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Contribution to the mapping of ancient watercourses of the Uruk – Larsa region (Southern Mesopotamia, Iraq) through remote sensing

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ABSTRACT

The deltaic plain of the Euphrates in the region of Uruk and Larsa, subjected to constant dune shifting due to strong deflation, allows for the identification of a dense network of ancient hydraulic structures and fluvial landforms. This study surveyed the area through remote sensing, using high resolution imagery and a Digital Elevation Model to enrich the watercourse map of the desertic plain between Uruk and Larsa. The use of a recently released worldwide open access DEM produced by the European Space Agency enabled an unprecedented quality of terrain analysis through open access large scale imagery and highlights the potential for many future applications in archaeological and paleo-environmental studies in the region. Finally, it unveils a new major connection between the cities of Uruk and Larsa, bringing new elements to reconstruct a complex hydraulic system over millennia of occupation.

1. Introduction

The deltaic plain of Southern Mesopotamia is interspersed by a network of ancient channels (natural and anthropogenic) punctuated with archaeological sites (Hritz, 2010). Within the Uruk-Larsa region, sites date back to the 4th millennium BCE (Jotheri et al., 2018) and present evidence of organised societies using water for irrigation and transport (Hritz, 2010). It results in a landscape that has constantly changed due to the strong alluvial processes of the Tigris-Euphrates delta, as well as major human development, that spans millennia. Considering the extent of these structures, remote sensing is a valuable tool to understand their spatial distribution, which provides information regarding the communication network between cities, smaller settlements, or agricultural areas for irrigation. Considerable work concerning watercourses in the Uruk-Larsa region was conducted by Adams and Nissen through the Warka Survey (Adams and Nissen, 1972; Adams, 1981) and since then, other researchers have further extended their work through archaeological, geomorphological and geoarchaeological studies (Geyer and Sanlaville, 1996; Pournelle, 2003; Jotheri and Allen, 2015; Jotheri, 2016; Jotheri et al., 2018). However, some areas remain unmapped, being concentrated mainly where dunes hide the ground surface.

The goal of our study is to bring new contributions to the mapping of ancient watercourses (paleo-channels and canals) through a remote sensing survey, specifically focusing on connections between Uruk and Larsa. As the high mobility of dunes regularly reveals previously hidden features, new high-resolution imagery allows for the identification of undetected features and to fill-in these geographical gaps, testifying to the need for consistent monitoring of this well-known, archaeologically important area. The re-examination of this part of the deltaic plain is also an opportunity to develop a catalogue of the signatures of anthropogenic and natural watercourses, highlighting the peculiarities of natural processes over human development and vice-versa.

2. General context

The study focuses on the deltaic plain of the Euphrates between Uruk and Larsa, two major ancient cities of Southern Mesopotamia that are located north of the current course of the Euphrates, in a wide desertic plain mostly impacted by aeolian processes and strong deflation (Fig. 1, A - B). Large areas of this plain are covered with highly mobile *barkhan* dunes. South of the desertic plain, agricultural lands on the sides of the Euphrates expand slowly northwards with the use of modern irrigation techniques, towards the desertic plain (Fig. 1, C). A dense network of channels (natural and anthropogenic) used to cross the plain from the early 4th millennium BCE until they gradually shifted (Adams and

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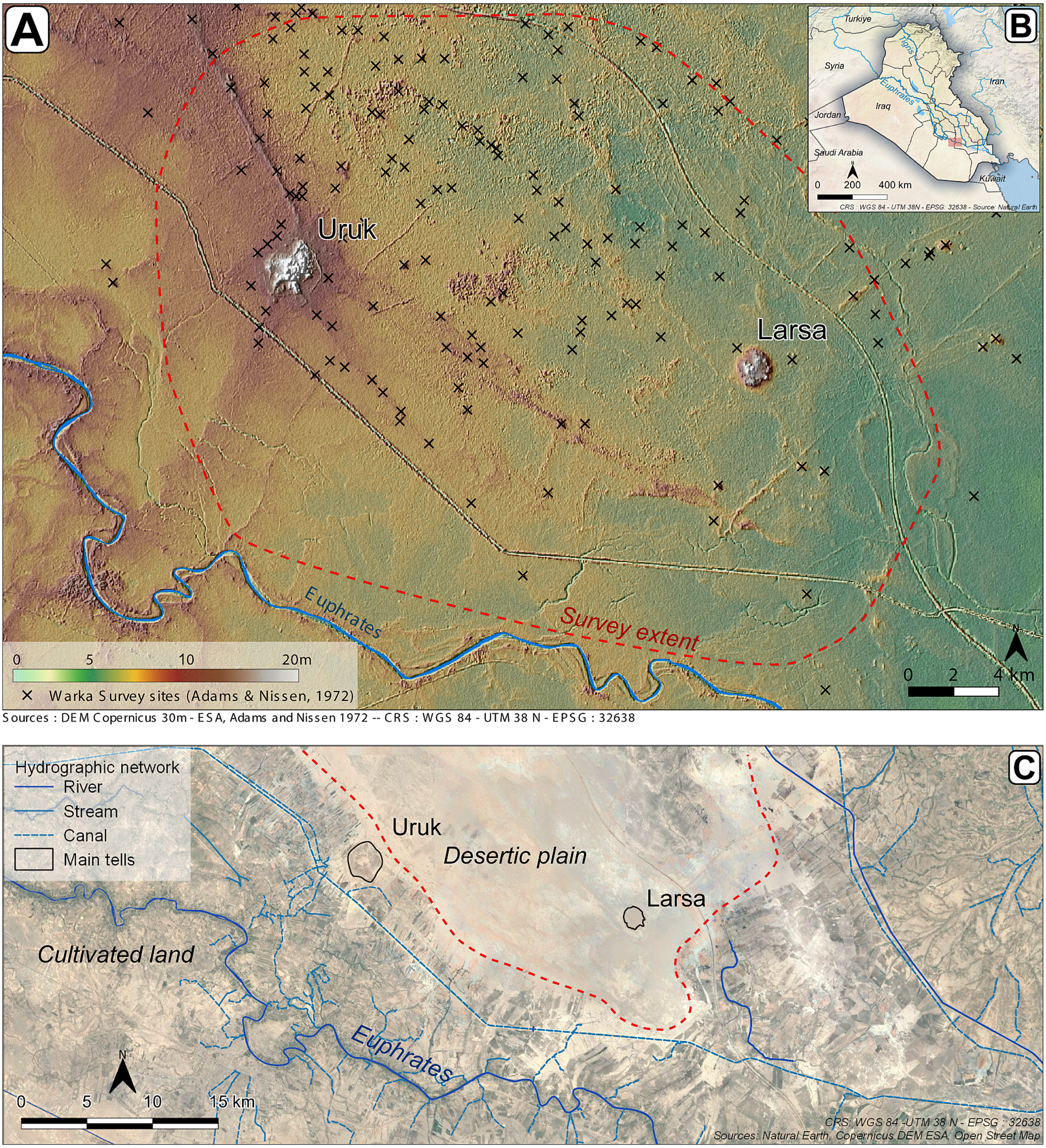

Fig. 1. Location of the study area: 1a, Digital Elevation Model map of the study area; 1b, location of the study area within Iraq; 1c, Satellite view of the current aspect of the study area highlighting the contrast between desertic and cultivated areas.

Nissen, 1972; Jotheri et al., 2018) around the 1st millennium BCE, leading to the progressive abandonment of sites. The area then turned into a wide marsh land during the Islamic Period (7th c. CE) and until the Ottoman Period (16th c. CE), with then a progressive aridification of the plain leading to its current desertic landscape (Sanlaville, 1989; Geyer and Sanlaville, 1996; Jotheri et al., 2018). The strong deflation, coupled with low sedimentation after the shifting of the channels, led the structures to be fossilized and clearly visible on the current barren ground (Geyer and Sanlaville, 1996; Sissakian et al., 2020).

High sedimentation linked to repeated flooding and the high mobility of the Euphrates, combined with urban and agricultural development in the area, prevent the detection of any features close to the current course of the Euphrates. This sector was also reached by the last maximum marine transgression around 4000 BCE (6000 BP) (Pournelle, 2003; Engel and Brückner, 2021), separating for a time the cities of Uruk and Larsa from Ur to the south. However, the marine transgression would not have reached Uruk and Larsa according to the latest studies (Pournelle, 2003; Jotheri et al., 2018; Engel and Brückner, 2021; Iacobucci et al., 2022). The Euphrates was thus used as a southern limit for the survey extent.

While the Warka Survey had mapped the evolution of watercourses in an undifferentiated way, our survey of the area attempted to

Table 1
Overview of the material used for the remote sensing survey.

Type of data		Year	Spatial resolution/scale	Data available from	Supplementary information
Satellite Imagery	SPOT CIB-10	1990	10 m	USGS	Open access
	Sentinel-2	2019, 2022	10 m	ESA	Open access
	Pleiade-1	2019, 2020	0,5m	Apollo Mapping - Airbus	
	Pleiade Neo	2022	30 cm	Apollo Mapping - Airbus	
	ALOS AVNIR 2	2006	10 m	ESA	Open access
	Google Earth	2011 to 2019	–	Google Earth - Maxar	Open access
	ESRI Satellite	2019	–	ESRI	Open access
	Bing Virtual Earth	2019	–	Bing	Open access
	Declassified CORONA	1967, 1968	3 m	USGS	Open access
	Declassified HEXAGON	1972, 1973, 1974	2 to 4ft / 0,6 to 1,2m	USGS	Open access
Digital Elevation Model	Copernicus DEM	2019	30 m	ESA	Open access
Maps	Warka Survey watercourses map	1972	–	Adams and Nissen (1972)	Georeferenced
	Main map - Fig. 4	2018	–	Jotheri et al. (2018)	Georeferenced

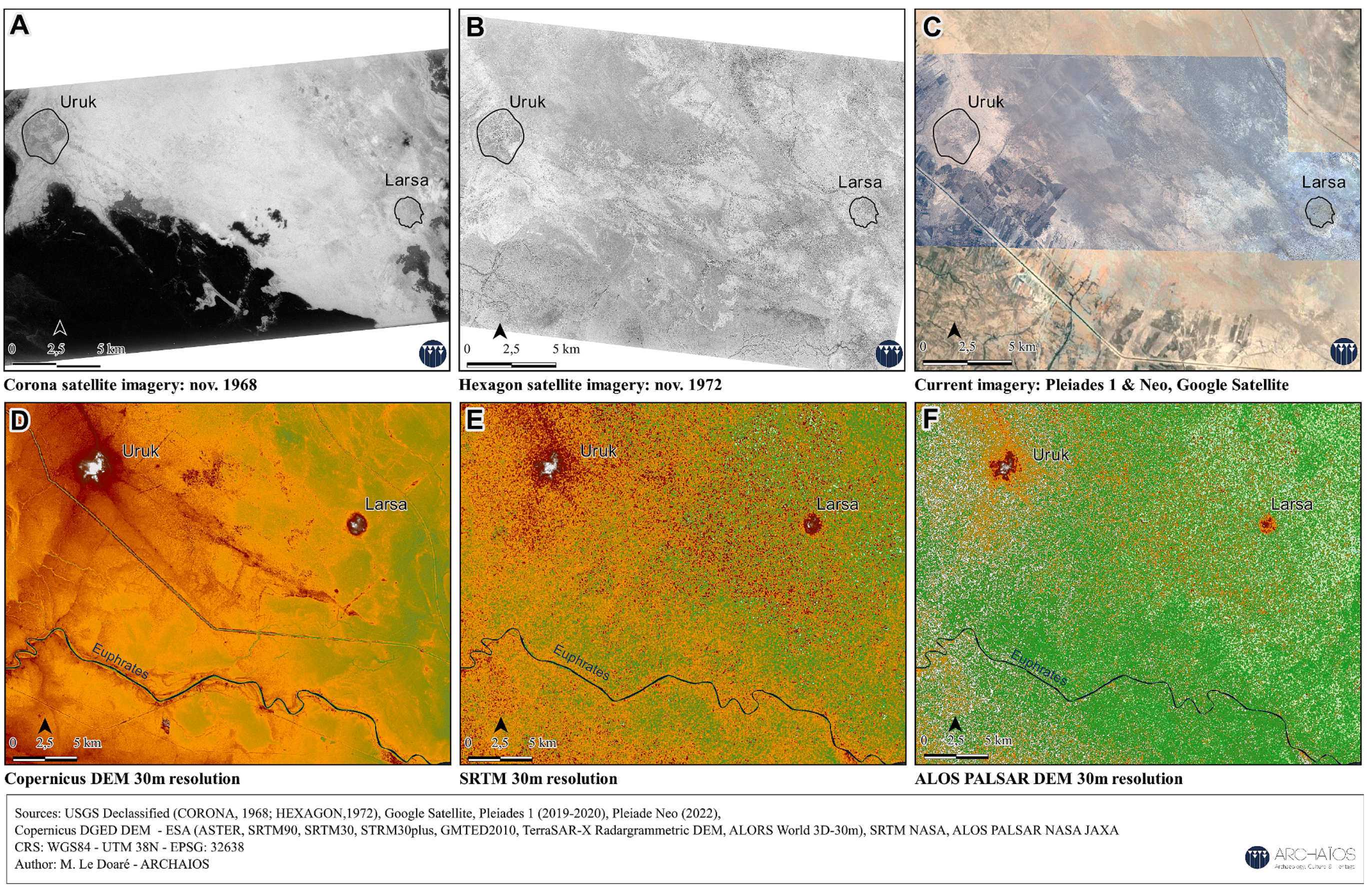

Fig. 2. Presentation of the remote sensing dataset and comparison of regional open access DEM for the area: 2a, Corona satellite imagery (1968); 2b, Hexagon satellite imagery (1972); 2c, Current imagery (Pleiades 1, 2019–2020, Pleiades Neo, 2022, Google Satellite); 2d, Copernicus DEM at 30 m resolution (ESA); 2e, SRTM DEM at 30 m resolution (NASA); ALOS PALSAR DEM at 30 m resolution (JAXA, NASA).

differentiate each section between natural paleo-channels and the anthropogenic hydraulic network of canals. This distinction could bring more insight into the understanding of the network development and use.

3. Material and methods

3.1. General methodology

The resources utilized for the survey combines satellite imagery that includes declassified imagery (CORONA and HEXAGON (USGS)), Digital Elevation Model (DEM), and georeferenced maps (Table 1 and Fig. 2).

Copernicus DEM, produced by the ESA and providing a 30 m resolution open access world cover, was developed from the combination of multiple elevation datasets that subsequently had corrections applied to improve its quality (Airbus, 2022). It was preferred for our survey due to the extreme flatness of the area (Geyer and Sanlaville, 1996), whereas other regional DEMs, such as the SRTM, present significantly noisier data which prevents an extensive analysis (Walstra et al., 2011) (Fig. 2). Copernicus DEM does not require the application of additional processes such as filtering or interpolation, and in the specific area of study, its quality is far superior (Fig. 2). Using this DEM and published maps, Warka Survey sites (Adams and Nissen, 1972; Adams, 1981) that presented an elevation were identified and then confirmed through satellite imagery. The watercourse map of Adams and Nissen (1972) was

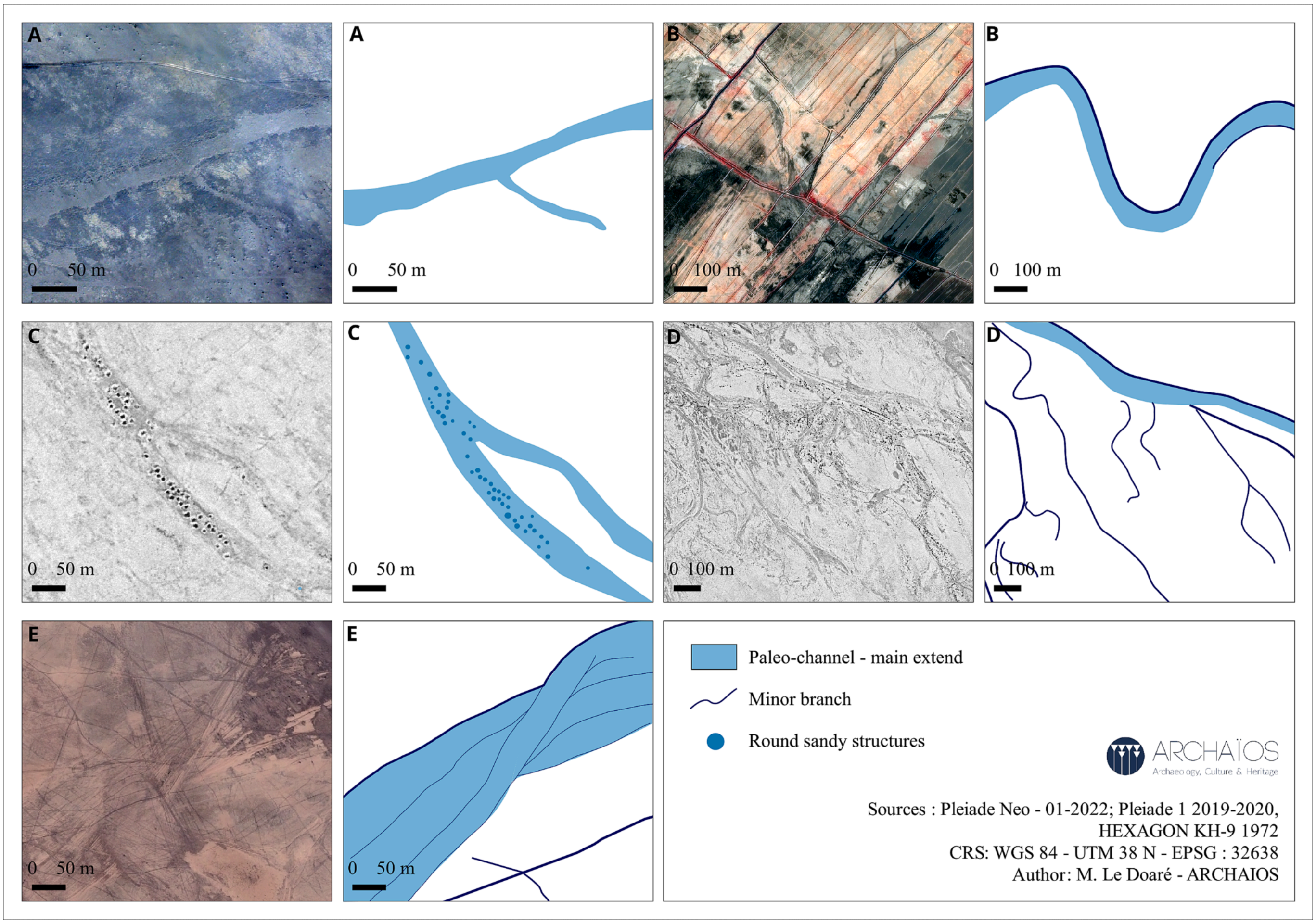

Fig. 3. Signatures for the detection of paleo-channels presenting the five identified types of paleo-channels (A to E). The example used for each type is located on Fig. 5.

georeferenced in QGIS 3.16 within our survey's extent (southern part of the Warka Survey – towards the current Euphrates) using the sites as reference points.

A lack of contrast in this desertic environment can lead to difficulties in the detection of features, as contrast is one of the main detection criteria. In order to overcome this limitation, multiple data sets were used that covered a long-time span and included different seasons (humidity focus), time of recording (light focus), and multi-spectral imagery. This allowed us to better distinguish features and to corroborate each of them with the different sets of imagery.

The remote sensing survey was carried out by the digitalization of the structures into QGIS 3.16, as well as in Google Earth Pro through their archive imagery. A combination of methods was applied that demonstrated their effectiveness for watercourse detection, such as: photointerpretation of recent and declassified archive images (previously used in Philip et al., 2022; Ur, 2003, 2013; Pournelle, 2003; Hritz, 2010; Walstra et al., 2011; Jotheri et al., 2016; Jotheri et al., 2018; Becker et al., 2019, Hammer et al., 2022), terrain analysis (previously used in Hritz and Wilkinson, 2006; Hritz, 2010; Walstra et al., 2011; Wilkinson et al., 2015; Jotheri et al., 2016; Jotheri et al., 2018; Iacobucci et al., 2022; Kawakami, 2022) and multi-spectral analysis (previously used in Geyer and Sanlaville, 1996; Pournelle, 2003, Jotheri et al., 2016; Rayne and Donoghue, 2018; Iacobucci et al., 2022).

Previous research, encompassing remote sensing and field survey that focused on paleo-channel (Pournelle, 2003; Jotheri et al., 2018; Jotheri, 2018; Walstra et al., 2011) and canal detections in Southern Mesopotamia (Geyer and Sanlaville, 1996; Jotheri and Allen, 2015; Darras and Vallet, 2021; Engel and Brückner, 2021; Hritz and Wilkinson, 2006; Hritz et al., 2012; Jotheri and Allen, 2015; Jotheri et al., 2019; Hammer et al., 2022, Jotheri et al., 2022) brought elements of identification and characterisation. The channels and canals identified by those authors were systematically searched across the datasets. Dune maximum extension was digitised for 1972 and 2022 using unsupervised classification and manual digitalisation on the materials of the corresponding years listed in Table 1.

Dune mapping for 1972 and 2022 (Figs. 5-6) enabled the observation of the main areas of mobility, as well as the ones that are still covered or where large gaps in detection remain. J. Pournelle (2003) had, in the same way, already presented areas where dune mobility allowed her to fill-in gaps from the Warka survey (Adams and Nissen, 1972). A general orientation of the dune displacement appears towards the southeast (Figs. 5-6), corresponding with the main wind directions coming from the northwest (*Shamal*) (Albarakat and Lakshmi, 2019; Sissakian et al., 2013).

3.2. *Watercourse identification criteria following former studies*

Following the traditional methods used in previous research, criteria for identification of watercourses based on colour, structure, shape, context, and scale were listed (Walstra et al., 2011). Canals described a few kilometres west of Larsa by Geyer and Sanlaville (1996) during the Larsa-'Oueli survey, were clearly visible through the available imagery and the detailed description provided by the authors (Figs. 6 – W1 & 2). Due to this, these canals were used as a starting point. Some of the main

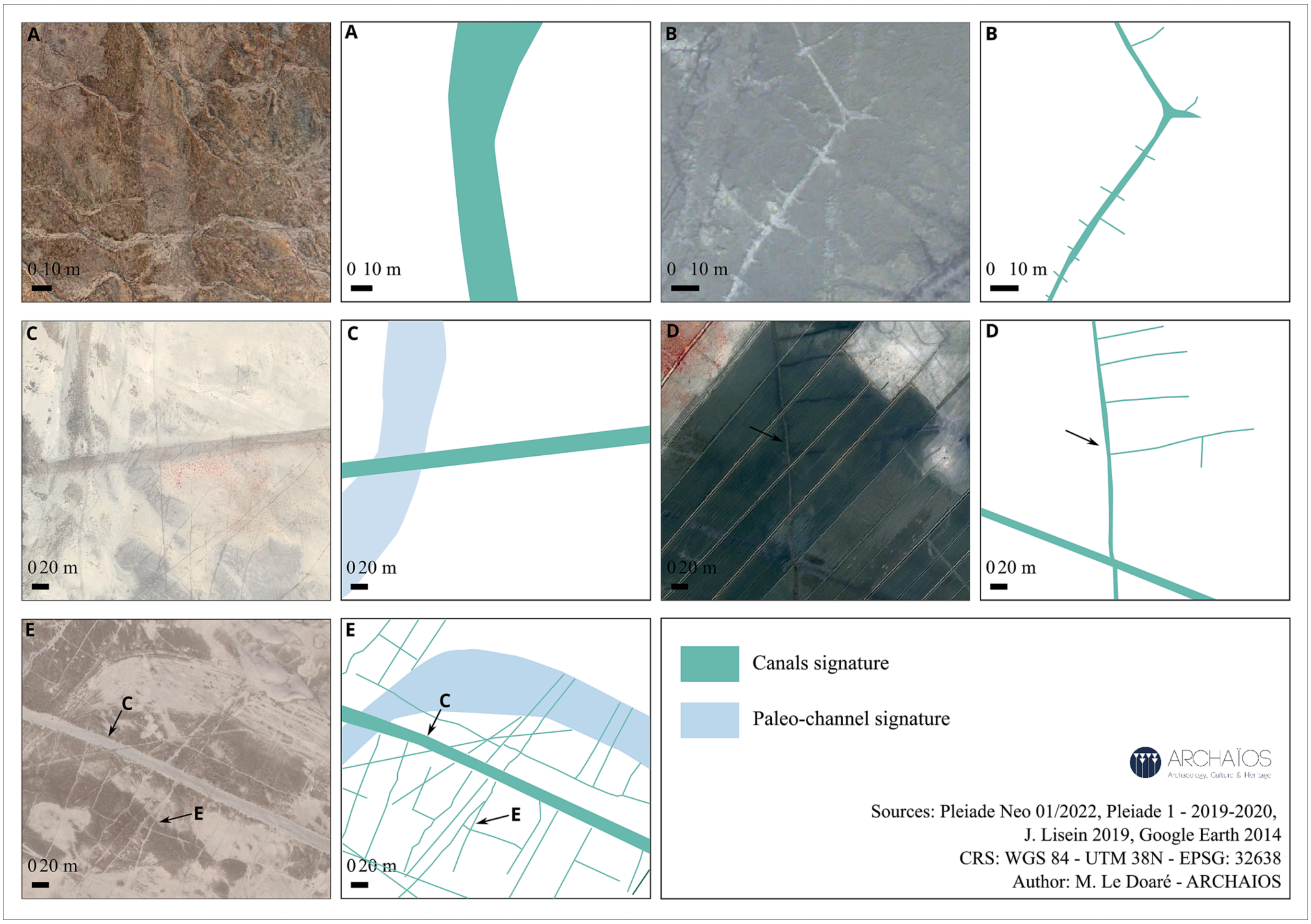

Fig. 4. Signatures for the detection of canals presenting the five identified types of canals (A to E). The example used for each type is located on Fig. 6.

criteria listed by the authors were regular width (mean of 7 to 14 m), colour contrast with the surroundings, and the presence of vegetation (Fig. 4 – C). The infilling of the structures is described as light coloured sandy aeolian material, while their surroundings were darker silty-sand (possibly alluvial) sediments (Geyer and Sanlaville, 1996). This infilling corresponds to a post-drying abandonment phase. Similar top infilling is described by Engel and Brückner (2021) in canal coring conducted in Uruk. Beneath those aeolian sands, sediments characteristic of low-energy fluvial environments were described (laminated with rounded ceramic fragments) supporting their characterisation as canals.

A catalogue of identification criteria for canals in Southern Mesopotamia was also developed by J. Jotheri (2018). It supports the criteria mentioned above and complements them, which allows differentiation of natural paleo-channels from anthropogenic canals. The pattern and shape of the anthropogenic structures are rectilinear with dendritic or herringbone patterns, unlike natural features that present meandering or anastomosed patterns. The shape and size of levees, when present, also allows differentiation of natural from anthropogenic features, with narrow and steep levees being characteristic of anthropogenic canals, while large and gently sloping levees are a significant indicator for natural channels (Jotheri, 2018; Kawakami, 2022) (Figs. 3 and 4). Additionally, orientation of the structures can distinguish between both types as anthropogenic canals can cross natural channels perpendicularly, or follow a path regardless of the slope (as it remains moderate within the area), while natural channels would follow the general slope of the terrain.

4. Main results

4.1. Catalogues of signatures

Following the characterisation elements from the pre-existing literature, and the newly detected structures from the present study, an original catalogue of signatures was established for natural and anthropogenic watercourses (Figs. 3 and 4).

4.1.1. Signatures of paleo-channels

Five types of paleo-channel signatures were identified (Fig. 3). The first one (A) concerns most of the detected features. It consists of features that are straight to curvy, with variable width and low-marked edges that present a slight depression and a contrast of colours with the surrounding soil. The second type of feature (B) is visible by contrast on cultivated lands, they are enhanced through infra-red composite imagery. The third type (C) is similar to the first, but presents clustered round structures in its former bed (Fig. 3, C). These structures can be observed through the whole plain, but always within former riverbeds. From ground survey, they appeared to be used as animal pens (Giraud et al., 2022). However, their exclusive location raises questions regarding a different original use and a later reuse for animals. They could also be wells dug by Bedouins, as mentioned by Geyer and Sanlaville (1996, p.393) and described as unshored temporary wells. The fourth type (D) designates crevasse splays and anastomosed channels. They could be linked to natural events or breaches voluntarily created in the riverbanks to irrigate nearby lands (Giraud et al. 2022). Finally, the fifth type (E) describes scrollbars, allowing observation of the mobility of paleo-

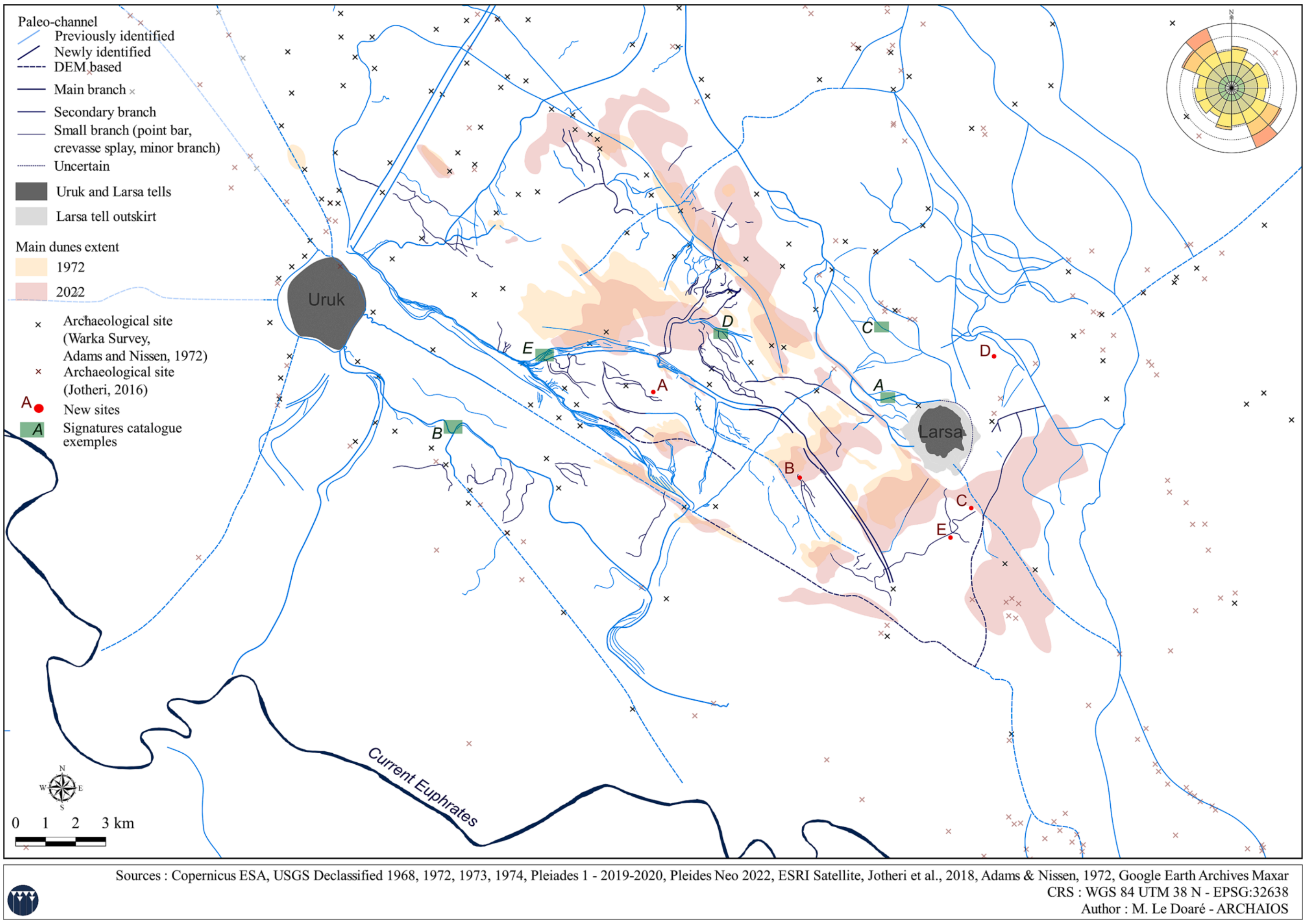

Fig. 5. Map of the paleo-channels detected in the surveyed area with the main dune areas and archaeological sites.

channels. It is also a discriminant criterion between anthropogenic irrigation features and natural fluvial ones (Jotheri et al., 2022).

4.1.2. *Signatures of canals*

Five types of canals have been defined within the survey (Fig. 4). Types A and C both correspond to previously identified canals. Type A corresponds to the Larsa *Grand Canal*, which is light in colour, significant in width, and has no apparent relief (Darras and Vallet, 2021; Giraud et al. 2022). Type C is the canal identified by Geyer and Sanlaville (1996) which is described in the methodology (3.2.).

Type B is composed of fine whitish linear structures, with smaller side-branches resembling distributary canals. They could correspond to the inverse canals mentioned by Engel and Brückner (2021) in Uruk, but we identified them east of Larsa (Figs. 4 and 6). They are caused by the cementation of the infilling of the canals, which results in differing erosion patterns that leads to the former canal appearing as an elevation due to relief inversion.

Type D is similar to the second type of paleo-channel, as it consists of features visible by their contrast within currently cultivated lands, which is related to the moisture variation of the ground. Their distinct orientation compared with the actual plot's configuration, as well as their continuation through several plots, aids in characterizing them as archaeological features.

Type E consists of a dense network of smaller linear features that could be plots or irrigation distribution canals for agricultural purposes. They present a generally lighter colour from the surrounding ground. On the example presented (Fig. 4), they are connected to a larger structure corresponding to a type C canal.

4.2. *Watercourse landforms network*

4.2.1. *Paleo-channels*

Paleo-channels run through the entire survey area in a dense network contrasting with the current desertic landscape (Fig. 5). Our study detected new sections from previous studies (Adams and Nissen, 1972; Adams, 1981; Pournelle, 2003; Jotheri et al., 2018), such as small branches or crevasse splays, but also hydrological levees (Hritz and Wilkinson, 2006; Jotheri et al., 2016) using a less noisy DEM, as mentioned in the methodology (3.1). The high density of channels is the result of hydrological processes over a long period of time (over the Holocene), as well as channels tending to anastomosed systems which create numerous branches. Most of the newly detected channels are located in the areas most densely covered by dunes (Fig. 5 – in dark blue). Subsequent to their detection, the focus shifts to distinguishing natural from anthropogenic features, with an important criterion for this being the specific orientation of the paleo-channels which follows a NNW to SSE course (Fig. 5).

4.2.2. *Canals*

Anthropogenic structures were detected across the study area and are denser in the central part of the survey, where they follow a general axis going from SE of Uruk to SW of Larsa (Fig. 6). Over and around Larsa, structure representation had to be simplified considering the scale of the study of the paper, as they are subject to an in-depth analysis within the framework of the MAFLU (*Mission archéologique française de Larsa-Uwaili)* (Darras and Vallet, 2021; Giraud et al. 2022).

The straighter watercourses (Fig. 6 - W3 & W5) from the Warka

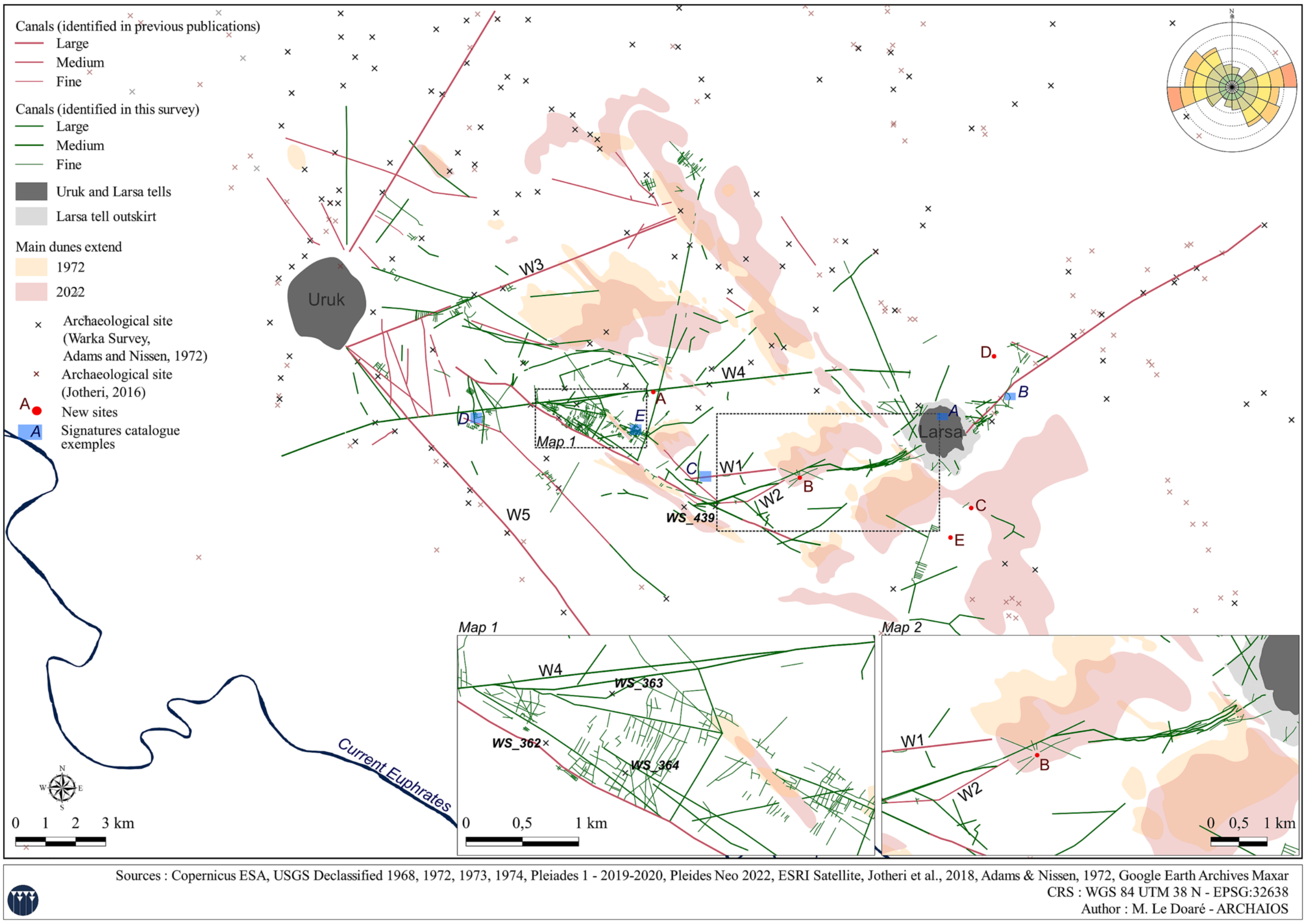

Fig. 6. Map of the canals detected in the surveyed area with the main dune areas and archaeological sites.

Survey (Adams and Nissen, 1972; Adams, 1981) as well as canals identified by Geyer and Sanlaville (1996) were used as a starting point for the survey, with previously sand-covered sections of these features being identified and recorded. Following this path, a wide network has been detected covering the whole survey area (Fig. 6).

One of the biggest structures (Fig. 6 – W4) is a 21 km long and 16 m wide linear structure crossing the plain from SSW to East, and intersecting at least four main paleo-channels between Larsa and Uruk. Some sections are currently covered by dunes, but with the use of declassified satellite imagery (CORONA and HEXAGON, USGS), most of it could be reconstituted. It clearly overlaps a paleo-channel close to WS363 (Fig. 6 – Map 1), indicating a relative chronology between them.

Similar features (Fig. 6 - W3 & W5) were identified during the Warka Survey (Adams and Nissen, 1972) in the western part of the survey area: long and wide linear structures with numerous side branches punctuated by archaeological sites. The sites along the W4 canal would tend to be dating from the Neo-Babylonian to Parthian periods (circa 500 BCE to 200 CE) (Adams and Nissen, 1972).

Many smaller canals were detected, sometimes only fragmentary. The denser area of identification of those fine structures is located near the sites WS362, WS363 and WS364 from the Warka Survey (Adams and Nissen, 1972) in the central part of the area (Fig. 6 – Map 1). It consists of many connected linear features which could be linked to irrigation or plot delineation, in a zone where J. Pournelle (2003) mentions a Parthian field system. Similar structures were ground surveyed on the outskirt of Larsa (Giraud et al., 2022) and were recognized as agricultural irrigation system. Of note were the observations of some herringbone patterns within the detected structures. This pattern is a typical irrigation pattern for the area (Pournelle, 2003; Walstra et al. 2011; Widell et al., 2013; Wilkinson et al., 2015; Jotheri, 2018) and a good indicator for anthropogenic development.

Most structures identified as canals are oriented along a SW-NE axis (Fig. 6), while the general, although very gentle, slope goes from NW to SE (Fig. 5). A possible distinct orientation from natural flows is mentioned (Jotheri, 2018) as an indicator for characterisation of canals of Southern Mesopotamia. The very gentle slope of the plain facilitates hydraulic construction in any direction, regardless of the slope. In contrast, for steeper relief areas, it would be a criterium for ancient track identification (Ur, 2003; Rayne and Donoghue, 2018).

4.3. Other discoveries: Archaeological sites

During the survey of the area, additional features were detected as potential archaeological sites that were not described in the literature (Table 2). They are located along paleo-channels and canals and display significant indicators of anthropogenic establishment. They all present similar surfaces and general shape.

Site A (Fig. 7) is located at the centre of the study area, close to the crossing of canal W4 with another perpendicular canal. It presents a pentagonal shape of 0.6 ha and is surrounded by a ditch which could be a canal on its eastern side.

Three kilometres west of Larsa, and of approximately 10 ha in size, site B (Figs. 7 and 8) is composed of a rectangular enclosure in which an ovoidal feature of about 1 ha is visible. As the area where site B is located is currently largely covered by sand dunes, the site was identified on declassified aerial imagery, especially HEXAGON (KH-9, 1972 and

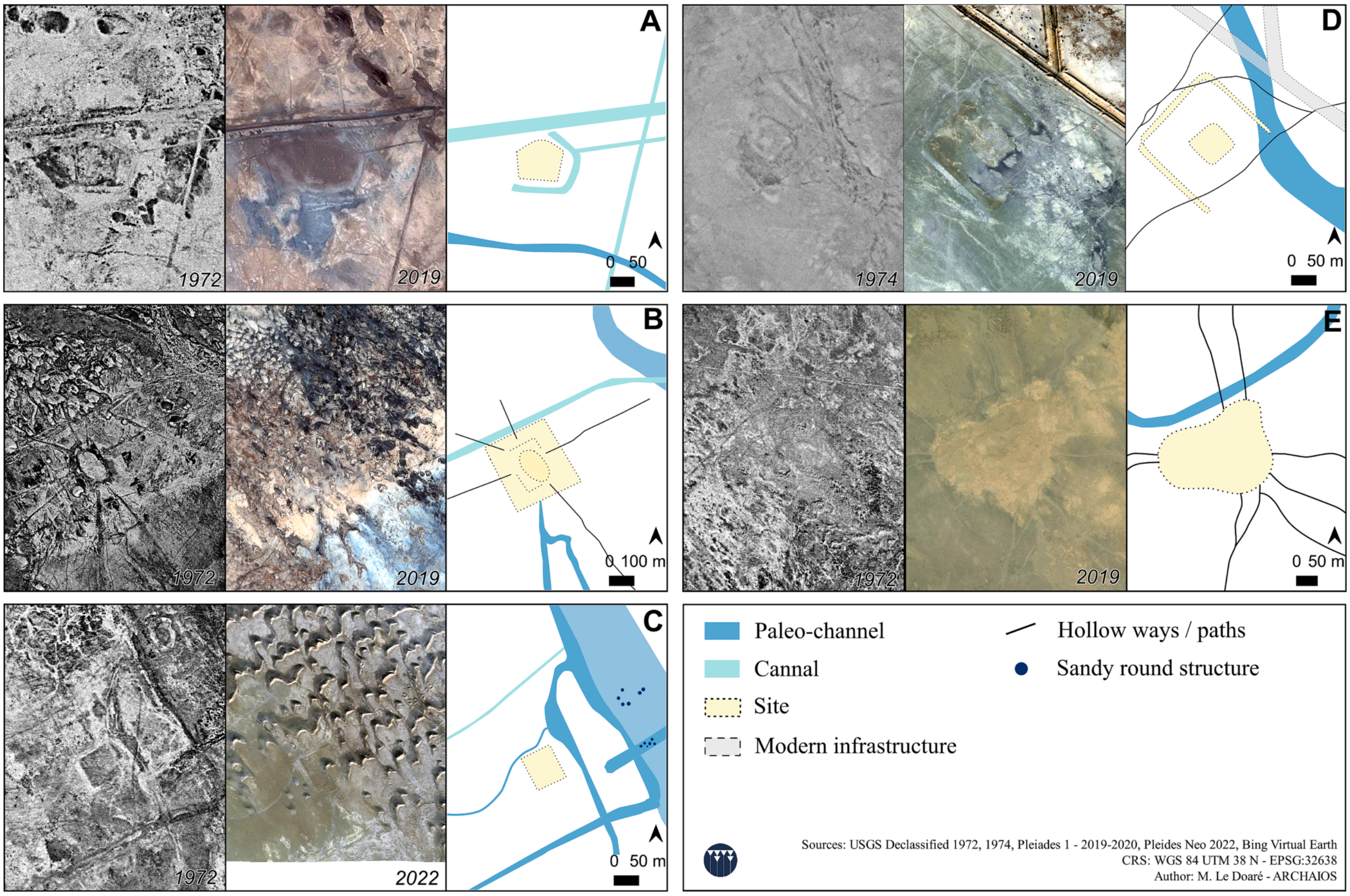

Fig. 7. Detailed presentation of the five newly identified archaeological sites (A to E). They are located on Figs. 5, 6 and 8, and their geographic coordinates are detailed in Table 2.

1974, USGS). On more recent imagery, and despite the dunes, traces of isolated and manual looting pits were detected (Google Earth, 2014; Pleiades 1, 2019). Many branches radiate from the structure, which could be possible hollow ways (Ur, 2003; Jotheri et al., 2019), or drains. The location of this site, within the continuation of the canals identified by Geyer and Sanlaville (1996) and on an axis that would join the west part of Larsa, highlights a new connection between Larsa and Uruk (Fig. 6 – Map 2). A large paleo-channel going from north to south is also located nearby. This site and the canals detected around it thus help to fill in a gap in the watercourse mapping of the plain.

Site C is situated 2 km south of Larsa and presents a square shape measuring 0.4 ha (Figs. 7 and 8). It is clearly visible on both older and current imagery, with it presently in the process of being covered by dunes (Fig. 7 – C – 2022). A canal was detected north of the site, and it is also close to a small paleo-channel that connects to a larger one.

Site D is located 2 km north-east from Larsa and close to the actual highway to the east (Figs. 7 and 8). It is a 0.4 ha square-shaped site, located close to a large paleo-channel orientated on a north-west/south-east axis. It is surrounded by a larger structure with a similar square shape, bringing its total surface to circa 3 ha.

Finally, site E is located near site C, approximately 2 km south of Larsa and 3 km north-west of Oueili. It measures circa 5 ha and is along a paleo-channel. It can be seen that the site has multiple traces of looting from the satellite imagery (Fig. 7, Pleiades 1, 2019).

5. Discussions

The results obtained through the study of satellite imagery and ground truthing at Larsa (Giraud et al., 2022), combined with paleoenvironmental studies performed in the region and at nearby sites (Jotheri et al., 2018; Hammer, 2019; Forti et al., 2022) allow for the reconstruction of the agricultural landscape associated with the significant urban development of the region from the fourth millennium BCE to the early CE (Fig. 8) (Adams and Nissen, 1972; Adams, 1981; Hritz et al., 2012; Jotheri et al., 2018; van Ess and Fassbinder, 2019). The *natural* landscape throughout the Holocene consisted primarily of Euphrates tributaries, anastomosing rivers, small lakes, and marshes (Jotheri, 2018; Forti et al., 2022). Despite the presence of the Persian-Arabian Gulf a few dozen to hundreds of kilometres away (Pournelle, 2003; Jotheri et al., 2018), the hydrological landscape surrounding the study area sites was composed primarily of flowing freshwater (Jotheri et al., 2018; Forti et al., 2022) from rivers or canals. Steady aridification processes began from the early Holocene.

Natural flows (Fig. 8) were gradually anthropized and controlled through the use of dams and dikes (Jotheri, 2018). Hydraulic resources from the Euphrates tributaries were rerouted into anthropogenic canals that brought freshwater where needed, such as for the creation of fluvial harbours, the implementation of protective canals around cities, or urban water structures meant to supply specialised workshops or local industries as existed in Uruk, Ur, Abu Tbeirah and Larsa. Smaller anthropized structures attest to irrigation canals intended for agricultural purposes.

Using previous studies to contextualize our own research (Jotheri and al., 2018; Hammer, 2019; Forti et al., 2022; Giraud et al. 2022) enabled us to associate functions to the identified canal signatures, resulting in the study distinguishing three major functional types.

The first functional type, which encompasses the widest canals, can be seen as having the main function of navigation, circulation, or

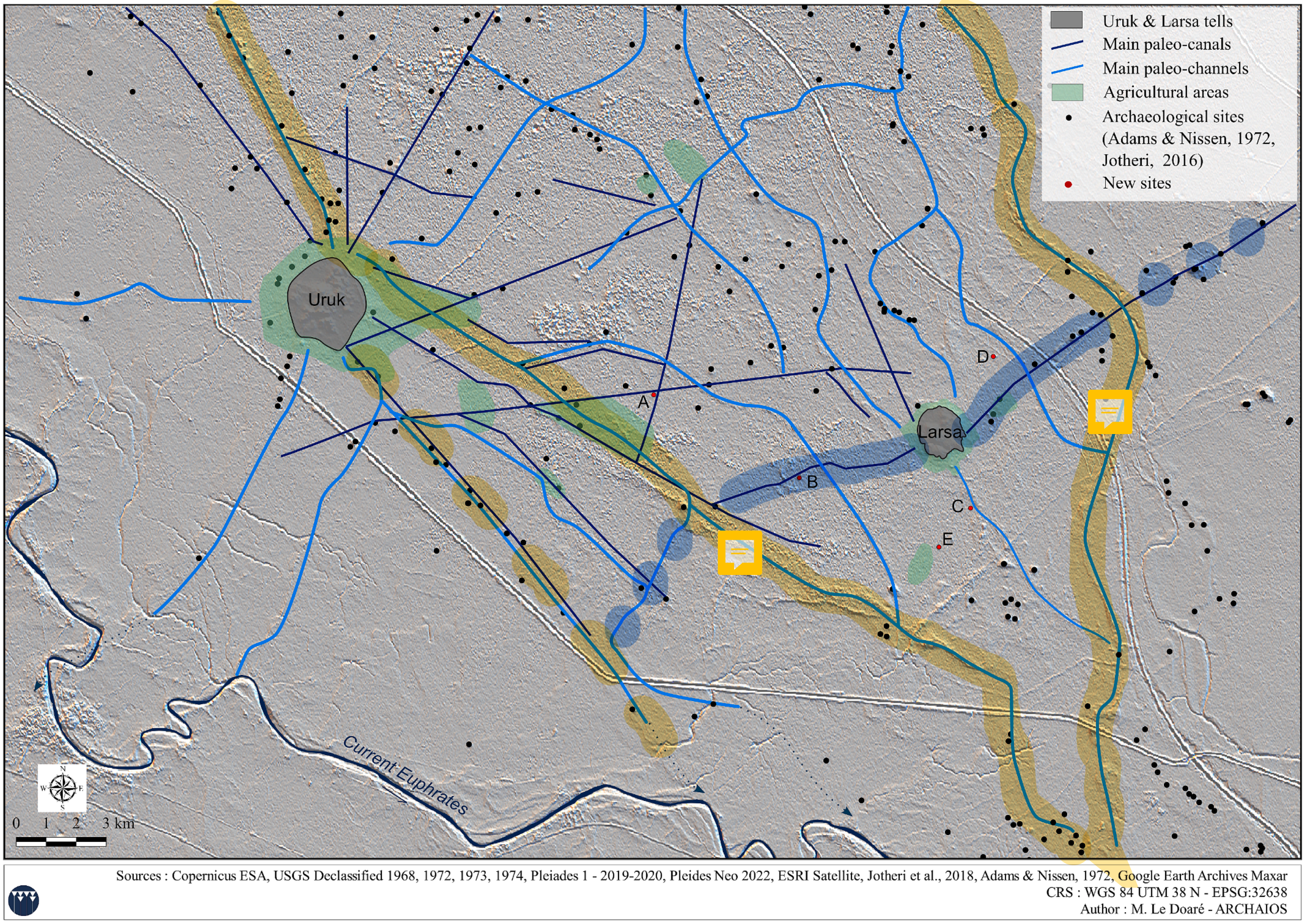

Fig. 8. Synthetic map of the ancient water systems between Uruk and Larsa.

Table 2
Geographic coordinates for the five new sites.

ID	Latitude	Longitude
Site A	31°17′48,00″N	45°45′10,98″E
Site B	31°16′14,20″N	45°48′14,55″E
Site C	31°15′39,96″N	45°51′50,12″E
Site D	31°18′23,94″N	45°52′20,33″E
Site E	31°15′8,15″N	45°51′23,74″E

transportation, as they acted as the main arteries that connected the largest sites. These canals correspond to the type C signature (Fig. 4). The colour of these features contrasts with their surroundings, as the infilling of the structures are light coloured sandy aeolian material while the surrounding soil is a darker silty-sand (possibly alluvial) sediment. They follow the natural slope and create a network between sites, such as W1 and W2 (Fig. 6) which connects Uruk to Larsa through Umm al Wawiyah (WS439) and Site B.

The second and most abundant type consists of type B, D and E signatures (Fig. 4), and corresponds to irrigation canals. They are narrower and often organized in a dense network of small linear structures. Type B, which are earlier canals, appear as inverted reliefs and consist of fine whitish linear structures with side-branches that resemble distributary canals. It could be interpretated as distribution canals for the entire irrigation system around a city, as identified in Larsa (Giraud et al., 2022), or as canals that connect water reservoirs to portions of the irrigation system. Types D and E (Fig. 4) consist of a complex network of small linear structures identified as irrigation canals that surround agricultural plots. Located only around settlements (Uruk, Larsa, Site B), this type of pattern, should it be analysed over a larger study area, would provide a more accurate picture of the general landscape and be an indicator for potentially unknown new sites if found away from recorded ancient settlements.

The third functional type, urban canals, can be associated to the type A signature. We only wish to mention the existence of this type here as it will be discussed more in-depth elsewhere, but current studies make it possible to draw a new image of the Mesopotamian city. What they begin to show is that these ancient city-states were surrounded by external canals that possibly served a secondary defensive function (Uruk, Ur, Larsa), and sometimes were constructed in conjunction with a city-wall (Larsa). The external canal systems served a diverse set of functions, as they supplied water to the interior ports (Larsa, Uruk, Ur, Abu Tbeirah), acted as a source of fresh water for consumption, and played a key role in brick, pottery, metallurgic, and dyeing activities (Giraud et al., 2022).

Progressively, it is possible to outline not only the ecological landscape but also an anthropized geographical space, highlighting the connections between human populations and their environment (Jotheri et al., 2018). It represents an anthropogenic space built around city-states that are economically and socially connected to one another, but who also share water resources and agricultural systems.

The restitution of this space, unfortunately, is limited to the data collected so far. For the time being, we can neither know how nor when this anthropisation of the landscape occurred. Thus, the presented maps (Figs. 5, 6 and 8) form a complex palimpsest, a landscape of multiple geographies where all detected canals are featured on the same temporal level, even though they correspond to millennia of occupations. The works around Uruk (Jotheri et al., 2018) put forward an interesting evolution in four stages based on a relative dating of the canals according to the nearby sites. In the outskirt of Larsa, we also attempted a relative dating of the agricultural canals and discussed three phases (Giraud et al., 2022). However, as no absolute dating has been carried out on these newly identified structures, it remains highly hypothetical and suggests fairly long durations for each identified stage.

6. Conclusion and perspectives

6.1. A regional network between Uruk and Larsa

The main intake from this study is the mapping of a connection between the south-eastern channel descending from Uruk and the west canals of Larsa, which are the continuation of the Geyer and Sanlaville (1996) canals. The newly discovered site B is located on this important axis and will be a key element in dating and understanding this section of the network. This previously empty area now presents a major connecting route in the hydraulic network of the Uruk-Larsa region, as it would be one of the most direct paths between both cities. Another canal was detected over a significant distance, up to 21 km long, crossing numerous sites. The study also highlighted the high potential of the analysis of the Copernicus DEM in comparison with others regional DEMs for remote sensing of hydrological and archaeological features in Southern Mesopotamia, and testify to the need to re-examine the area regarding the mobility of dunes and the improvement of the available open-access data.

By proposing a functional typology associated with the signatures of the canals, it brings new elements to reconstruct a complex hydraulic system and anthropized landscape that was constantly manipulated over millennia of human occupation. The functional typology also provides additional data regarding the communication networks between cities, smaller settlements, and agricultural areas.

6.2. Perspectives

More features most certainly remain to be found and other datasets could be examined, such as the U2 Declassified Aerial Imagery (Hammer, 2019; Hammer and Ur, 2019), which presents a better resolution than CORONA and HEXAGON (USGS) and is available for the area of study (Ur and Hammer, 2018). The aerial photographs used for the Warka Survey, from 1961 to 1962, could also be, if located at the SBAH, geo-referenced and re-examined comparatively with other imagery (Adams and Nissen, 1972; Adams, 1981). Finally, an extended ground survey of the identified structures, and of the area in general, would be necessary to precise this study and sample dating material.

CRediT authorship contribution statement

Maureen Le Doaré: Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing. **Mathilde Mura:** Data curation, Software, Validation, Writing – original draft. **Jessica Giraud:** Funding acquisition, Conceptualization, Project administration, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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