from satellite imagery. The canal continues into the *Uskof* canal, topographically and morphologically similar to *Bandawai*, ultimately leading to a tributary of the *Khosr* near the town of Uskof. While the course of this canal is known from previous archaeological research, until now no off-takes have been identified for this reach. Another nearby channel, the *Tarbiṣu*, is rather straight and does not follow the natural contours, which could mean that it is not a Neo-Assyrian canal–as these tend to follow local topographies rather precise.

The fourth stage of Sennacherib's hydraulic program was the construction of the *Khinis* canal, which originates at the homonymous village and shares a large drainage basin (525 km^2) with the river *Atrush*. It is fed by the River *Gomel* (the continuation of *Atrush* in the Navkur plain) and a series of karstic springs located along its course, as it proceeds towards the top end of the Navkur plain. Five stone aqueducts have been identified along its course before it reaches the *Mubarak* area, the fourth (the Jerwan aqueduct) being the largest with an estimated 400,000 limestone ashlars (stones cut in regular shape). The *Jerwan* and *Mubarak* areas have 16 off-takes (7 and 9 respectively), all leading into the fields of the Navkur plain. After the *Mubarak* complex, the canal pours into a tributary of the *Khosr*, which ultimately guided its waters to the capital. Issues regarding the cross-sections of these canals are discussed in the methodology section, while their length and average slopes are presented in Table 1 below (Morandi Bonacossi 2018b; Ur 2005).

These canals were fed by water from rivers, springs, and wadis. The region being primarily influenced by Mediterranean weather patterns, annual precipitation would have occurred predominantly during the cool season (November–April), making up to 90–95% of the yearly amount. The hinterland of Nineveh is located within the domain of secure rainfed agriculture, with average rainfall rising, from south to north, from 450 to 600 mm per annum. Even in dry years, this region remains suitable for dry farming, with annual rainfall in the range of 350–450 mm. These values are higher than the many zones of marginal cultivation in the region with annual rainfall of 200–300 mm with high annual variability (40–60%), where limited and unpredictable water availability makes rain-fed cereal agriculture a highly speculative endeavor. In dry years, this marginal zone moves northward and closer to the Assyrian core, while during wetter years it moves further south, expanding the range of rainfed agriculture and possibly providing higher yields in the areas located safely within the dry farming belt. In extremely dry years, such as the recent 2007–2010 drought, the "zone of uncertainty"–where crop cultivation by means of dry-farming is at risk due to the vagaries of rainfall–could even reach the hinterland of Nineveh and Arbela and beyond (Sinha et al. 2019, Fig. 1B).

In their recent paper, Sinha et al. (2019) shed some light on the hydro-climatic history of the region between 950 and 550 BCE, through a comparison with more recent periods. Stable isotopes (δ^{18}O) and (δ^{13}C) measurements in speleothems gathered from Kuna Ba Cave in northern Iraq, located around 300 km southeast of the modern city of Mosul, near the city of Sulaymaniyah, provide proxy indications for regional precipitation and the precipitation/evaporation balance near the cave, while uranium–thorium dating provides a high-resolution sequencing of these climatic fluctuations over the past 4000 years. The authors suggest peak wet conditions for nearly two centuries (925–725 BCE), leading to a 15–30% higher rainfall compared to the 1980–2007 period. A so-called Assyrian mega-drought followed it in the 675–550 BCE period (exhibiting the largest increase in δ^{18}O, δ^{13}C over 125 years of aridity), partly overlapping with the alleged period of imperial collapse that Sinha et al. date to 660–600 BCE (a questionable claim, since the actual demise of the Neo-Assyrian empire only took place under the successors of Ashurbanipal in the 620 s and 610 s). In the speleothems, the driest years within the Neo-Assyrian period are comparable to the period 1980–2007 (Sinha et al. 2019). The dry Assyrian years, however, do not seem to be as drastic as a few years in this longer modern period, like the years 1999–2001 (Reculeau forth.)–which were responsible for significant cereal crop failure and livestock decease spread across northern Iraq and Syria–let alone the 2007–10 drought, the most severe ever recorded in the region (Kelley et. al. 2015).

Agriculture in semi-arid areas is directly limited by water availability and soil fertility. More generally, cropping options depend on climate, natural environment, and cultural features, such as cultivation technology and land use patterns (Morandi Bonacossi 2018b). Little is known about Neo-Assyrian agricultural practices from textual records, but a preference of wheat over barley as well as the existence of vegetables and potentially orchards has been reported. Due to the lack of available data for the Neo-Assyrian period, our crop analysis was based on Middle Assyrian practices regarding crop choices, sowing rates, and yields (Reculeau 2011).

Through fieldwork and computer simulations based on ASTER digital elevation models, LoNAP could suggest extensive land surfaces being theoretically available for irrigation, extending far beyond Nineveh's northwestern and northeastern fields, in close proximity to many of the canals discussed above, including the *Jerwan*, *Mubarak*, *Bandawai*, *Faida*,

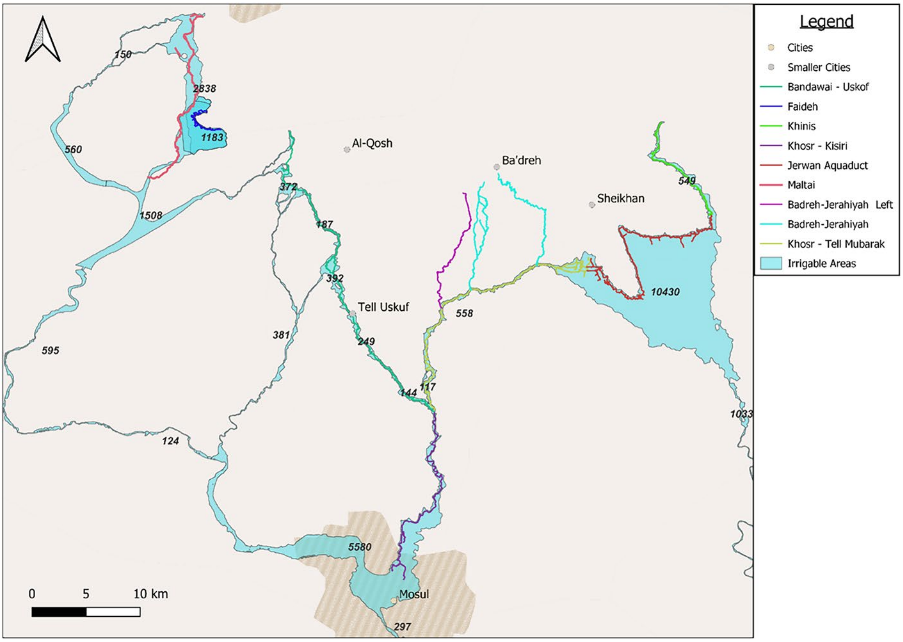

Fig. 2 Th canal systems and associated irrigated areas of the study

and *Maltai* areas. These lands could have been brought under cultivation in stages 3 and 4, to reduce harvest uncertainty and increase yields. This suggests a methodical promotion of the piedmont belt of the Zagros mountains as a staple food supplier for the capital (Morandi Bonacossi 2018a). Adding to this image of possible intensive use, the discovery of quay walls on the *Gomel* and *Khazir* rivers suggest that water courses were also used for transportation (of goods and/or people). Water courses could have allowed for relatively frictionless transport of agricultural production towards the cities of Nineveh and Nimrud (Morandi Bonacossi 2018b).

Methodology

We focus on Sennacherib's stage 1, 3 and 4 canals, using data from LoNAP, with additional satellite image analysis for stage 1 (*Kisiri*) coming from Ur (2005) (Fig. 2). We have applied two software packages to study the canal system. Sobek (version 3.7), a one-dimension numerical open channel flow model provided by Deltares, was used to simulate the hydraulic behavior of the canals for different operational and flow conditions. AquaCrop (version 6.0), an agriculture model from the Food and Agriculture Organization, was utilized to assess production yields under varying water availability. To summarize our approach, using hydraulic modelling to study how much water could reach fields in different scenarios regarding the control of the water flows, we could compare that amount of water with the water demand of the crop computed by the agricultural model, to determine potential yields for each scenario. For this approach, we needed to apply data sets and make modelling setup decisions, which we will explain in a few steps. Readers who are interested in much more detail of the modelling process would be interested to read Stampoultzidis (2021; the original study).

Water demand modelling

To quantify the water needs for crop growth and resulting yields we used data and made decisions concerning weather data, soil types, crop type and irrigation scheduling.

Weather characteristics for early 6th or seventh century BCE Neo-Assyrian mainland such as precipitation and temperature are assumed to roughly equate with the 1979–2010 datasets of the region (following Sinha et al. 2019). These data were obtained through the National Oceanic and Atmospheric Administration. Three sets of daily values for rainfall and temperature were defined to represent conditions for farming in the vicinity of Nineveh, Navkur and Faida respectively. Nineveh's time series was used to identify the wettest 1980 (494 mm) and driest 1999 (128 mm) years based on annual precipitation amounts in millimeters. These two situations offer pretty extreme scenarios compared to what would have been the case during the so-called Assyrian megadrought. As such, they provide an idea of the worst possible case scenario.

Soils in the modelling are based on the 1960 study from the Iraqi Ministry of Agriculture (Buringh 1960), supplying general characteristics such as soil type and average depths. Two distinct soil types were assumed for the Nineveh and Navkur-Faida fields, the former being categorized as loamy with a depth of 3 m and the latter as silt loam with a depth of 2.25 m. Salinity amounts of these soils are deemed insignificant, while groundwater levels were considered uninfluential (Buringh 1960).

As model crop, we selected two-row barley as crop of choice for this study, even when mentions of wheat as the dominant crop are presented in Morandi Bonacossi (2018b). The lack of Neo-Assyrian evidence for planting periods, sowing and yield rates forced the use of Middle Assyrian estimations for these parameters. It is not unreasonable to assume that crop practices would be rather similar in these two periods. Widely accepted sowing rates in their original units *qu*/*iku* range from 30 to 35 *qu*/*iku* (Mari-Middle Assyrian), while *qu* and *iku* conversions to kg and hectares respectively are a more controversial topic (Reculeau 2011; 2018). Based on Reculeau (2011; 2018) we used 30 *qu*/*iku* as sowing rate, with 1 *qu* = 0.5 kg and 1 *iku* = 0.42 ha, resulting in 35.71 kg/ha for a maximum seed to yield rate of 1:10.

Determining the water demand of the barley was done in AquaCrop including determining possible timing and amount of irrigation events throughout the growing season (the irrigation schedule), in addition to estimating dry harvest yields (Table 2). Two years were chosen to conduct simulations representing wet (1980) and dry (1999) periods, for which both spring and autumn seasons were modelled. These simulations were run for all pairs of weather-soil characteristics selected for the three areas mentioned earlier (Nineveh, Navkur and Faida). Continuous irrigation was ruled out due to the extremely low flow required per day and the associated high labor requirements. We selected an irrigation gift of 30 mm per hectare per turn as standard, after the effects on yields were investigated for 20, 30 and 40 mm respectively. Calibration of modelled yield to the maximum yield (1:10) was performed for Nineveh's fields during a wet autumn season. Another output of simulation runs was the irrigation event timing, which was converted to available days to complete one irrigation event.

Table 2 Initial model yields in kg/ha for different scenarios in Aquacrop

Modelled yield (kg/ha)		Wet year			Dry year			Irrigation schedule	
	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

Table 3 Canal off-takes, irrigable hectares and bed material classification

Canals	Off-takes	Off-takes added	Irrigable hectares	Bed-material classification
Maltai_upper	4	3	1495	Earthen canal
Faida	4	0	1183	Rock cut canal
Bandawai_upper	1	0	90.86	Rock or hearth canal/Earthen canal
Bandawai_up_thin_strip	1	1	187	Earthen canal
Bandawai_mid	1	1	376	Earthen canal
Uskof_upper	1	1	392	Earthen canal/Canalized wadi-River
Uskof_lower	1	1	393	Earthen canal/Canalized wadi-River
Khinis	3	3	549	Rock or hearth canal/Earthen canal
Jerwan	16	0	10,430	Earthen canal/Aqueduct
Koshr_tributary	3	3	675	Canalized wadi/River
Kisiri_Nineveh	3	0	5264	Earthen canal
Khosr_thin_strip	2	2	316	Canalized wadi/River
Maltai_low	1	1	160	Earthen canal
Badreh-Jerahiyeh	7	7	5011	Earthen canal
Total	39	19	***23,684***	–
Off-takes	–	–	–	Earthen canal

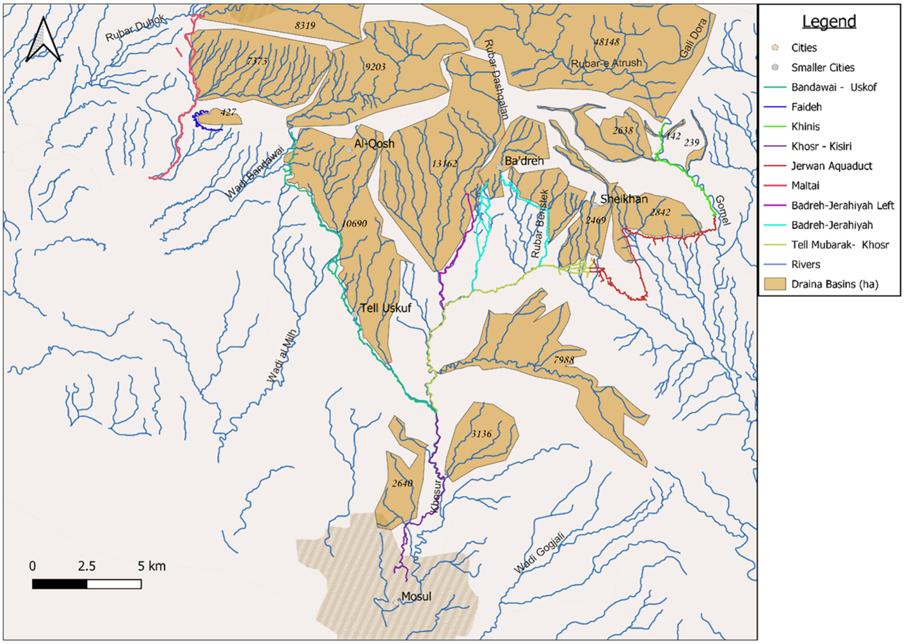

Fig. 3 The drainage areas associated with the canals of the study

Hydraulic modelling

In order to model flows in the canal system, we used data and made decisions concerning canal shapes, flow control options and potential inflows.

Concerning canal shapes, key canal features are slopes, cross-sections, and bed roughness. We applied cross-section types of trapezoidal shape, with variations of bottom width and maximum water depth. Roughness of bed material was assessed using data provided by the LoNAP team (Arcement & Schneider 1989) (Table 3). The canals can have quite different roughness properties, with the Faida canal cut through natural bedrock, while the Maltai upper region is earthwork. 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.

Flow control was modelled by including so-called off-takes to the canal system (Table 3). Two rectangular off-take options were simulated, with 1- and 2-m bottom widths and with water depths of 1 and 0.5 m in the off-take, respectively. Flow control is enforced through operating gates positioned a few meters downstream of the off-take into the secondary canals. In some scenarios weirs are placed about 20 m downstream of the off-take in the main canal. Control scenarios were based on three options for water inflow (Wet-Reference-Dry) and for flow control (Maximum-Absent-Limited) for these two off-take widths. *Maximum Control* (MC) refers to a weir placed downstream each off-take, while *Absent Control* (AC) has no form of control. For *Limited Control* (LC), off-takes further than 5 km from an archeologically identified settlement do not receive a weir.

Computing inflows in the canals and wadis was done by associating drainage catchments determined in QGIS with the canal's origin or junctions in Sobek (Fig. 3). With canals associated with drainage basin surface areas, discharges brought into the system could be determined. We applied a runoff coefficient of 65% in combination with several values for annual precipitation (in mm) for each location to create mean annual inflow, cool season inflow (90% of rainfall in 6 months Nov-Apr) and dry and wet alternatives respectively–with the latter two based on the region's max/min variability between 1979 and 2010, presenting 64% decrease and around 77% increase in 1999 and 1980, respectively. Worth mentioning is that basins draining in the *Faida*, *Maltai*, *Khinis*, *Jerwan* and *Ba'dreh* canals most likely experience higher annual rainfall amounts as they are located in the Zagros mountains and therefore may have had higher potential discharges (Sinha et al. 2019).

Calibrating the resulting hydraulic model was done by computing the Maximum Control scenario with inputs roughly equal to the sum of the water requirements for all areas per system and specific weir crest levels. In principle inflows are equal to the sum of water requirements for all areas plus the needed inflow in the canal stretch to deliver that amount, but exact delivery of the demanded amount for all off-takes can be hard to achieve in the model. Some upstream areas surpassed 100% of water need, introducing the need for higher total canal inflows (especially in the Absent, less so in the Limited and hardly ever in the Maximum control scenarios). The calibration check to satisfy water coverage over the selected areas was done through manipulation of weir crest levels and gate opening time schedules. When these settings no longer affected coverage results, water inputs were increased to meet the water needs. The same process was afterwards carried out for the Limited Control and No Control scenarios.

Box 1 Coverage percentages for areas with descriptions

Maltai upper ***AC*** Reference (Ref) Spring and Autumn coverages are about 50 and 80%, and roughly equal for the 1 and 2 m off-take widths scenarios. During Dry years, ***MC*** and ***LC*** scenarios dominate, reaching 45%, while **AC** barely surpasses 10%

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

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

Coverage for *Khinis* ***AC*** Ref Spring is over 100% for 1 m off-takes, and drops to 65% for 2 m off-take widths. In Dry seasons, 1 m ***AC*** have slightly higher (4–7%) coverage than ***MC*** and ***LC*** scenarios. For 2 m off-takes, this effect strengthens, reaching 16–18% higher values for ***AC***

Jerwan's ***AC*** Ref Spring coverage remains at 72% for 1 and 2 m widths. Noteworthy is that Dry year seasons ***MC*** and ***LC*** control scenarios provide almost double coverage compared to ***AC*** in both 1 and 2 m off-take width alternatives. Dry year differences between 1 and 2 m widths for each control scenario are negligible (around 1–2%)

Khosr tributary's ***AC*** Ref Spring coverage follows the Autumn pattern, surpassing 100% for both 1 and 2 m widths. ***AC*** Dry Spring–Autumn coverage is slightly higher 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 ***MC*** and ***LC*** scenarios for both widths, while for ***MC*** and **C** differences between widths are minimal at 2–3%

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

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

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

The *Bandawai middle* stretch struggles during 1 m ***AC*** Ref seasons, barely passing 50% in Autumn, while for 2 m, coverages drop down to 8 and 15% for Spring and Autumn. ***AC*** Dry year coverage is virtually non-existent for both widths, ranging around 1–2%. 1 m ***LC*** Dry year runs outperform ***MC*** 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 ***MC*** scenario Dry year coverages are met. However, for 2 m, the ***LC*** and ***MC*** Dry seasons are largely unmet, with the prior dropping to 48 (Spring) and 54% (Autumn) and latter to 38 and 43%., respectively

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

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

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

Modelling outputs

The Assyrian canals were possibly both used to bring water to fields to produce crops and as means to transport the crops.

Table 4 Dry yields in kilotons and differences in percentages for different control scenarios

Off-take Widths Control	1 m Yield (kilotons)	2 m
AC_reference spring yield	37.79	37.59
AC_reference autumn yield	60.63	60.8
AC_dry spring yield	22.4	20.48
AC_dry autumn yield	40.54	35.83
MC_dry spring yield	35.01	34.75
MC_dry autumn yield	59.94	59.71
LC_dry spring yield	31.85	31.1
LC_dry autumn yield	53.93	53.68
	Percent differences	
AC vs MC-LC reference spring	0.01	0.52
AC vs MC-LC reference autumn	0.24	0.04
MC vs LC dry spring	9.03	10.5
MC vs LC dry autumn	10.03	10.1
AC-MC dry spring	56.29	69.68
AC-MC dry autumn	47.85	66.65

Evaluating the relative success of a water control scenario is determined by converting the total discharge provided by an off-take in a given time computed by Sobek into a percentage of the required delivery within the available time to irrigate. These percentage coverages for irrigation schedules are then used in AquaCrop to compute dry harvest yield estimates. We did this for 14 hydraulic scenarios applied to 10 field areas near 10 defined canal reaches.

As one of the possible usages suggested in the literature for the Neo-Assyrian canals was transportation (see Introduction), we did also evaluate the transport capacity of the canals. Rafts, barges and boats for river transport are often mentioned in the Neo-Assyrian sources (Fales 1993) and represented on palace reliefs. We used the weight balance of a loaded raft or barge against displaced water (utilizing water density = 1000 kg/m^3). A raft with width, length and height of 3 * 10 * 0.5 m, with a loaded raft's total weight of 9 tons, creates 0.3 m of draft. Adding a 0.1 m safety water depth sets a nominal minimum water depth of 0.4 m required for navigation. It is likely that different rafts were used in Assyria, but this model raft seems reasonable given the available evidence on water-based transport in the empire.

Results

Dry harvest yields from AquaCrop's initial results in kilogram per hectare for Nineveh, Navkur and Faida across both growing seasons and years, are shown in Table 2. The two last columns show the yields when applying delivery amounts deemed possible through Sobek, for AquaCrop's defined Irrigation Schedules.

A selection of results in terms of water demand coverage percentages for canal areas are given each area (Box 1), with full results available in Stampoultzidis (2021). We do

Box 2 Yields as modelled explained

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

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

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

Khinis until Khosr

Khinis 1 m **AC** Ref seasons are at optimal yield rates, while **AC** Dry year harvests are quite near. Spring is trailing by 19 and Autumn by 10 kg/ha. Spring yields suffer in control scenarios **MC** and **LC**, compared to **AC**, with 45 kg/ha, but less so in Autumn with 14 kg/ha. For 2 m widths, **AC** Dry year yields increase slightly (6 and 9 kg/ha Spring–Autumn), while **MC** surpasses **LC** by 39 kg/ha during Spring, with Autumn yields remaining unaffected

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

Khosr tributary **AC** Ref seasons reach maximum harvest per hectare. Dry year **AC** Spring–Autumn practically reach optimal values in both 1 and 2 m widths too. For both off-take widths **MC, LC** Dry Autumn seasons lack just 6 kg/ha for optimal yields, while during Spring they are both around 13–17 kg/ha lower than **AC.** Differences between 1 and 2 m scenarios are minimal

Badreh-Jerahiyah **AC** Ref seasons produce maximum yields in Kg/ha, while **AC** Dry year Spring–Autumn yields trail with 13–14 kg/ha respectively under 1 m off-take widths. For 2 m widths, only **LC** Dry Autumn yields drop with 6 kg/ha

Bandawai-Uskof until Khosr

For 1 m widths, **AC** 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 **AC** trails **MC** and **LC** by around 68 kg/ha during Spring, while in Autumn this is 32 kg/ha. For 2 m widths, **AC** Dry years drop to 50 and 91 kg/ha (Spring–Autumn), where **MC** Dry seasons reach maximum harvests, followed with marginal or no changes in **LC** Dry Autumn-Spring

Bandawai thin strip yields are only in the **MC** Dry season near maximum harvest, while the rest (**AC**, **LC**) show terrible yields ranging from 13 to 22 kg/ha. For 2 m scenarios, the **AC** and **LC** yields drop to zero, as plants die before harvest

Both Bandawai middle width scenarios produce no harvest during **AC** Dry year. For 1 m, **MC** and **LC** they are nearly optimal for both seasons. Using 2 m widths results in a drop during **MC** Dry Spring with 22 kg/ha, a marginal drop in **MC** Dry Autumn and a rise for **LC** Dry Autumn

Uskof upper's 1 m width **AC, LC** Dry Spring–Autumn yields are near the maximum, while **MC** 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 **LC** Dry Spring

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

Khosr until Nineveh

The Khosr thin strip scenarios produce harvests extremely close to optimal under Ref-Dry years and **AC**, **MC**, **LC** control scenarios between 1 and 2 m widths are almost absent

Kisiri-Nineveh features an identical yield pattern with the Khosr thin strip, except for **MC** Dry Spring, which is 10–12 kg/ha lower under both 1and 2 m widths realize that the list with results is rather long, but would argue that providing the overview is important as this shows the sensitivity of our modelling setup and assumptions.

For each system under Reference-Dry years, and for all three control scenarios, the total dry yield for all irrigated areas taken together is presented in Table 4. Similar to the coverage percentages, Box 2 provides observations per canal area. The results suggest that the irrigation system is mostly unaffected by a change in off-take widths, with just a small increase observed for 1 m width *AC* Dry year harvests by 8,6% and 11,6% during Spring and Autumn, respectively. These results suggest that off-take widths primarily influence scenarios with *AC* and (secondarily) *LC*.

During Dry Spring, *MC* and *LC* scenarios, crop production differences are around 9–10% favoring *MC* (with 1 to 2 m widths). Likewise, Dry Autumn *MC* shows the same 10% increase. When comparing *AC* Dry year seasons with *MC*, the irrigated area manages higher yields when applying *MC* during Dry seasons, with Spring–Autumn ranging from 48 to 56% and 66–69% for 1 to 2 m widths, respectively. Overall, mild contrasts between control scenarios provide evidence that the Reference year is roughly uninfluenced by control. During Dry year seasons, MC favors production immensely for the irrigation system (by almost 70%).

Navigation options depend on water depth of a given canal segment, as mentioned in the Methodology. In Reference years with AC, both off-take widths can cover this requirement. In the *Khinis* area the depth condition is also met for *MC* and *LC* in 1 and 2 m runs. *Jerwan* drops below 0.4 m for *MC* with 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 *MC* and *LC* scenarios, but *Badreh-Jerahiyah* fails to provide the needed water depths. *Bandawai* and *Uskof* are non-navigable only for the 2 m *MC* control scenario, while the *Khosr-Kisiri* stretch supports transport throughout all control scenarios. Dry year 2 m off-take 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 *MC*, while *LC* is only met for *Khosr-Kisiri*. *AC* satisfies transport needs for all areas, except the *Badreh-Jerahiyah* canals.

These results suggest that transport within the canal system seems possible for Reference inflows. Contrary to Reference settings, Dry years are more susceptible to control than off-take width change, with only AC providing navigable water depths throughout the system. We could tentatively conclude that there is a trade-off between water control benefitting grain production, but limiting transport options of that grain.

Discussion

In this paragraph we make several observations concerning yields, distribution patterns and control settings–as these appear closely related. After observing some limitations of the current study, options for further studies are identified.

Modelling water distribution and control

Modelling outcomes show interesting differences between harvests of rainfed versus irrigated fields. Dry years require irrigation for both Spring and Autumn for all areas to produce a harvest, which strongly suggests that irrigation would be a profitable choice for all areas. Irrigation would boost *Faida*'s production even in wetter years. 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 observation is that there 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 *AC*. *Jerwan*, however, just downstream, shows its best harvest performance for *MC* and *LC* scenarios. This modelling result may be related to the model setup of the *Khinis* off-takes 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). Because the *Khinis* canal has a water accessibility (location) advantage and the largest associated feeding basin, it will have higher flow inputs.

The *Mubarak complex* consists of a split into two separate canal routes, both with off-takes. Further downstream, the two routes rejoin into one main course again. An interesting observation is that forcing flow towards the secondary route requires a weir in its primary course very close to the split 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 *AC* and showing little to marginal improvement by applying control.

For upstream–downstream effects, control settings are important, as for example observed in the *Bandawai* upper region. The *Bandawai* strip performs rather poorly in AC and LC Dry years. The *Bandawai* middle stretch shows zero harvest under Dry year AC, as it is located on one side of a split (in the main route) with its lower slope attracting less flow. In scenarios MC and LC, a weir is used on the secondary route to push flow towards the "main route", next to its own typical weir located 20 m after the off-take-along the main reach. This suggests that a weir (or a gated off-take) on the favored (secondary) course's reach to arrange the flow distribution, would be highly beneficial to the water managers in Assyrian times.

Uskof upper is situated on the favored route of the split and hence shows much less change in terms of control impacting harvests. *Uskof lower* under *AC* Dry year seasons experiences the consequences of being the furthest downstream off-take in the stretch by receiving extremely low flows, pointing out the gains in harvest security when installing weirs. 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 thin strip*, as they appear to be largely uninfluenced by control–only the *MC* Dry Spring chips on the optimal kg/ha.

The lower end of *Maltai* exhibits relatively decent *AC* Dry Spring and high Autumn yields in kg/ha. However, the upper part of *Maltai* has difficulty to produce yields without control, probably due to its very high slope (4 m/km) not allowing sufficient water depths for irrigation unless weirs are applied. For *Faida*, a similar situation occurs, even though a much lower slope is identified (0.9 m/km). Here, our modelling suggests that–especially because Dry year flow through the main course being very low–realizing sufficient water depth for irrigation requires at least some weirs. So far, field work has not identified such structures.

Costs and benefits of flow control

During a Dry year, all areas require irrigation for the barley crop to survive and produce harvest. When considering the system's total irrigable area, this results in around 13–19 kilotons difference in Spring and Autumn, respectively. 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 the *Navkur* lands no improvement is observed. However, control does not only potentially increase yields, it will also need labor. When evaluating labor needed for canal management (for weir/gate maintenance and operation), the *LC* setting uses 12 fewer weirs and requires 2–3 (1–2 m width) fewer gate operations compared to *MC*, but dry yields only drop by 10% across both seasons and widths. This suggests that fewer 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. It is worth mentioning 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.

Limitations of our modelling

A main source of uncertainty on the above modelling results can be defined in the data that we have used to complete both Sobek and AquaCrop models.

Canal cross-sections, bed-roughness, slope, and off-take features are all determining the irrigation systems capacities and behavior. With various reaches using approximations or data from other reaches (provided resemblances were reasonable), it is clear that large discrepancies between modelled and actual properties may suggest a segments' or systems' hydraulic behavior that is not realistic. *Faida* is the canal described with most detail in the archaeological record, showing a small drop in slope near off-takes, 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 increased roughness leading to higher water depths for the same flow values–but pushing more water through the off-takes leaving less water downstream. Number and location of off-takes influence discharge amounts they need to convey, with sparsely located off-takes benefiting greatly from control, while clustered ones can cope better with the absence of canal control. The added off-takes were spread out with the idea to cover land needs, but less distance between off-takes 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 off-takes in the vicinity.

Assumptions on weather patterns, soil profiles and runoff coefficients obviously influence AquaCrop and Sobek's results and parameter values. Weather patterns consist of daily precipitation, temperature, sunlight hours, and evaporation, amongst others. We did neglect evaporation in our flow considerations in detail, but by setting the discharge coefficient one can allow for more or less water becoming available for runoff (either due to evaporation or infiltration). The total runoff from a catchment would be influenced by evaporation, but meaningful incorporation of evaporation requires higher certainty regarding inflow data first. Runoff coefficients determining possible flows in wadis, rivers, and streams, were roughly 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.

For crop water demand, we did obviously include evapotranspiration. 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, however, 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 changes in the required irrigation schedule, as water may be drained faster or kept at the crop's reach for a longer period.

Finally, our assumptions relate to 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, all affecting yields. These factors are deeply tied with historical and archeological findings, but are scarce for the Neo-Assyrian setting. We used data from the Middle Assyrian period, with their own associated uncertainties.

Options for further research

Next to continuing with field studies in general, additional field surveys to investigate the spring near the *Khinis* canal intake will provide insights in inflow possibilities. Additional field surveys uncovering cross-sections, more detailed slopes and bed-roughness may provide alternative boundary conditions for defining potential inflows. Survey and test trenches conducted in Faida during the 2021 and 2022 LoNAP field seasons have shown that the potential off-takes identified through remote sensing along the upper stretch of the Faida canal were recent erosive features.

Concerning ways to deliver water to fields, application of shadufs (a water raising technique also known as the counterpoise lift), may be taken into account. Shadufs, known in Babylonia since the early third millennium BCE at the latest, are attested on Neo-Assyrian reliefs from the time of Sennacherib (Bagg 2012). These devices would provide greater flexibility to extract water on demand, especially when irrigating thin strips along canals, without the need for extensive secondary canal networks and control applications. Navigation in dryer years may also benefit, as the amount of weirs in main canal routes may decrease. However, fields irrigated by shadufs only represent a negligible amount of all the irrigated land recorded in cuneiform records. These flexible, but labor-intensive devices seem to have only be used for small plots with high-value crops requiring regular watering, such as orchards (Civil 1994). Their broad use for the cultivation of cereals is therefore unlikely, and gravity-flow irrigation is the most probable method across the Nineveh systems.

Different crop simulations, for example for grapes (in vineyards) or fruit-trees (in orchards), would add additional options to study how the agricultural areas could have been supported by the canals. Barley being the only crop is highly unlikely, as the Neo-Assyrian empire has documented use of wheat, vineyards, and orchards. Morandi Bonacossi (2018b) refers to imperial documents mentioning the king's desire for wine, strengthening the argument that vineyards were used during Neo-Assyrian times. Including patches of land with different crops will introduce varying irrigation schedules and a more complex, but more realistic insight on water demand. These extra crops would also possibly require more sophisticated network planning and control approaches to satisfy multiple crop water demands, with regards for timing and amounts of discharges to specific areas.

Conclusions

Acknowledging the limitations observed above, our modelling has shown that Assyrian water controllers and users would benefit from irrigation on the fields upstream of Nineveh. However, they would not benefit automatically from more control of flows in and from the system. More control does not necessarily achieve better results in terms of water availability or cereal yields. Canal water coverage and dry yield amounts perform better during Absent Control for reaches far up- and downstream. The *Khosr-Kisiri* stretch behaves differently, probably as it represents the far downstream part of the canal system. The canal may benefit from unusable/leftover flows from (irrigation) upstream, with increased control hindering its coverage performance for dry years. Furthermore, off-take widths have limited effects on harvests when responding to heavier control.

Dry years greatly benefit from more control, allowing to extract more water and obtain higher cereal yields 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. Having said that, barley is a rather forgiving crop regarding water needs and temperature impact, which may actually downplay the importance of (more or less controlled) irrigation. Modelling more susceptible crops like grapes will most likely reveal higher yield benefits for heavier control applications.

Weirs can show varying importance for the system, depending on off-take location, proximity to other weirs in the area and special cases like the splitting of the main course. Regarding off-takes, clustered ones cope better with Limited Control, while spread out off-takes (which are primarily added without archaeological evidence) show the same response with the absence of weirs. Two examples are clear illustrations: *Jerwan* with its clustered off-take area and the *Bandawai thin strip* with off-takes spread out. The *Jerwan* complex shows no decrease in harvests even though five weirs are removed for scenario LC, whereas *Bandawai* shows a decrease to almost none (or at least extraordinarily low) harvests. Both the canal splits in the *Jerwan* and the *Bandawai* middle area, respectively, have been modelled with weirs providing flow management for each route dictating water quantities through them. Even in Reference inflow years, the lowest canal coverage is observed for *Bandawai* middle for AC Ref Spring and Autumn. With the weir for the split removed, hardly any water reaches the off-takes – stressing the importance of general flow control in this part of the system.

Finally, let us return to the highly debated archeological question at the heart of this article: were Sennacherib's hydraulic accomplishments motivated by the Neo-Assyrian empire's agricultural benefits in the larger hinterlands (in terms of harvest and/or transport) or by the direct benefits of watering Nineveh, especially its imperial gardens? Our results do not provide a single, definitive answer, given the uncertainty in data and the many options to model and understand the water systems. Nevertheless, especially for inflows below reference levels, the importance of controlled irrigation is evident. This suggests that irrigation will have been very likely to increase yields throughout the canal area. Further detailing key parameters, including frequency and to a lesser extent also magnitude of low flow years (within the system's operation period) will provide a better evaluation of yield improvement and transport capabilities of these impressive canals – allowing for a better-founded judgment about these systems as options for the Neo-Assyrian king Sennacherib to use and possibly his original motivation to construct such colossal water systems.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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