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Settling the riverscape of Erbil (Kurdistan Region of Iraq): long-term human overprint on landforms and present-day geomorphological hazard

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ABSTRACT

This paper presents a geomorphological reconstruction of the urban landscape of Erbil (Kurdistan Region of Iraq), aimed at explaining how human groups settled the region since the prehistory and contributed modifying natural surface processes. Our reconstruction on landforms evolution is based on satellite and historical aerial images and field control allowing the reconstruction of changes in land use over time. The city of Erbil was established along a fertile alluvial plain during the Chalcolithic period and grew around the pristine citadel, which was likely built on top of fluvial features. Prior to the mid-20th century, Erbil was centred around the citadel and relied on traditional systems for water management such as artificial basins and qanats. The city underwent intense urban expansion since the 1950 s and changed its shape due to the construction of roads and residential and industrial areas, which led to the obliteration of the pristine fluvial network. The analysis of historical and current satellite images highlights the profound modification of the landscape triggered by human actions and a progressive shift of local land use from agricultural to urban. This, coupled with human agency on the natural hydrography led to the increase susceptibility of the city to geomorphological hazard (especially floods). Our investigation suggests that during the Anthropocene the dynamic of urbanization reach a tipping point, when excessive urban growth suffers the effect of geomorphological hazard. For that reason, urbanization in the Anthropocene must consider the existence of natural geomorphological processes.

1. Introduction

The geoarchaeological investigation on regions continuously attended by humans since the prehistory reveals how humans adapted to settle specific ecosystems, as much as helping to interpret the long-term influence of the human actions on the Earth surface processes (Goudie and Viles, 2016; Brown et al., 2017). In such perspective, the geomorphological investigation on urbanization processes reveals early attempts of human groups of modifying the landscape and tune natural geomorphological processes (Wilkinson, 2003; Bernabo Brea et al., 1997; Brown, 1997; Cremaschi, 2014). In such process, the continuous growth of urban agglomerates may encounter specific issues or menaces related to the interplay between human activities and surface processes (Wilson, 2011). This is especially true considering the effects of climate changes (Bigelow et al., 2005) and the rapid increase of urbanization and demographic pressure that are a distinctive marker of the Anthropocene Great Acceleration (Bini et al., 2018; Elmqvist et al., 2021; Zerboni et al., 2021). For that reason, diachronic studies on urban geomorphology, carried out on historical cities and exploring the mutual evolution of urban plan and natural processes and ecosystems, contribute to better characterize the Anthropocene, its inceptions and how the interaction between humans and surface processes evolved across the Holocene (Chin, 2006, 2022; Hung et al., 2018; Thornbush and Allen, 2018; Harlan et al., 2019; Brandolini et al., 2020; Douglas, 2020; Pérez-Hernández et al., 2020; Pan et al., 2021; Goudie, 2022; Brandolini et al., 2023). Moreover, the interest on urban geomorphology (Quesada-Román et al., 2021; Quesada-Román and Mata-Cambronero, 2021; Vergari et al., 2022; Singh et al., 2023) as well as urban geoheritage (Chandel et al., 2022; Herrera-Franco et al., 2022; Prabhakar and Radhika, 2022; Xu and Wu, 2022; Quesada-Valverde and Quesada-Román, 2023) is growing because they represent key points for better understand the relationship between natural landscape shaping processes and human activities, in environmental reconstructions, geoheritage assessment, and geoarchaeological studies (González and Ballester, 2011; Salazar et al., 2014; Pica et al., 2016; Emmanuel et al., 2017; Reynard et al., 2017; Moradipour et al., 2020; Pelfini et al., 2021).

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If we consider the factors controlling the distribution of human settlements in the Late Quaternary, as much as the inception of early forms of (proto-)urbanizations the distribution of existing landforms and active geomorphological processes are among the most important criteria (e.g., Morozova, 2005; Cremaschi and Zerboni, 2009; Macklin and Lewin, 2015; Lü et al., 2019; Persico et al., 2018; Aucelli et al., 2021; Brandolini and Carrer, 2021). For instance, geomorphological processes influence the availability of natural resources as much as offering natural substrate for buildings or defenses. Since the onset of the Great Acceleration, human agency progressively became more important in reworking landforms and influencing surface geomorphic processes (Jefferson et al., 2013; Ghanavati et al., 2017; Tarolli et al., 2018; Goudie, 2020; Aguilar et al., 2020; Gibbard et al., 2022); this major transition increased the possibility to establish new settlements and possibly pushed the process of urbanization. The effects of human geomorphology in the Anthropocene are, therefore, distinctly evident in urbanized areas and large cities. Dismantling of natural landforms, excavation and filling processes, burial of pristine landforms and watercourses are some of the anthropogenic geomorphic processes that can modify landscapes in urban areas (Goudie and Viles, 2016) and fuel scenarios of hazard and risk (Bathrellos et al., 2016; Brown et al., 2017; Zambrano et al., 2018; Abdelkarim et al., 2019; Brandolini et al., 2020; Cappadonia et al., 2020), including the menacing of the cultural and natural heritage (Del Monte et al., 2013; Pica et al., 2016; Reynard et al., 2017; Jeong et al., 2018; Górska-Zabielska and Zabielski, 2018; Kubalikova et al., 2019; Moradipour et al., 2020; Zerboni et al., 2021; Pelfini et al., 2021; Forti et al., 2023b).

To recognize topographical and geomorphological features in human-modified territories and in the urban contexts is nowadays fundamental for better understanding the environmental responses to extreme events, to assess hazard and risk scenarios and geoheritage vulnerability. In the contexts of urban areas, recent geomorphological mapping and analyses thus allowed the reconstruction of (i) human-impacted surface processes, (ii) the creation of anthropogenic landforms, (iii) the identification of urban geomorphosites, and iv) the increased susceptibility of cities to geomorphological risks (Cremaschi, 2014; Brandolini et al., 2019; Faccini et al., 2021; Mandarino et al., 2021; Pelfini et al., 2021; Roccati et al., 2021; Vergari et al., 2021). Moreover, the long-lasting stratification of urbanization makes difficult the observations of medium to small scale landforms and the interpretation of surface processes. In fact, buildings, infrastructures, and anthropogenic landforms may hide pristine natural landforms (Faccini et al., 2021; Mandarino et al., 2021; Pelfini et al., 2021; Roccati et al., 2021; Vergari et al., 2021). To overcome this issue, a recent approach to reconstruct ancient riverscapes disturbed by human actions employed declassified intelligence satellite imageries. In fact, the geomorphological investigation on historical maps (Gurnell et al., 2003; Grabowski et al., 2014; Brandolini et al., 2019) and remote imagery (aerial and/or satellite) acquired before the great acceleration of urbanization started after WWII (Steffen et al., 2015; McNeill and Engelke, 2016; Forti et al., 2022) is an effective tool able to disclose the complex interaction between natural and anthropogenic shaping process. If we consider Southwestern of Asia, and especially the Kurdistan Region of Iraq (KRI) that was part of ancient Mesopotamia, the inception of human overprint on landscapes dates back to 8000 yr BP, when the emergence of the first urban centres settled along watercourses led to the building of multiperiod mound or tells, composed by the accumulations of multiple archaeological layers, which grew up through time due to stationary occupation of the site (Butzer, 1982; Rosen, 1986; Wilkinson, 2003). This led to a modification of natural hydrography and a shift in land use towards agriculture and herding tuned surface process (Zerboni and Nicoll, 2019; Forti et al., 2023a). More recently, the rapid and uncontrolled expansion of urban areas, soil overgrazing, the over exploitation of natural resources, and anthropogenic modification of the fluvial networks increased the susceptibility to geomorphological hazards of local urban areas (Benito and Hudson, 2010; Youssef et al., 2011; Bathrellos et al., 2016; Faccini et al., 2016; Zambrano et al., 2018; Bourenane et al., 2019; Link et al., 2019; Abdelkarim et al., 2019; García-Soriano et al., 2020; Mustafa et al., 2020; Carabella et al., 2021; Arnous et al., 2022; Feloni et al., 2022; Sissakian et al., 2022; Sakijege et al., 2023).

In this contribution, we explore the geomorphological evolution of the urban area of Erbil in the KRI, where the exploitation and modification of the fluvial landscape started several thousand years ago, and in the last decades experienced a dramatic and rapid urban expansion. Our investigation identified (i) the geomorphology of the early inception of urbanization in the area, (ii) ancient strategies to exploit local water resources by means of artificial landforms, (iii) the patterns of evolution of the city and how this process affected the natural hydrography, and (iv) the major consequences this process had on the susceptibility to geomorphological hazard (e.g., floods) of Erbil. This case study highlights the importance of geomorphological mapping of urban areas using different data sources with a geoarchaeological perspective (Brandolini et al., 2019), giving fresh tools to answer key questions: can geomorphology and geoarchaeology support the reconstruction of the mode and tempo of urban expansion since the foundation of a city? Can we trace the interaction between natural and human-controlled surface processes in urban areas? Do we have effective geomorphological tools based on the geoarchaeological record to predict the potential consequences of Anthropocene human overprint on geomorphic processes in urban areas? In this perspective, our approach demonstrate that a diachronic geomorphological reconstruction of urbanized areas is a crucial task when investigating the Anthropocene of cities, and to establish tools for sustainable urban expansion.

2. A geographic and historical perspective of Erbil

The city of Erbil or Arbil (in English) or Hawler (in Kurdish), located in a flat region at foothills of Zagros Mountain, is the capital and most populous city of the KRI (Fig. 1A), being also one of the four largest cities in Iraq. The city is located along an alluvial plain limited to the North, the South, and the East by the Zagros Mountain and to the West by the Zab River; the main geological, geomorphological and (paleo)climatic features of the region have been recently investigated, including a reconstruction of its geomorphological evolution (Forti et al., 2021; Forti et al., 2023a; Regattieri et al., 2023). The climate of Erbil is a semi-arid to Mediterranean climate with wet-cold winter and dry hot to very hot summer and mean temperature ranging from 0° to 38°. The average annual rainfall is around 420 mm with 90% of the annual rainfall occurring in the winter months, between November and April (Kramer et al., 1998; Hussein et al., 2019; Harris et al., 2020). The history of Erbil is very long; the city was established in the Sumerian period (912–609 BCE) with the name of Urbilum (from Sumerian Cuneiform Ur III); it is likely one of the longest continuously settled places in the world (Ibrahim et al., 2015; Almukhtar, 2020). Today it includes the area occupied by the most recent urban growth (the modern city built since the 20th cent.) and the citadel (or Qalat) that is the historical heart of the city. Erbil is located 30 km south of the Great Zab River in an alluvial plain composed by reddish clay, dissected by several streams and valley that flow from the Zagros foothills to join with the Great Zab River (Shekhmamundy and Surdashy, 2022; Forti et al., 2023a). Before the middle 20th century urban expansion of Erbil, the Bastè and Tchekunem rivers were the water courses that crossed the city south and north respectively to the citadel (Fig. 1B). The first traces of the long settlement history of Erbil date to the Ubaid and Chalcolithic periods (6450–4950 BCE). Since the first settlements were established, the city progressively grew and its centrality in the socio-political scenario of Northern Mesopotamia increased during the third millennium BC (Nováček et al., 2008). Several written sources report that Erbil was conquered and incorporated into the empire of the Ur III dynasty (3931–3923 BCE) (Vacin, 2011). At the time of the Assyrian Empire, Erbil was an important economic and cultural centre for the heartland of

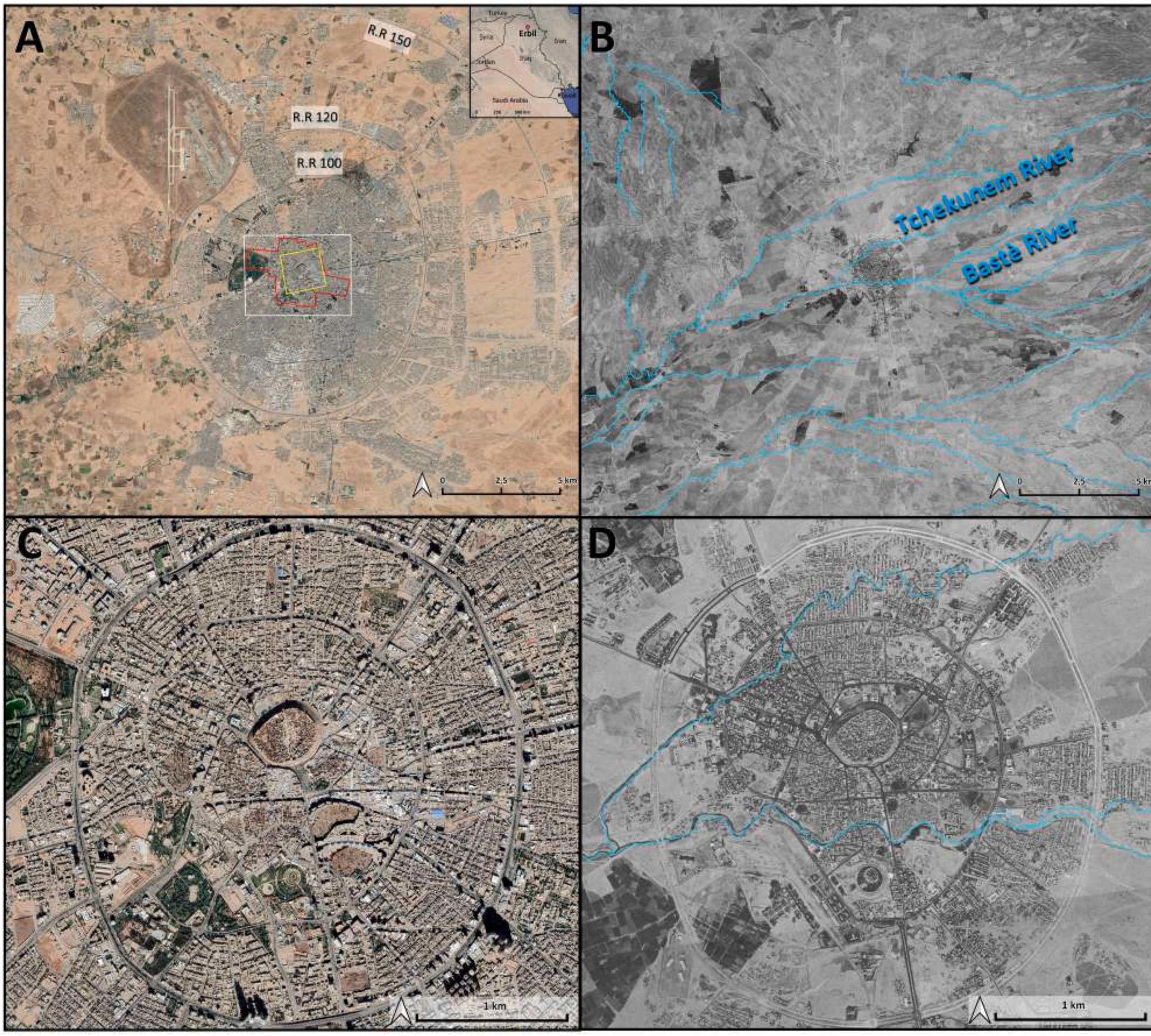

Fig. 1. A) Recent (year 2022) high resolution satellite imagery of Erbil urban area derived from GoogleEarth™. The red polygon indicates the area covered by RAF 1919 dataset, the yellow polygon the RAF 1951 dataset, and the white polygon is the area covered by declassified satellite imagery from 1968 to 1972. The latter is also the area covered by the detailed mapping of Fig. 7. B-C) The Corona declassified imagery of the urban area of Erbil in 1968 highlights the local landscape and the pristine hydrographic network at the onset of intense urbanization. C) Recent (year 2022) high resolution satellite imagery of centre of Erbil with the citadel. D) The Corona declassified imagery of the centre of Erbil in 1968.

Assyria as a crossroads between the cities of Babylon, Nineveh, and Assur. Under the Neo Assyrian control of the region, Erbil maintained the status of a major economical centre, and achieved a great prosperity linked to the presence of a temple dedicated to the goddess Ishtar. Immediately after the fall of the Neo-Assyrian Empire (609 BCE), the city was besieged by the Medes, who turned it into an administrative centre. In the Parthian period, Erbil became one of the most important centres of Christianity in the Middle East and experienced a great economic growth (Ur et al., 2013; Nováček et al., 2013). With the conquest by the Muslims in 642 CE, Erbil initially lost its centrality that was gained again later with the rebuilding of the fortress and the expansion of the lower agglomerations of the city during a period of strong conflicts and occupation by the Mongols between the 13th and 12th century CE. Under the Ottoman Empire, from 1534 CE onwards, the city lost importance, and in 1743 CE it was damaged during a siege of the Persians. After this event the citadel was restored and turned into a military stronghold. Erbil remained part of the Ottoman territories until the end of World War I (1918). Some travellers of the late 1800 s reported the state of decay of building in the lower city and citadel (Sarre and Herzfeld, 1920; Rich, 1836; Doxiadis, 1959; Al-Hashimi, 2016). New improvements for the city came at the end of World War I, when the city passed under the British control with a population growth from 3260 in 1892 to about 12,000 in 1920 (Hay, 1921). This is evidenced by urban expansion occurring in the south and southwestern sectors of the citadel, along the main artery of communication towards Kirkurk (Doxiadis, 1959). The city from 1920 began a real social and economic growth coming to be established in 1971 as the capital of the Autonomous Region of Iraqi Kurdistan. In the late 20th century, the city took advantage of its administrative separation from the Republic of Iraqi and continued to grow despite several conflicts hit the region: in the last 30 years, the population increased to 1.6 million. Finally, in 2014 the citadel was addicted to the UNESCO list of World Heritage Sites thanks to its archaeological and historical value (Fig. 1C-D-2A). In fact, UNESCO acknowledge Erbil as ‘an imposing example of a multi-layered archaeological mound still physically emerging from the surrounding landscape’ (UNESCO, 2014); this definition intrinsically highlights that this site has great relevance as cultural heritage as much as in the context of geoheritage.

3. Methods and data

The geomorphological mapping of the Erbil urban area was performed through the comparison of different historical aerial imagery ranging from 1919 to 2022 were taken from different datasets. The oldest imagery of Erbil taken from aerial flights carried out in February 1919 by the British Royal Air Force (RAF), when the urban agglomerations were concentrated within the citadel and the lower city extended only the southern flank of the acropolis. These imageries derived from the Archaeological Institute of the University College of London were used to map the pristine fluvial landscape before the middle 20th urban expansion. Other aerial images used to compare the beginning of the urbanization in the citadel and in the northern sectors of the city were acquired by a RAF mission in January 1951 and collected by John Bradford; they are archived in the repository of the Pitt River Museum, University of Oxford (John Bradford Photographic Collection 1998.296.68) (Table 1). Declassified Corona satellite image dataset was derived from CAST Atlas of the University of Arkansas (https://cast.uark.edu/research/corona.php) (USGS, 1968); taken in August 1968 (1104–2138) they were analysed to map the changes in land use and the rapid urbanization occurred at the end of 60ies (Table 1). Furthermore, declassified HEXAGON intelligence satellite imagery of 1972 was downloaded from Earth Explorer of USGS (https://earthexplorer.usgs.gov/) and compared with the Corona declassified imagery to highlight the fast expansion of urban areas (Table 1). Historical satellite imagery has been compared to the more recent high-resolution (0.5–1 m) natural colour satellite images provided by Google Satellite imagery and Bing Virtual Earth visualized through the “QuickMapServices” plugin (NextGIS, 2021) in QGIS 3.16 (Fig. 1A). Digital Surface Model (DSM) AW3D30 with horizontal resolution of 1″ (circa 30 m at the equator) and hillshade model were used for highlighting the detailed scale landforms in the alluvial plain (Forti et al., 2023a). The 37 imagery of the 1919 RAF acquisition were imported and processed into Agisoft Metashape Professional (Version 1.5.5) (Agisoft Metashape, 2022) with the standard workflow that includes photo alignment, built of dense cloud and mesh to produce a 3D model from which an orthophoto was extracted. The whole imagery dataset was projected to WGS84-UTM Zone 38 N reference system in QGIS 3.16. Remote images were desk-analysed to detect natural landforms (Dramis et al., 2011; Bishop et al., 2012), especially those related to the hydrography, anthropogenic landforms, and evidence of land use before the urban expansion of Erbil (Fig. 1B). Studies have previously investigated of historical aerial imagery to trace and monitor modifications of the citadel over the course of the decades (Nováček et al., 2013; Pavelka and Matoušková, 2015; Housarová et al., 2019).

Table 1
Summary of the datasets of the historical and recent aerial/satellite imagery used in this work.

Dataset	Name	Acquisition	Ground resolution
UCL Institute of Archaeology Collections, Air Survey Photographs Box: 248	RAF AP 319 to AP 356	10/02/1919	-
Pitt-Rivers Museum, John Bradford Photographic Archive	Collection 1998.296.68	02/01/1951	-
Declassified Corona Imagery (CAST Atlas of the University of Arkansas)	ds1104–2138df004	16/08/1968	6 feet
Declassified Corona Imagery (CAST Atlas of the University of Arkansas)	ds1104–2138df005	16/08/1968	6 feet
Declassified Hexagon Imagery (USGS)	D3C1204–200196A006_i	26/10/1972	2 feet
Google Satellite imagery and Bing Virtual Earth		25/08/2022	0.5–1 m

4. Results

In this section, we report data describing the evolution of the natural landscape around Erbil and the onset of human-driven processes as detected starting from multitemporal remote sensed-data (aerial and satellite imagery). We also report our interpretation of the geomorphological evolution of the region.

4.1. *The 1919 RAF dataset: the riverscape, urban features and anthropogenic landforms*

The aerial imagery captured in February 1919 defines the urban setting of Erbil before its major expansion occurred since the 1950 s (Fig. 3A). The main features of the landscape are related to the interplay between the fluvial network, in particular the streams flowing North and South of the citadel, and human excavations accomplished to exploit natural resources, such as clay for brick production as all those buildings were constructed by bricks. The latter includes the qanat (“Kahreez” in Kurdish) shafts and several artificial ditches; moreover, the intense land use due to agricultural and herding activities is also evident. Geomorphological mapping was performed on the 1919 RAF dataset to detect natural fluvial features and early human control on the behaviour and shape of the streams (Fig. 2B). Here, we consider the alluvial plain portion stretched from the eastern termination of the alluvial fans from the Zagros foothills and the eastern side of the Daamer Dagh hills. The alluvial plain mainly consists of reddish silty-clay deposits interbedded with coarser layers while the alluvial fans are mainly conglomerates alternated with reddish-brown clay, the conglomerate became finer and almost disappear south of the Qalat (Figs. 4B and 2B). The eastern slope of Daamer Dagh hills is a badland landscape due to the exposure of Bai Hassan Formation (Plio-Pleistocene conglomerates). Before the extensive urban expansions, this area was crossed by a hydrographic network that joined toward West into the Great Zab River (Shekhmamundy and Surdashy, 2022; Forti et al., 2023a) (Fig. 4). The main rivers flowed surrounding Erbil were Bastè River (or Chai Erbil) in the southernmost and Tchekunem River (or Shaik Qazi) in the North that joined with the Bastè River 7 km after Erbil centre. In the area covered by 1919 RAF imagery, the Bastè River, located 600 m South of the Qalat, flowing from E to W for ca. 4 km and display a meandering planform with a regular to irregular meanders (Fig. 5A). In the southeastern sector, the river initially flows in a semi-confined valley setting with a channel width of 50 m that reduces to ca. 10 m in correspondence with the urban centre. At this location, an imposed confined valley setting occurred (Fig. 4B). The 1919 RAF imagery was captured during the low flow stage of the rivers (February), when different fluvial geomorphic units were exposed. Along the low sinuosity reaches, lateral, diagonal, and middle longitudinal bars are evident, while point, compound and scroll bars occurred in the inner bend of high to low sinuosity segments. Vegetated bars and compound bars are crossed by a chute channel, likely active during seasonal high discharge. The seasonal discharge oversees the progressive erosion of the stream banks, where escarpment occurred sometimes marking the instream boundaries of fluvial terraces. Surrounding the Bastè River, paleochannels and ephemeral streams are evident (Fig. 3B). Different from the Bastè River, the Tchekunem River, 900 m NE to Qalat, is less wide and deep with a low to sinuous/meandering planform and some straight reaches; already in the 1919 its banks seem to be reworked by human activity. In the RAF 1919 dataset, the Tchekunem River flows for ca 3 km from NNE to SSW with an upstream portion characterized by irregular meanders and steep banks that downstream display a reduction of the degree of sinuosity

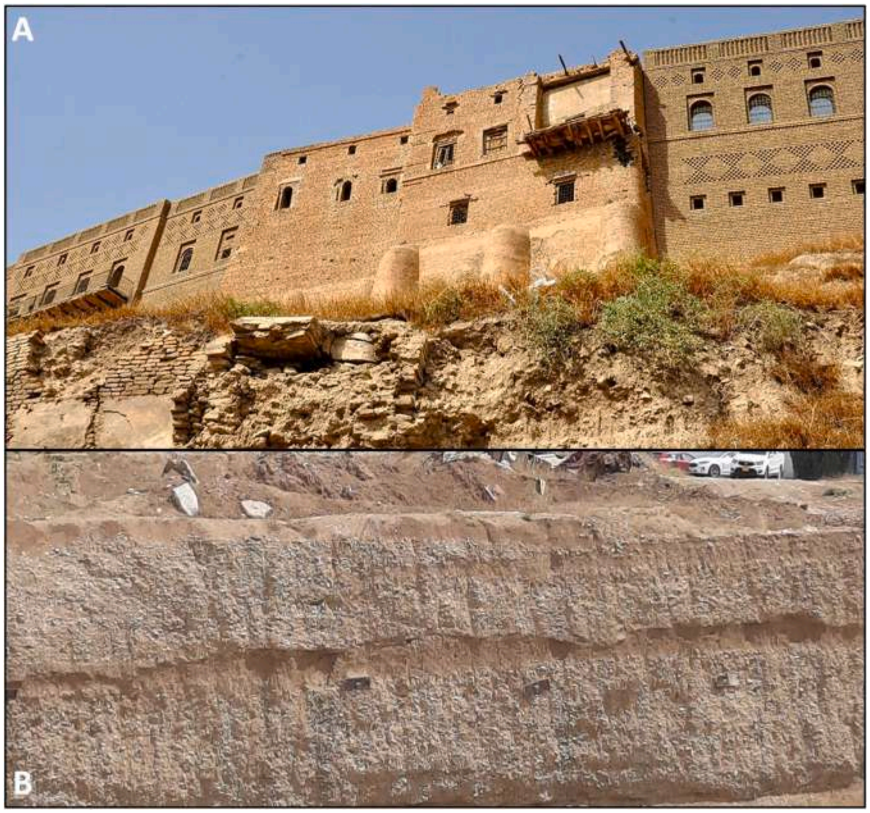

Fig. 2. A) Outer portion of the citadel (Qalat) of Erbil; buildings lie on the archaeological layers of the ancient urban agglomerate. B) An example of alluvial sediments outcropping in the northern part of the city.

and the development of small point and lateral bars (Fig. 5C). The Tchekunem River suffered a wide operation of artificial rectification in the proximity of the northern fortification walls that occurred during the construction of the Assyrian fortifications (Nováček et al., 2013) (Fig. 5D). Erbil, being one of the longest-settled places in the world, underwent numerous human modifications of the surrounding territory, but particularly of the citadel. In fact, the latter has been a fundamental point for human aggregation, which over the centuries also began to settle the territories to the south with the creation of the lower urban agglomerates and several settlement mounds surrounding the area of Erbil. The long settlement history of Erbil and the evolution of the Qalat is addressed by numerous authors in the literature (Nováček et al., 2013; Al-Hashimi, 2016; Housarová et al., 2019 and reference herein). In this context, the geomorphological map based on the RAF 1919 dataset highlights the extension of the urban setting at the end of the Ottomans dominance (ca 1919–1920) (Fig. 3B).

Nowadays, the city is subdivided into two portions: the first one is the Qalat, inhabited since 2005 – 2006, while the second is the lower city. The Qalat settlement is on the ancient artificial mound – the tell – that started growing since the Chalcolithic and arise 25–32 m above the surrounding plain (Nováček et al., 2013). Traces of ancient Assyrian to Medieval city walls and settlement mounds were mapped in the northern and southwestern sector of the area (Nováček et al., 2013; Al-Hashimi, 2016). The urban setting is characterized by palace, public, administrative, and residential buildings with a fan-like alleyways and roads that converge toward the southern gate destroyed in the 1940 s and rebuilt several times until today (Nováček et al., 2013; Al-Hashimi, 2016). The toe of the Qalat is characterized by a circular moat, partially filled by rubbish, became a pathway that running along the entire perimeter of the mound. The core of the lower city consists of bazaars, public areas, trading centres, mosques and an old minaret located to the SW of the citadel along the right bank of the Bastè River. The lower city is crossed by several roads and alleyways. Other urban elements mapped are the Islamic and pre-Islamic cemeteries used until the early 2000 s (Nováček et al., 2013; Al-Hashimi, 2016 and reference therein); the largest of them are located south and southwest of the citadel of Erbil along the banks of the Basté River (Fig. 5B). The main anthropogenic feature identified in the area are the qanat (Kahreez) shafts, which drained groundwater from the alluvial fan located at the highlands NE of Erbil to lowland (Soroush et al., 2020). They consist of underground gravity-driven filtration galleries constructed for irrigation (Lightfoot, 2000; Wilkinson, 2003; Cremaschi et al., 2018); the underground galleries were connected to the surface through a series of shafts spaced 50, 100 and 200 m where the groundwater infiltrating and transported by gravity through a gently sloping tunnel to a main canal and basin. From the geomorphological point of view, the qanat system for water management represents an anthropogenic landform of excavation (the shafts) and accumulation (the soil heaps). At the termination of the underground system, the water flow was diverged by artificial ditches to fed farms, crop fields and villages. In the case of Erbil, the water supply for the qanat system come from the alluvial fans located at the foothills of the Zagros Mts. (Soroush et al., 2020) and provided water to the city and the countryside from the 12th century CE until the mid-20th century (Al-Hashimi, 2016 and reference therein) (Fig. 6 A). The 1919 RAF imagery highlight that around the citadel, excluding the urban portions, there are numerous agricultural fields, many of which are cultivated, while others have been ploughed. In some cases, due to the somewhat nadiral aerial image acquisition, it was not possible to recognise the land use of each field that were destined for agricultural and pastoral use. A wide artificial water basin located 500 m SE the citadel with an area of approximately 6200 m^2 (Fig. 6B) and a large clay quarry located ca. 1 km south of the citadel on the left of the Bastè River (Fig. 5C) are two further anthropogenic landforms recognized in the 1919 RAF imagery.

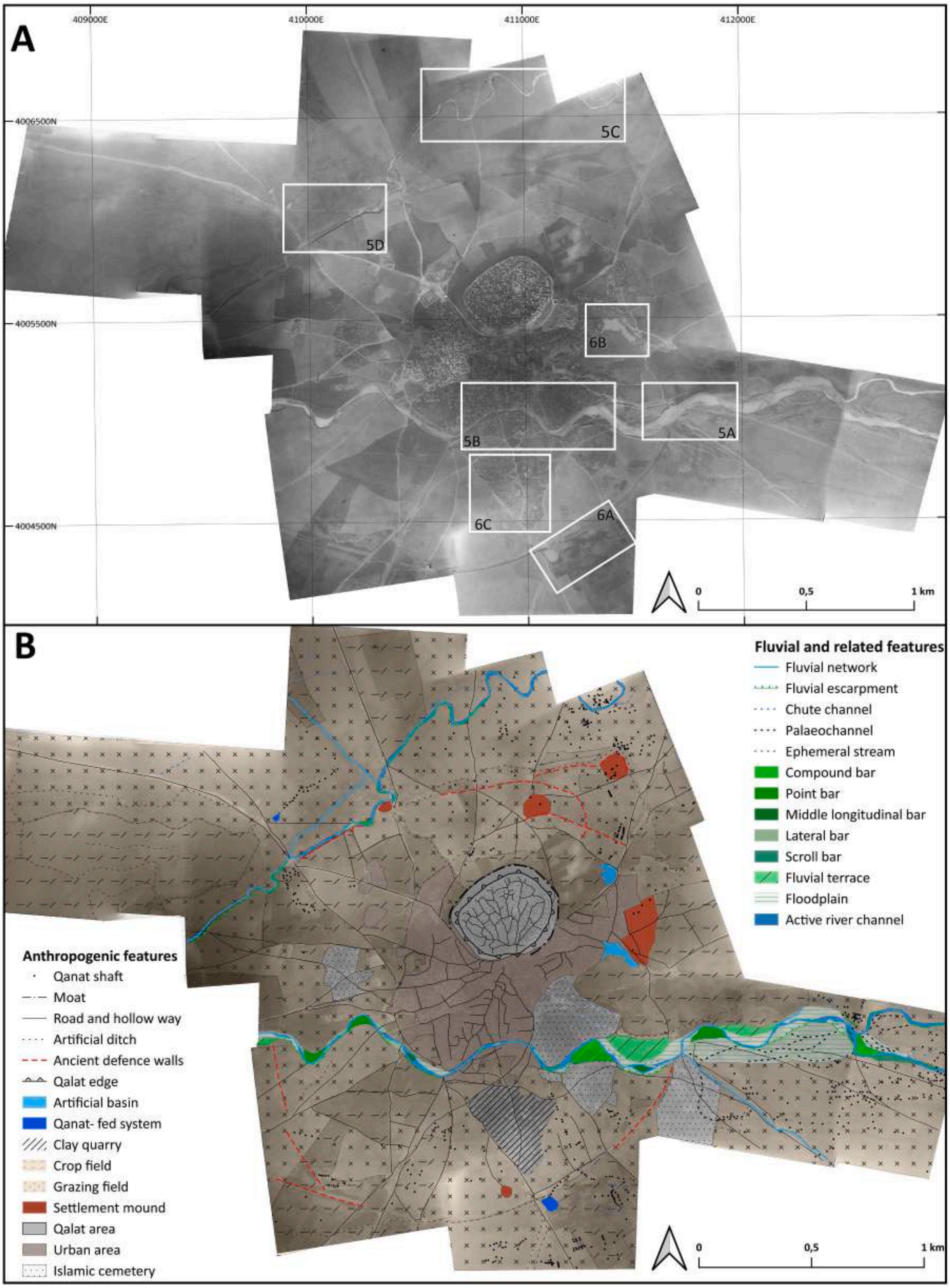

Fig. 3. A) Orthomosaic map of Erbil derived from RAF imagery acquired in February 1919, in which with the white polygon are reported some details of Fig. 5 and 6. B) Geomorphological mapping of Erbil performed on the RAF 1919, where the fluvial and anthropogenic features were mapped.

4.2. The 1968 Corona dataset: the accelerating urbanization and changes to the riverscape

The geomorphological mapping performed on the declassified Corona imagery taken in the August 1968 (Fig. 7A) displays the intense urban expansion that overshadowed natural elements of the landscape. In this process, the development of buildings and residential districts was organized following the urban master plan approved in the 1951 (Doxiadis, 1959). The expansion of the urban area in the western and north-western sectors was realised with a grid pattern where the ring road envelops a series of residential and industrial districts (Al-Hashimi, 2016) for a radium of 1.5 km from the city centre (R.R. 100). These

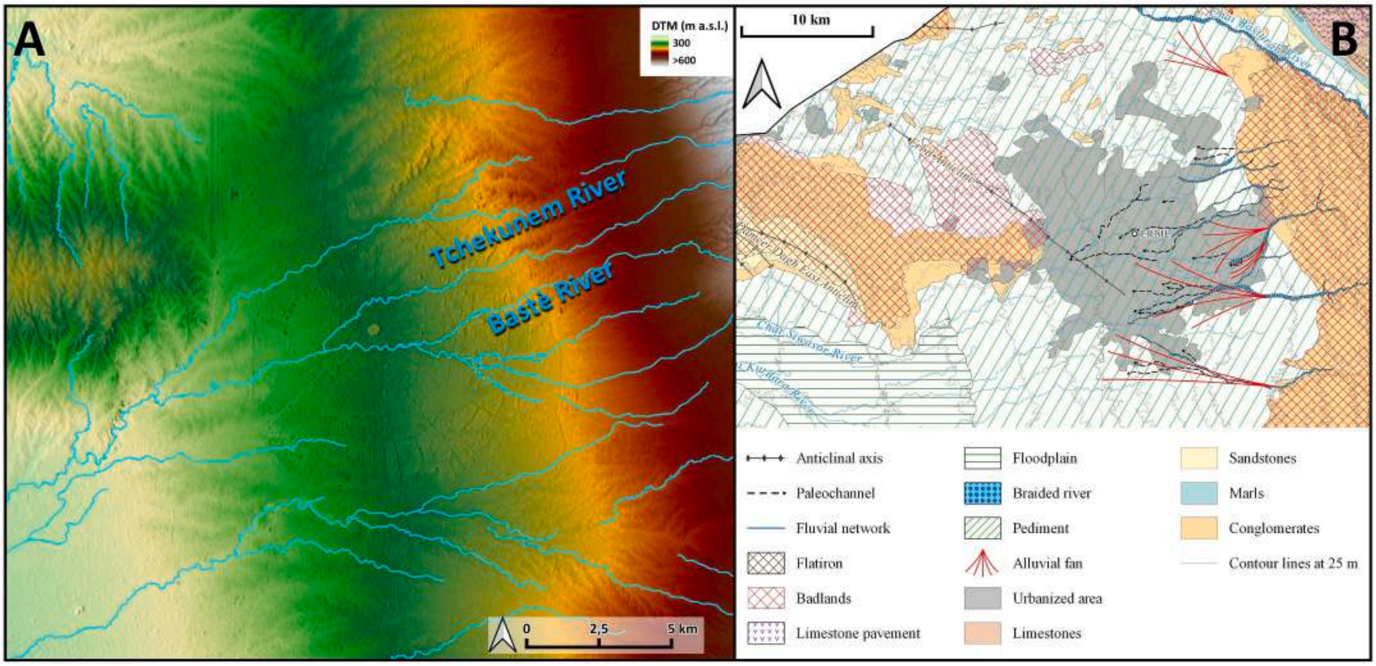

Fig. 4. A) Digital Terrain Model of the landscape on which Erbil developed.
B) Geomorphological map of the study area modified from Forti et al. (2023a).

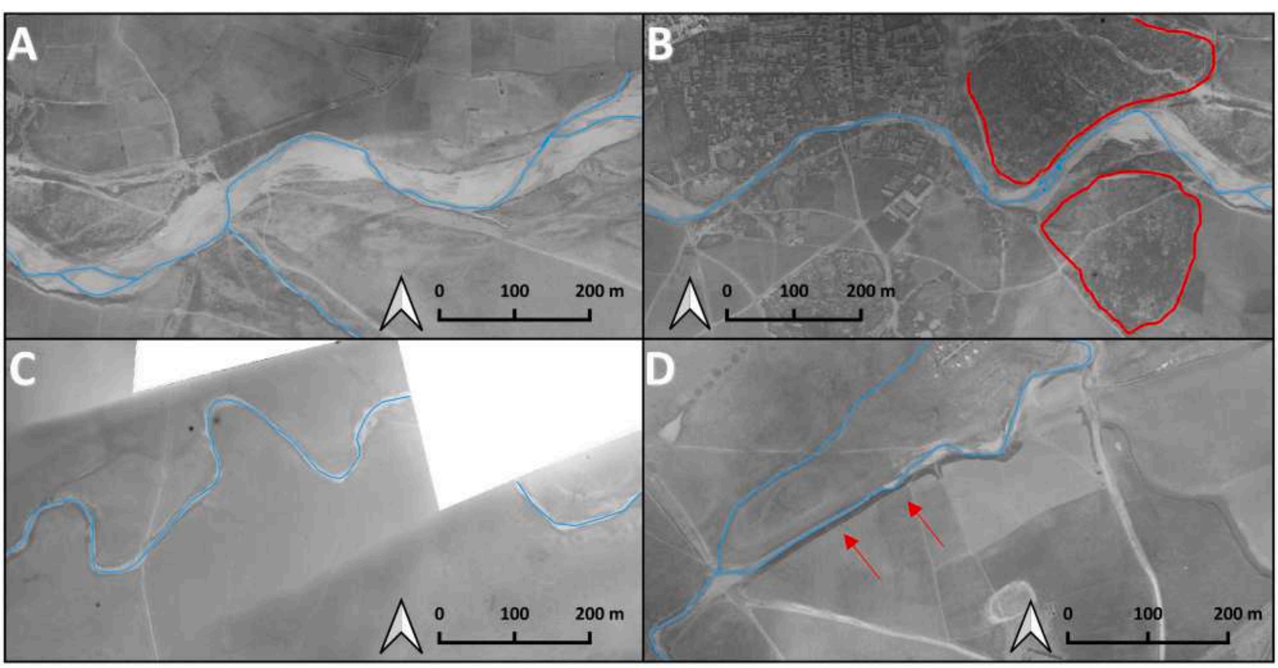

Fig. 5. A) Detail of the upstream Bastè River, where a meandering to anabranching river planform occurred in a semi-confined valley setting. B) Downstream of Bastè River characterized by a reduction in a cross section with a progressive passage toward confined valley setting in the proximity of the urban area. The red line indicates the Islamic cemeteries. C) Detail on the upstream portion of Tchekunem River, where regular to irregular meander occurred. D) The downstream artificial reach of Tchekunem River (red arrows).

operations reduced the extension of cultivated patch of land; consequently, almost all field surfaces appear to have been reworked by human action, with the construction of buildings, parks, roads, and several earth movements operations (Fig. 8B). The patch of land devoted to cultivation and pastoral activities occurring in the vicinity of the citadel were moved outside the ring road. Moreover, within the ring road, archaeological and historical features such as cemeteries and settlement mounds successfully escaped from the intense growth of the city. In the western sectors of the city a qanat systems composed by a series of shafts, are lined up parallel to the main western road that connects directly to the city centre (Fig. 9B) (Al-Hashimi, 2016). If we consider the hydrography in the surrounding of the city, the Corona 1968 imagery illustrate that the fluvial geomorphic units of the Bastè and Tchekunem Rivers identified in the 1919 RAF pictures were drastically modified by the human action. Different reaches of the watercourse riverbed were disrupted by bulldozing activity for buildings

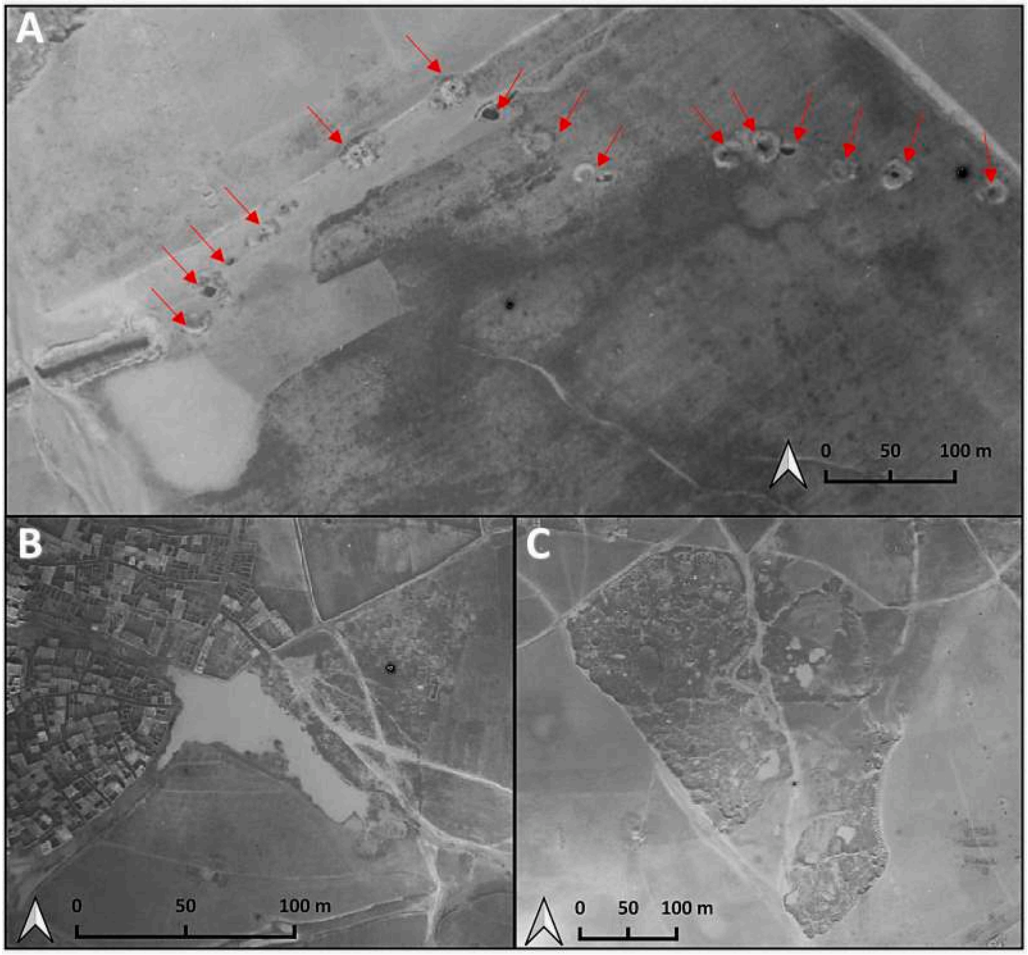

Fig. 6. 1919 RAF imagery. A) The qanat (kahreez) system with alignment of shafts (red arrows) with the terminal basin for water storage and a ditch to redistribute water. B) The artificial basin SE of the Qalat. C) The clay quarry located in the southern sector respectively to the Qalat and the Bastè River.

while others are cemented or culvert to build roads. The complete upheaval of the in-city hydrographic network led to a strong reorganisation of river courses into a system of paleochannels, and ephemeral streams activated during heavy rainfall (Fig. 9A).

4.3. Modern high-resolution satellite imagery: Erbil today

Current satellite imagery of Erbil shows the rapid urban expansion of the city occurred in the last decades. The city was embedded within two circular roads where the first (R.R. 100), built in the mid-1960 s, has a radius of about 1.5 km, while the second (R.R. 120) has a radius of 5 km. A third circular road (R.R. 150), currently in the construction and partially in use, encompass the airport with a radius of 10 km. The continuous urban growth and expansion of Erbil lead to a deep and permanent modification of the city's drainage network (Fig. 9A). Today it is completely covered by road and buildings. In the urban area natural watercourses were over time straightened by the human action with modification and management of the former fluvial planform; this modification contributes to increase in flood hazard (Mustafa et al., 2022; Kareem et al., 2022; Sissakian et al., 2022) (Fig. 9B-9 C-9D). The current literature reports on the susceptibility of Erbil to flood risk: after intense heavy rainfall different districts of the city, in the north, east and south of the citadel, are inundated for several hours. The increased flood risk was recorded with three floods events occurred in Erbil between 2021 and 2022. Several authors argued that overbuilding, culvert, reduction in channel cross-section of the natural streams, the poor maintenance of riverbeds and the inadequate stormwater system drainage oversee the enhanced flood risk in Erbil (Kareem et al., 2022; Mustafa et al., 2022; Sissakian et al., 2022) (Fig. 9). Finally, the effects of climate change, the expansion of the city and shift in land use hampered the capacity of infiltration of the water, thus being further factors threating the vulnerability of the urban tissue of the Erbil increasing in runoff and triggering street flooding and overland flow (Mustafa and Szydłowski, 2020; Kareem et al., 2022; Mustafa et al., 2022) (Fig. 9). Other authors affirmed that the several economic, social, and political instabilities that occurred in the KRI, influenced the management of the water supply with an inadequate system of distribution within the urban centre of the Erbil (Nanekely et al., 2017).

5. Discussion: the progressive obliteration of the pristine riverscape

Our geomorphological reconstruction based on historical images, makes possible to infer considerations on the establishment of the settlement and to reconstruct the urban landscape of Erbil immediately after the Ottoman occupation. Our data also allowed mapping changes in land use that the area underwent during the intense urban growth started at the beginning of 1920 s and exploded since the 2020 s

In the Chalcolithic period, Erbil was established along a fertile alluvial plain, in a landscape characterised by numerous streams, which provided water supply for irrigation. Moreover, the alluvial plain was a favourable place to gather raw clay to produce mudbrick for the construction of the buildings. Since that time, the growth of Erbil is happened around the citadel, which is an elevated feature in the

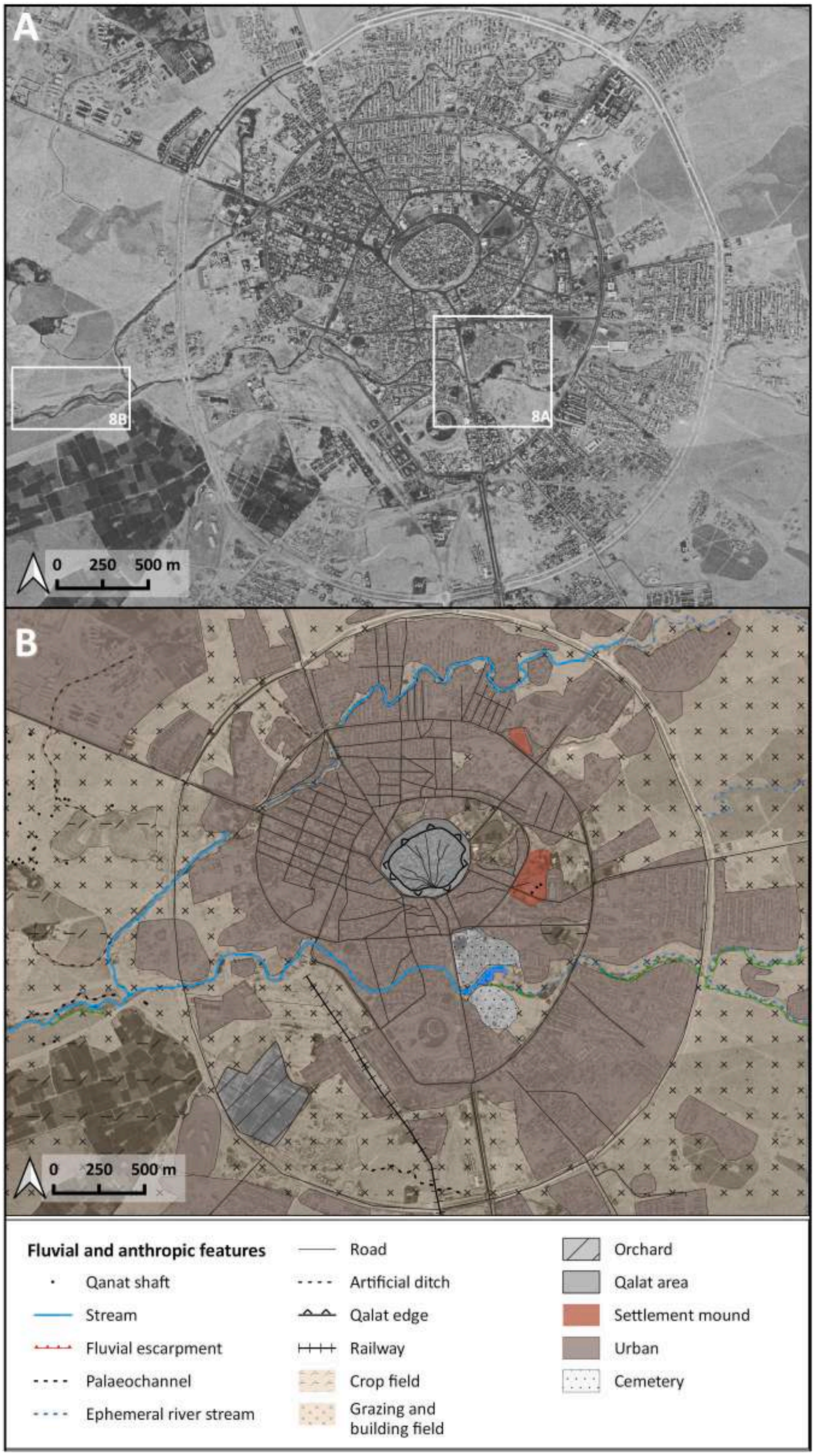

Fig. 7. A) The 1968 Corona declassified Imagery of the Erbil urban area. B) Geomorphological map performed on the 1968 Corona declassified and reporting major fluvial and anthropogenic features.

surrounding plain. This anthropogenic geomorphological element (the Qalat) was likely built on the top of an existing natural feature, such as a fluvial bar or above the levee of river course; such context is a favourable place, close to natural resources but well protected against floods, and its exploitation represents an example of geological opportunism (*sensu* Vita-Finzi, 1969).

The geomorphological mapping and reconstruction of Erbil's hydrographic setting prior to middle 20th century urban expansion has yielded a wealth of information regarding the management of water resources within the city. In the last 100 years the two main watercourses, which in 1919 showed an almost entirely natural setting, were modified, remodelled, and finally obliterated to obtain new land for

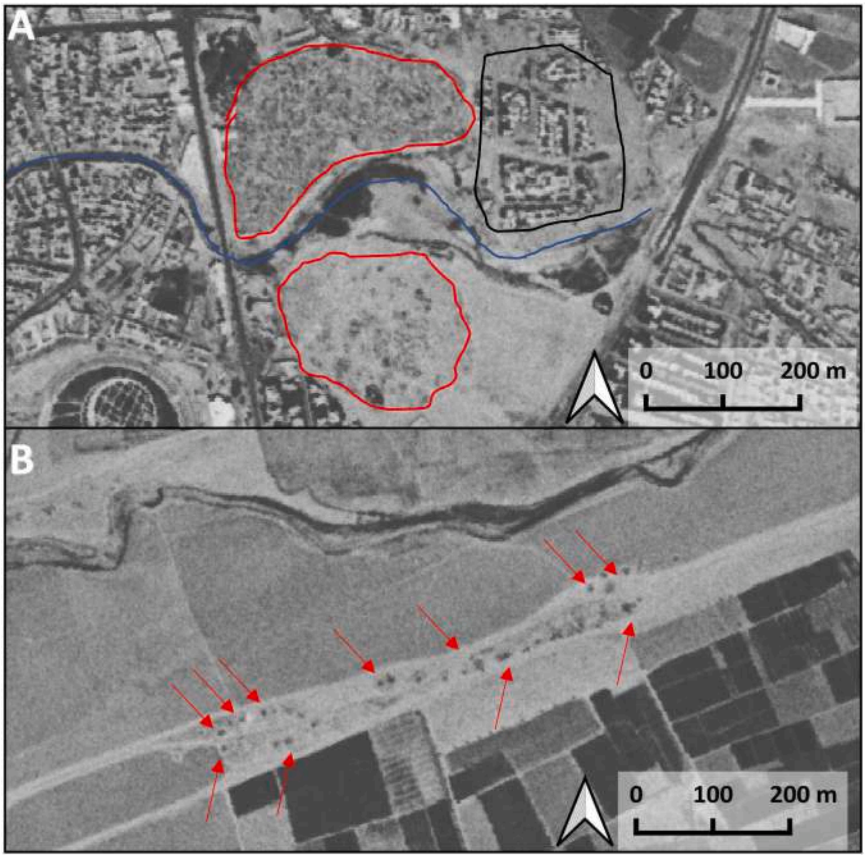

Fig. 8. A) Detail of the reach of the Bastè River in the proximity of the cemeteries (red polygons), where a residential district (black polygon) was built. The latter covered the Bastè River banks and in its riverbed. B) The qanat (or kahreez) system in the western sector of the mapping area; red arrows indicate the qanat shafts.

intensive urbanisation with the construction of residential neighbourhoods, parks and numerous new roads that totally altered the urban layout of Erbil. From the Assyrian period until the Middle Ages and later Ottoman rule, the city was totally concentrated close to the Qalat. Only a few structures, such as cemeteries, public and trade buildings, two lines of fortifications and old settlements represented the only human-made elements that colonised the plain. Towards the end of Ottoman rule, in 1919, the major urban centre was concentrated in the citadel and the lower town, and their organisation was based on an organic pattern designed to support the main activities of commerce and daily life to sustain a population of about 8000 people. During this phase, many fields were exploited for pastoralism and agriculture and fed through a system of qanats and artificial ditches. During the mid-20th century, Erbil began to expand according to an organised plan through the construction of a road network within the Qalat, and the lower city related to a ring road built 1.5 km radius from the centre of the Qalat (R.R. 100). There was a parcelling of lands for different uses, in particular the construction of grid shape residential districts and industrial areas related to agricultural activities in the south-western part. Since the end of the Gulf War (1991) and the administrative detachment from Iraq, Erbil became the most important centre in the Kurdistan Region of Iraq and encountered a large population growth, the city began a major expansion through the construction of a several lots of residential and industrial districts enclosed within a 5 and 10 km diameter ring roads (Ibrahim et al., 2015; Al-Hashimi, 2016). Until the early 1900 s, the use of natural resources around Erbil seems to be respectful of the natural setting of the territory; in fact, in this phase the use of water resources relies to traditional systems for water management, such as artificial basins and the use of the qanat (kahreez) technology, which is the most common strategy for water collection adopted in arid and semi-arid regions. Up to the Ottoman period, the city developed in accordance with the natural fluvial landscape that show only limited reworking (rectification), but afterwards the Ottoman dominance the city changed its shape due to an urban expansion and growing project that completely hid the pristine fluvial landscape (Nováček et al., 2013; Al-Hashimi, 2016 and reference therein). Such a strong human impact was detected along the Tchekunem River, N of Qalat, through a comparison of declassified Corona and Hexagon images from 1968 and 1972 with current high-resolution satellite images. The declassified Corona satellite imagery captured in 1968 revealed the construction of residential districts in the proximity of the Tchekunem River banks (Fig. 10A). During this period the fluvial plain planform shape is still evident, but a comparison with the Hexagon satellite image acquired four years later (1972) showed the speed of expansion and construction of new houses within the riverbed (Fig. 10B). In this case, the general shape of the river course was obliterated and reshaped by intense urbanisation. 50 years later, the river course has been completely obliterated by human-made structures. The analysis of current satellite images of the area revealed that traits of secondary roads are superimposed over the old course of the Tchekunem River (Fig. 10C). In this case, historical RAF images from 1919 and 1951 compared with the 1972 Hexagon and the more recent satellite imagery revealed a profound modification of the river course caused by human operations. The geomorphological mapping recognized that in this portion the river displayed a meandering planform with regular to irregular meanders with a transition from semi confined to confined valley setting in the proximity of Islamic cemeteries (Figs. 3B and 5A). Therein, a fluvial escarpment developed in the upstream outer portion of the regular meander (Fig. 11A). A comparison between 1951 and 1972 historical imagery highlights the progressive retreat of the river escarpment related to the interplay between fluvial and human processes with an intense exploitation along the banks and within the riverbed. Moreover, a shift in land use was recognized easternmost of

Fig. 9. A) A large valley crosses SE part of Erbil reworked by bulldozing. B) A blocked culvert, which led to overflooding of the valley during a heavy precipitation. C) A dumped valley in the eastern sector of Erbil city. Note the valley floor was transformed in paved road. D) A portion of the new ring road (R.R. 150) flooded during the 2021 event.

the cemeteries, in correspondence of a fluvial terrace mapped on the RAF 1919 dataset, from cultivated fields in 1951, they transformed into a grid pattern residential district in 1972 (Fig. 3B-11B-11 C). High resolution imagery highlights the intense urban expansion along the pristine natural fluvial landscape visible from the big shopping galleries built along the left bank that displays an arcuate shape in according to a meander of the Basté River. Toward W the pristine Bastè riverbed was turned into a road (Fig. 11D).

Our reconstruction highlights the opportunistic expansion of Erbil, based on the exploitation of specific geomorphological features, but at the meantime, we also noticed a deep human agency on fluvial landforms, whose most recent implication is related to an increased susceptibility to geomorphological hazard. In fact, the continuous expansion over the past decades caused a complete culvert of the hydrographic network, with increased sensibility to geomorphological hazard. The management of the Erbil hydrographic network consisted in channelization, cemented and culvert lead to an increased hydrogeological and flood risk (Kareem et al., 2022; Mustafa et al., 2022; Sissakian et al., 2022) (Fig. 9). The increase in floods hitting the city from 2021 to 2022 after intense heavy rainfall had a major impact on different districts of the city, in the north, east and south of the citadel, that were completely inundated. Such districts are those in direct connection with parts of the natural hydrography buried under the urban expansion demonstrating that the urbanization did not take into account the potential geomorphological risk related to flooding. Sensitive land use changes in Erbil associated with an increase in anthropic operations led to an increase in soil erosion, a reduction in infiltration coefficients, enhancing storm runoff and increasing the magnitude of flood peaks provided a disequilibrium in the response time of the fluvial system (Fig. 9).

This is common in rapidly grown urban context in dryland especially in the SW of Asia and Africa (Bourenane et al., 2019; Youssef et al., 2011; Ghanavati et al., 2017; Zerboni et al., 2021; Sakijege and Dakyaga, 2023). In the Arabia Peninsula and Egypt several authors investigated the susceptibility of cities to extreme flash flooding events caused by a mismanagement of urban growth plan and the ongoing climate changes based on models and remotely sensed data (Abdelkarim et al., 2019; Bahrawi et al., 2020; Saber et al., 2020; Khan et al., 2022). The progressive obliteration, modification and management of natural riverbeds occurred in different urban context and the Holocene climate change revealed a strong impact on the flood hazard risk also in the Mediterranean area. Studies carried out in Italy well describe the relationship between climate change, extreme rain events and the responses of territories in populated areas and in urban contexts (e.g., Ferrario et al., 2015; Sperotto et al., 2016; Brandolini and Cremaschi, 2018; Cremaschi et al., 2018; Mandarino et al., 2021; Nanni et al., 2021). For example, the urban expansion and land use change of the Genoa town and surrounding area coupled with the progressive culvert of the hydrographic network and the increase in rainfall lead to an intensification of flash floods event (Faccini et al., 2016, 2021). Worldwide, many urban centres are affected by intense expansion and progressive reduction and obliteration of the natural environment. In the published literature, numerous authors have realised remote sensing models and scenarios to estimate and mitigate the risk of flooding in different climatic and environmental contexts. In this perspective, we may consider the increased susceptibility to floods of cities developed along rivers a further marker of the Anthropocene; huge human-driven modification of fluvial landforms and urban expansions not supported by geomorphological analyses strengthen the vulnerability of cities. (Chin, 2006; Hooke, 2006; Gurnell et al., 2007; Benito and Hudson, 2010; Hunter et al., 2007; Bathrellos et al., 2016; Braud et al., 2016; Link et al., 2019; Bahrawi et al., 2020; Nkwunonwo et al., 2020; Cea and Costabile, 2022).

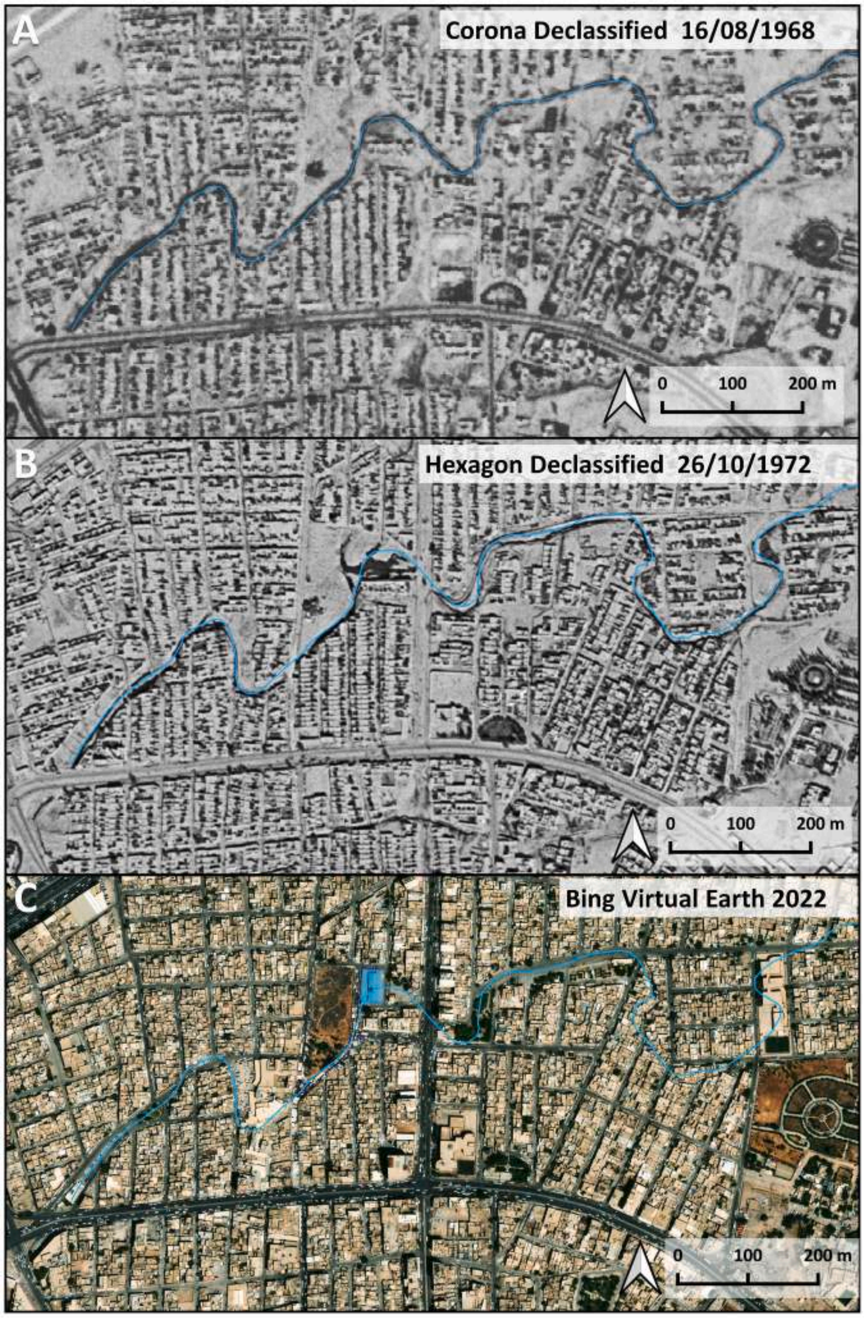

Fig. 10. A) 1968 Corona Declassified satellite imagery of Tchekunem River where the urban expansion spread out. B) 1972 hexagon Declassified satellite imagery taken in 1972 revelated the speed of urban expansion that in just four years had almost obliterated the river course. D) High resolution satellite imagery displays the influence of the pristine fluvial setting on the secondary roads.

6. Conclusion

Our investigation on the geomorphological evolution of the city of Erbil in the KRI, whose fluvial landscape has been exploited and modified – especially in recent times – by the dramatic urban expansion occurred in the last decades, suggest that Human-made modification of landforms and human overprint on geomorphic processes are a distinctive marker of the Anthropocene. Our investigation identified (i) ancient strategies to exploit local water resources by means of artificial landforms (e.g., using the qanat system), (ii) the patterns of evolution of the city and how this process affected the natural hydrography, and (iii) the major consequences these had on the susceptibility to geomorphological hazard (e.g., floods) of Erbil. Additionally, this case study highlights the importance of geomorphological mapping of urban areas (Campobasso et al., 2018) using different data sources, investigated using a geoarchaeological perspective. This allows reconstructing the tempo and mode of urban expansion since the foundation of a city and the potential consequences of human overprint on geomorphic processes. In a more general perspective, we confirm the ability the geoarchaeological approach in reconstructing the long-lasting and multistratified interaction between natural and human-controlled surface processes in urban areas, that evolved since the onset of a settlement and are related to the exploitation of natural resources and modification of landforms. At the same time, a diachronic (e.g., across the Holocene-Anthropocene continuum) geomorphological investigation in urban areas produces tools to predict the potential consequences

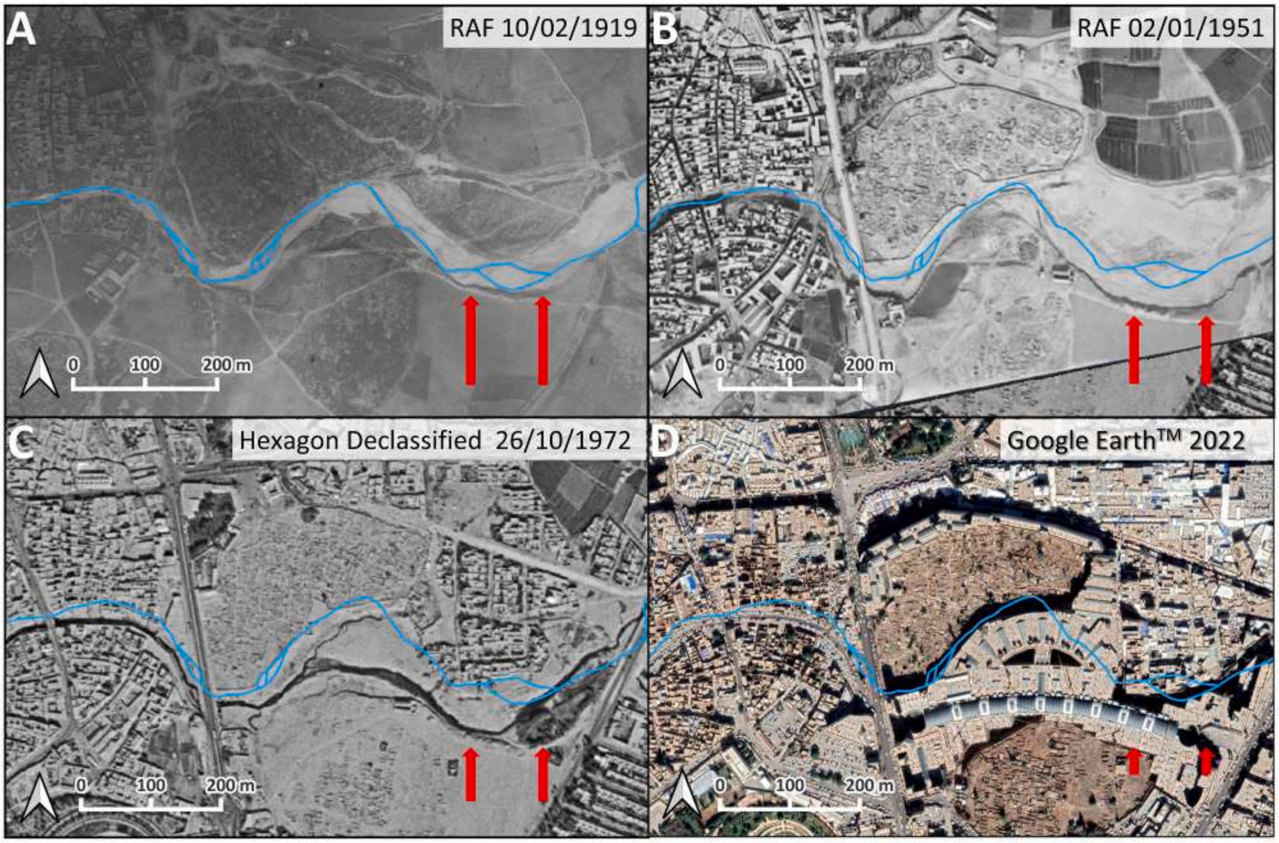

Fig. 11. A) 1919 RAF imagery of the Bastè River in the proximity of the Islamic cemeteries. The red arrows indicate the fluvial escarpment. B-C) RAF 1951 and Hexagon Declassified satellite imagery display the intense exploitation of the area with a retreat of the fluvial escarpment (red arrows). D) Google Earth™ urban expansion spread out. B) 1972 hexagon Declassified satellite imagery taken in 1972 revelated the speed of urban expansion that in just four years had almost obliterated the river course. D) Actual high resolution satellite imagery displays the influence of the pristine fluvial setting on the secondary roads.

of human overprint on geomorphic processes, thus supporting the definition of strategies for the sustainable growth of cities. Based on the evaluation of the lessons embedded in the archaeological record, we can learn how to prevent hazard and reduce the susceptibility to geomorphological risk of human infrastructures. Our results not only represent a contribution in urban flood management but open towards broader perspectives involving both risk education and cultural heritage assessment, valorization, promotion, and conservation. Methods and techniques used for environmental reconstruction as well as results about landscape changes, as applied in this study, are useful also in geoeducation (e.g., Pelfini et al., 2016). The Erbil town could represent a sample site to analyze the evolution from an ancient tell towards a modern city which preserves, in the multiplicity of its aspects, archaeological, geological, geomorphological, and cultural elements that are in constant evolution, with implications both for the cultural heritage promotion and conservation and for what concerns the management of natural events.

Finally, the case of the urban expansion of Erbil suggests that onset of the Great Acceleration marked – here as much as in other urban contexts (e.g., Bini et al., 2018; Zerboni et al., 2021) a tipping point in the mutual relationship between human agency and surface processes. During this phase, unprecedented urban growths and demographic pressures have enhanced the susceptibility of cities to geomorphological hazards, even in localities that in historical times developed with a greater attention to the dynamic of natural surface processes. In a broader perspective, the contribution of human geomorphology must be considered in future planning, because the Anthropocene climate extreme are further enhancing the susceptibility of urban areas to environmental hazards.

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

The authors are unable or have chosen not to specify which data has been used.

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