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Reconstructing long-term settlement histories on complex alluvial floodplains by integrating historical map analysis and remote-sensing: an archaeological analysis of the landscape of the Indus River Basin

Arnau Garcia-Molsosa[1*], Hector A. Orengo[1,3] and Cameron A. Petrie[2*]

Abstract

Alluvial floodplains were one of the major venues of the development and long-term transformation of urban agrarian-based societies. The historical relationship between human societies and riverine environments created a rich archaeological record, but it is one that is not always easy to access due to the dynamism of alluvial floodplains and the geomorphological processes driven their hydrological regimes. Alluvial floodplains are also targeted for urban and agricultural expansion, which both have the potential to pose threats to cultural heritage and the environment if not carefully managed. Analysis that combines Historical Cartography and Remote Sensing sources to identify potential archaeological sites and river palaeochannels is an important first step towards the reconstruction of settlement patterns in different historical periods and their relationship to the history of hydrological networks. We are able to use different computational methods to great effect, including algorithms to enhance the visualization of different features of the landscape; and for processing large quantity of data using Machine-Learning based methods. Here we integrate those methods for the first time in a single study case: a section of the Indus River basin. Using a combined approach, it has been possible to map the historical hydrological network in a detail never achieved before and identify hundreds of potential archaeological sites previously unknown. Discussing these datasets together, we address the interpretation of the archaeological record, and highlight how Remote Sensing approaches can inform future research, heritage documentation, management, and preservation. The paper concludes with a targeted analysis of our datasets in the light of previous field-based research in order to provide preliminary insights on how long-term processes might have re-worked historical landscapes and their potential implications for the study of settlement patterns in different Historical periods in this region, thereby highlighting the potential for such integrated approaches.

Keywords Remote sensing, Hydrology, Geomorphology, Landscape archaeology, Indus civilisation, Punjab

Introduction

Many of the earliest complex societies developed on alluvial floodplains where populations living in settlements varying in size from small villages to larger settlements including cities and conurbations benefited from the combination of a reliable supply of surface water and the deposition of nutrient rich sediments. Floodplains are by nature dynamic, and this dynamism continually

*Correspondence:
Arnau Garcia-Molsosa
agarcia@icac.cat
Cameron A. Petrie
cap59@cam.ac.uk
Full list of author information is available at the end of the article

transforms the landscape through avulsion and shifting watercourses and the associated redistribution and incision of sediments, all of which influence the distribution of ancient settlements, and act to obscure and reveal ancient landscapes.

Landscape archaeologists have long made use of data obtained from remote sources to aid in the reconstruction of these ancient landscapes [1–9]. Extensive use has been made of aerial and satellite imagery, and remote methods are increasingly indispensable as new data sources and computational approaches continue to be added to the analytical toolbox, and many regions of the world remain inaccessible to archaeological fieldwork. It is arguable that remote methods are contributing to a high level of sophistication in our understanding of ancient landscapes in regions such as north and south Mesopotamia even without work on the ground [10–15]. These methods are also making it possible for heritage practitioners to document, manage and preserve cultural heritage in the face of agricultural and urban expansion.

Approaches that combine digitisation of historic and more recent data sources with innovative computation methods have the potential to transform our understanding of extremely dynamic alluvial landscapes. National and imperial mapping programmes that were started in the late nineteenth and early twentieth centuries in many parts of the world created an oftentimes-unique record of landscapes as they were at particular points in time, and updated editions of those maps show change in landscapes over clearly definable time-slices [16, 17]. In some instances, the documentation of change was extremely detailed, and maps have provided insights into micro-historical processes [18]. Detailed analysis of such maps from several parts of the world has revealed that they are often an excellent source of data on the distribution of archaeological sites that were still preserved before the Great Acceleration of the mid-late twentieth century [16, 17, 19–23]. Much of this historical map data and associated documentation is scattered across different archives and its collation requires a multidisciplinary approach involving archaeologists, historians and library archivists that it is rarely undertaken.

At the other end of the data resource spectrum is the ongoing proliferation of publicly accessible remote sensing data produced by the continuous documentation and improvement of global-scale satellite coverage. These programmes are making it possible to carry out a range of large-scale change analyses that are relevant to archaeologists, including hydrological reconstruction [24, 25] and archaeological site detection [21]. It is also possible to use these tools to monitor threats to archaeological heritage that are occurring because of development, the expansion of agricultural land, and looting [26–28].

In this paper, we present and analyse an ensemble of datasets directed toward understanding the relation between river morphodynamics and the distribution of archaeological sites, revealing the dynamics of settlement patterns over time. To do this, we take a large part of the plains of Punjab province, Pakistan as a case study. Archaeological and historical evidence suggests that this region has been intensively occupied and exploited during the last six millennia. However, comprehension of the interrelations between hydrological processes and human settlement on the floodplains of Punjab presents a significant challenge. Several processes of urbanization and de-urbanization have accompanied a succession of complex societies, states and empires, as witnessed at the major Indus Civilisation city of Harappa, and great Early Historical and Medieval cities like Tulamba and Multan. Intense occupation continued through the Early Modern and colonial periods and up to the present. The archaeological evidence relating to the settlements and landscapes of these periods has been subjected to continuous transformation by the geomorphological dynamics of the Punjab floodplains and more recent large-scale landscape modifications, including the development of an extensive network of irrigation channels. As a result, the rich archaeological record of southern Punjab is best seen as the product of interwoven long-term geomorphological and cultural dynamics. There is already a long tradition of archaeological survey and interpretive models developed to explain historical settlement patterns in southern Punjab [29–35]. These models have incorporated factors such as the spatial distribution of sites, hierarchical analysis of site size, and consideration of proximity to existing rivers or perceived palaeorivers. This last factor has exerted a particularly strong influence, and the relationship between water and settlement has been central to elaborating archaeological maps [35, 36] and mapping river paleochannels [37, 38].

This paper thus outlines an integrated method to remotely map the relationship between hydrology, palaeohydrology and features of archaeological interest in a region that has a complex interplay between hydrology and archaeology. This case study demonstrates that to understand such environments, these factors must be considered in conjunction to gain a coherent understanding of ancient cultural landscapes and how they change over time. This approach will also facilitate the establishment of coherent cultural heritage management strategies that take into consideration ancient and modern human and environmental processes. The multi-source approach used in this paper builds on previous work and contributes a comprehensive analysis of new and newly accessed datasets for the identification of ancient settlement and river movements. For that purpose, we have developed a series of enhanced analytical techniques that have been applied to the available historical cartography and Earth Observation products of the study area, but which are also available for many parts of the world. These resources are tested here as part of a rigorously assessed archaeological, historical and hydrological case study that makes it possible to evaluate the importance of such approaches for understanding an archaeologically and hydrologically complex region like Punjab, but more broadly for the understanding of similar contexts using similar sources in other parts of the world.

Study area

Geographic and geomorphological context

The study area investigated here (Fig. 1A), encompasses an area to the south of central Punjab in Pakistan, which spans the interfluvial area known as Bari Doab. The area is delimited by the rivers Sultej (to the south), Ravi (to the north) and Chennab (to the west).

The geographic expanse of Punjab occupies the upper part of the Indus River basin and is now shared between Punjab province in Pakistan, and the states of Punjab and Haryana in India. It is characterised by the extensive alluvial plains resulting from the uplift of the Siwaliks and the Himalayas and sedimentation caused by snowmelt, rainfall and water runoff. The formation of the Punjab floodplains started in the Oligocene and continues up to the present. Over this time span, sediments from the hills and mountains have been deposited continuously, and the processes of alluvial deposition have been affected by a combination of tectonic activity, glacial processes and rainfall variation, creating a complex and dynamic fluvial geomorphology across the different parts of the Indus River Basin [39].

All the rivers of the Indus Basin are characterised by seasonal floods and channel migration, which produce distinct floodplains delimited by bluff lines between which the rivers flow in braided channels that sometimes form meandering courses [40]. Geomorphologists [41–44] have distinguished three geomorphologically distinct formations on the Punjab floodplains: (a) the active alluvial floodplains that include the main river channels and areas seasonally flooded in a given moment; (b) recent and sub-recent floodplain deposits in the form of expansive terraces created by old courses of the rivers and their active fluvial plains, which include remains of multiple channels and oxbows that are visible in the microtopography of those areas, and where old channels become active on occasion; and (c) elevated bars that occur between the main river systems. The recent and sub-recent floodplain deposits have not been dated systematically, but for reasons explained below, they are likely to date to some point in the Holocene prior to the twentieth century. The bars are typically considered to be the older sediments of the area, and although no accurate dates are available, typically they are interpreted as remnants of the pre-Holocene alluvial plain that have been less affected by later geomorphic process [43, 45, 46]. The area of interest (or AOI) being considered here (Fig. 1B) includes parts of the recent and sub-recent terraces of the Ravi and Sultej-Beas River systems and the older Ganji Bar that separates these two systems. The Chenab, Ravi and Sultej rivers, and the now dry course of the Beas, traverse this region. The land between the Ravi and Sultej, which includes the old course of the Beas, is known as the Bari Doab.

Landscape history

Today, the landscape of the study area is dominated by agrarian irrigated land. This land-use pattern is the result of an intensive investment in hydraulic engineering along the rivers linked to an extensive canal network that covers almost all Punjab plain, which has been in development since late nineteenth century, when the British colonial administration set up a large program of "canal colonization" (Fig. 2) [47–51]. The written sources suggest that geographical and economic constraints previously limited intensive agriculture and related settlement to areas relatively close to the rivers, where populations could benefit from inundation caused by their flooding and/or the recharging of the water table, which was accessible by wells. Typically, the bars and interfluvial areas were described in maps as "saline soils scantly covered with herbage and peopled by an erratic tribe called Kattia" [52] or "Extensive Jungles" [53].

The dynamism of the fluvial network in Punjab has been recognised for some time, and several scholars have noted that it is an important factor for understanding the archaeological record and interpreting settlement patterns in protohistoric and historic times. Recent and ancient changes in river courses were noted by the British colonial authorities, as illustrated in the Chenab Colony Gazetteer [54], which noted: "The other doabs in the Punjab contain similar well-marked nalas with sites of old towns in their banks" [48]. Some important changes, including flood events, affected the course of the Indus at the end of the eighteenth century [18, 50] and around this time, the Beas underwent an avulsion and joined the Sultej in the northern part of Punjab, abandoning its downstream course completely [55, 56]. These relatively recent changes give insight into long-term morphological dynamics, but at present few data are available to make it possible to delineate the chronology and nature of previous episodes of change.

A significant amount of research has been directed towards trying to understand the Ghaggar-Hakra

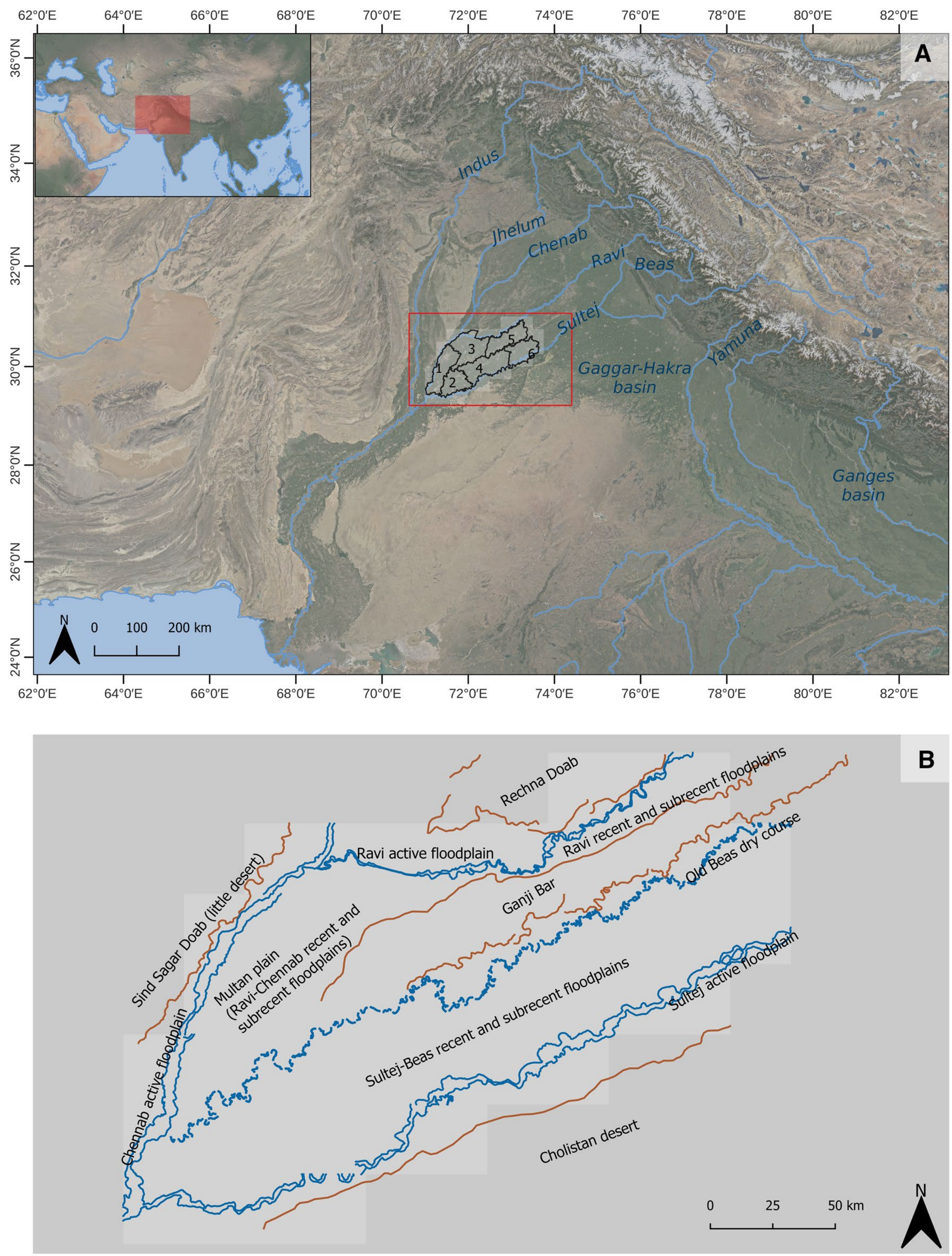


Fig. 1 The study area (**A**) is located within the confluence of several of the tributaries of the river Indus that define the region of Punjab. It includes the modern districts of Multan (1), Lodhran (2), Khanewal (3), Vehari (4), Sahawal (5) and Pakpattan (6) in the Punjab Province (Pakistan). The area is part of the Bari Doab (**B**), as it is known the region situated Today between the rivers Ravi and Sultej, which includes the active floodplains of both rivers, its recent and subrecent floodplains and the Ganji Bar that separates both systems

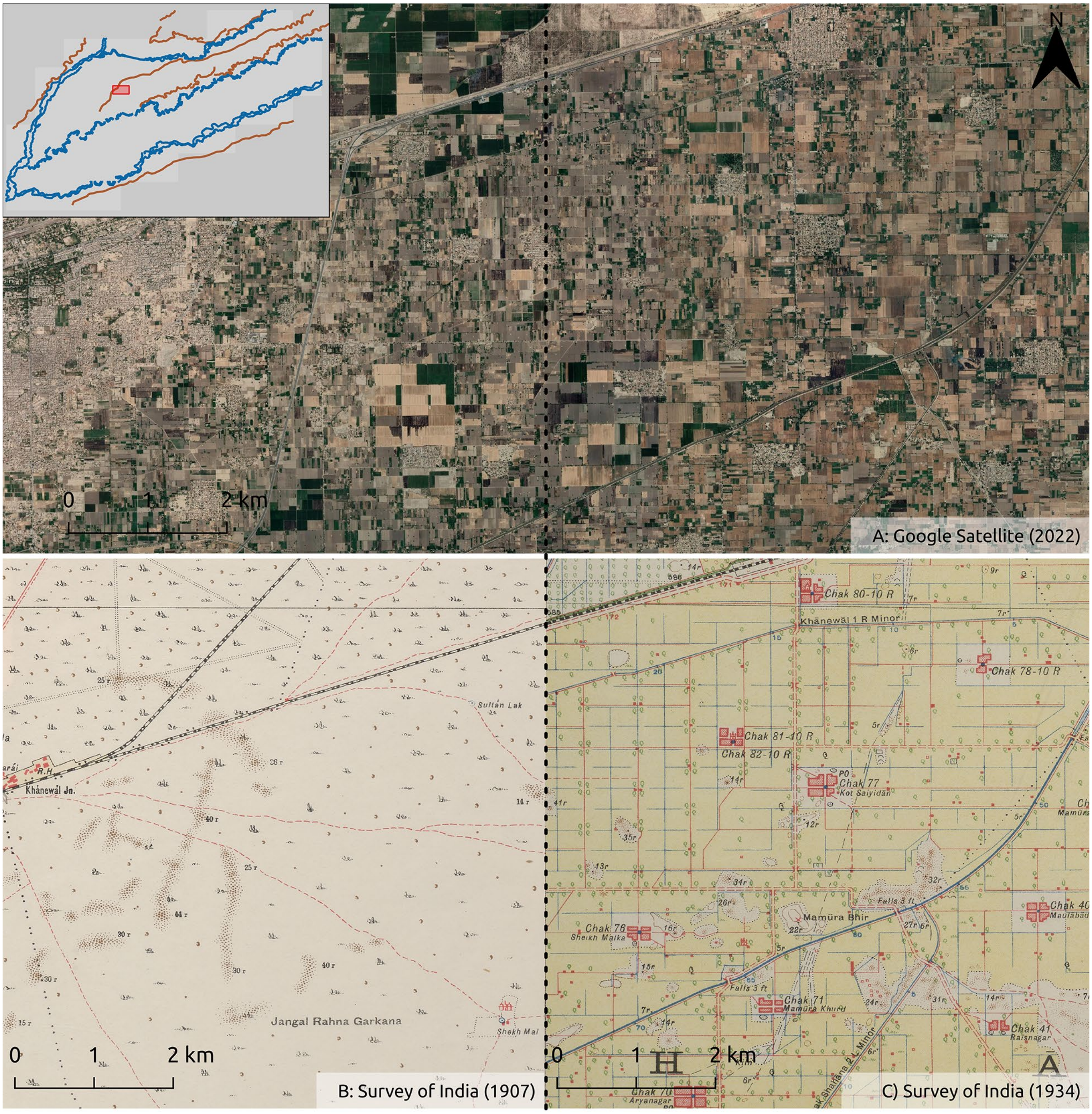


Fig. 2 Transformation of the landscape during the twentieth century, exemplified by the area around the city of Khanewal, situated in the border of the Ganji Bar. The town is nowadays (**A**) a district capital surrounded by irrigated agricultural lands. The historical maps of the Survey of India, show that at the beginning of the twentieth Century (**B**), the area was occupied by uncultivated lands labelled as "jungal". The construction of a railway junction and a dense network of irrigation canals and related colonization settlements transformed the area. The process was already well advanced in the 1930s (**C**), as later editions of the SoI allow us to track

palaeochannel in terms of both its fluvial dynamics and its relation to archaeological record. It's possible identification as the Vedic Saraswati and the identification of protohistoric settlements along its course has generated abundant bibliography since the nineteenth century [29, 57–62], though a range of issues continue to be debated [21, 25, 63].

Less work has been directed toward understanding the archaeological significance of the long-term dynamics of the major rivers of Punjab. H. Wilhemy [37, 39, 64, 65] proposed a broad sequence of river morphodynamics, and this remains widely used, though there is recognition that there it was created with an absence of systematic absolute dating. Some specific work has been directed towards the understanding of the local conditions around the Indus Civilisation city sites of Mohenjo Daro [39, 66] and Harappa [44, 67, 68]. A palaeoclimatic model has also been analysed to assess the potential impact of climate on the river regimes in Punjab [35], but consideration of broader morphodynamics has actually been quite limited [37].

History of archaeological research

The archaeological character of many of the mounds that dot the Indus basin has long been recognised by local populations and was often reported by early travellers and colonial officials, including sites like Harappa in the study area [69]. Many of the historical societies of South Asia where known, at least to some degree, thanks to references in the historical texts from contemporary societies, and these documents provided the first guide to interpret the archaeology of the basin [70, 71]. The mounds at Harappa were visited and formally documented from the mid- to the mid-late nineteenth century [69], but it was not until the 1920s that the site was identified as a protohistoric urban centre related to the Indus Civilisation [72]. This recognition put Punjab in the foreground of archaeological research in the Indus River Basin, though the surrounding region has only seen limited further research through the excavations of sites like Tulamba in 1963 [73] and Jalilpur in 1971–2 [74].

Beyond these single site excavations, there are several phases of archaeological survey that have been carried out in the region. In conjunction with his excavations at Tulamba in 1963, Mughal [73] also lead a survey that identified sites to the south and east of the medieval and modern city of Multan. In the 1970s, Mughal [36] also lead an extensive survey of Cholistan in south Punjab which followed in the steps of the initial survey of that region by Stein [29]. These surveys were followed by the more extensive Punjab Archaeological Survey carried out from 1992 to 1996 by the Department of Archaeology and Museums of the Federal Government of Pakistan, which was the first and thus far only systematic mapping of cultural heritage across Punjab province [33, 34].

This work opened the possibility to analyse both settlement patterns and landscape dynamics. During the late 1990s and early 2000s, the Beas Landscape and Settlement Survey revisited a number of the sites identified by Mughal along the now dry course of the Beas [35, 37, 44, 68, 75, 76], and initiated the identification of potential archaeological mounds using CORONA imagery [38]. This project analysed the nature of rural settlement, including an assessment of long-term settlement dynamics by making use of cartographic information and satellite imagery to draw inferences about riverine dynamics [38, 77]. Taken together, the research that has been carried out thus far provides a framework for assessing the archaeological record of the study area.

The distribution of known archaeological sites in Punjab investigated here has been reconstructed by digitising the list of archaeological sites and monuments of Punjab published by the Punjab Archaeological Survey [34]. This publication included all accumulated information about site distribution that had been collected since the creation of the Archaeological Survey of India in 1861, including the result of the extensive surveys carried out during the 1990s. Sites are documented in terms of their location—with coordinates—and an Indication of their chronology. It is important to note that all these surveys were carried out before the introduction of the GPS as standard tool in archaeology. Although the site locations have been documented with a considerable degree of accuracy, the scale in which the surveyors worked introduces a margin of error in the position of the sites that can be up to several hundred meters in any direction [37].

Materials and methods

Historical cartography

The *Survey of India* (SoI) produced a 1″-to-1 mile map series that was published incrementally between 1906 and 1947, and was based on surveys undertaken from the mid-late nineteenth century onwards that made use of topographic techniques that were cutting-edge for that time. The maps within these series can be subjected to accurate georeferencing using modern GIS software [17, 79]. More importantly they offer a high level of detail about historical landscape features, including human land-use, infrastructure, water courses and topographic features and in some instances evidence for change in those features [18]. Significantly, these maps document the traces of numerous relict river channels (Fig. 3).

The topographical detail recorded in these maps has proven to be critical for archaeological analysis, since the maps record a large quantity of small topographic anomalies, including mounds, that correspond to the remains of early settlements. Those features are topographically distinct, and their incidental documentation unintentionally provided a systematic record of potential archaeological sites [17]. An initial assessment of historical map mound features, and an associate programme of groundtruthing in the state of Haryana in northwest India has confirmed the usefulness of these maps to detect archaeological sites, with 60% of some types of features corresponding to archaeological sites [20, 80, 81]. In fact, the percentage is probably higher as some of the depicted

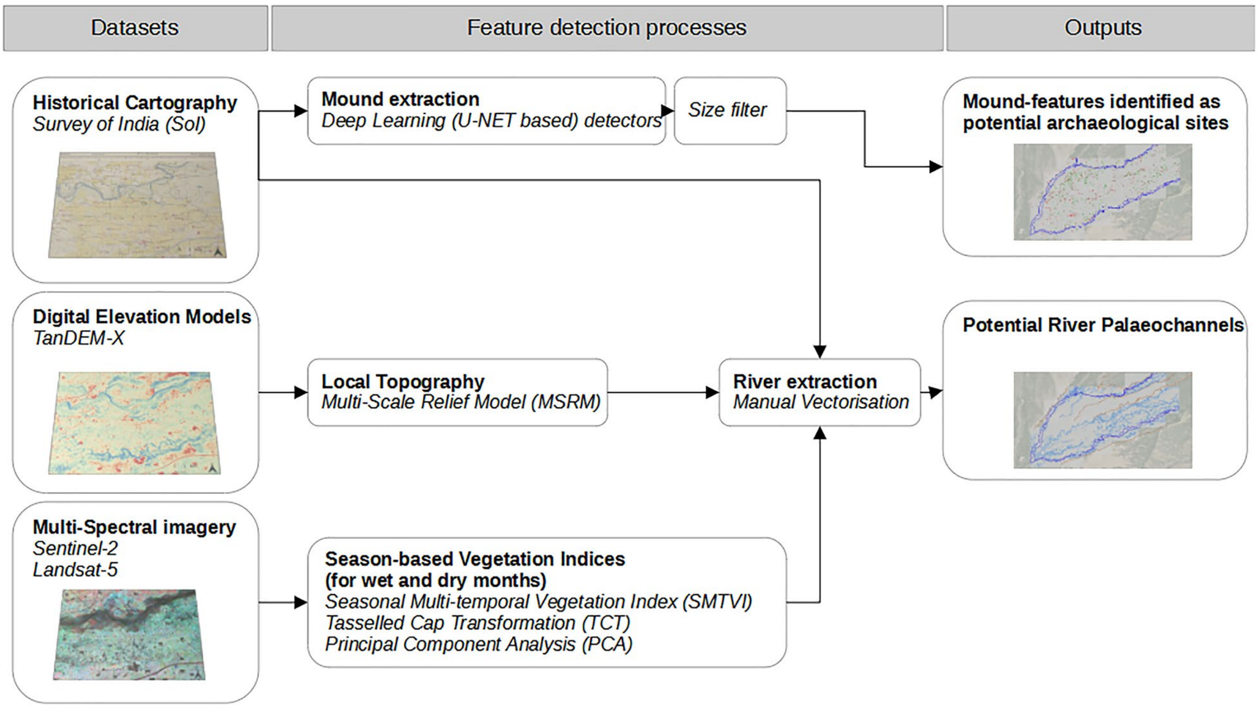


Fig. 3 Schematic workflow used in this study for the extraction of potential mounded archaeological sites and river palaeochannels. Each of the methods employed here is described in detail in specific publications [22, 25, 78]

mounds have been completely flattened and their soil removed, which has left no cultural remains that could be used to validate this correspondence. In the semi-arid and arid areas of Cholistan, the map coverage was much more limited, but mound features are also detectable on the available maps [21].

For the analysis presented here 49 maps that cover the AOI have been georeferenced (Fig. 4). These maps were produced between 1907 and 1944. Most of these sheets (34) correspond to editions published during the inter-war period, mainly during the 1930s. These map sheets are well edited, reproduced in colour and use a standardised symbology. Of similar quality, although somewhat simplified and less standardised are the maps produced before the First World War (13, dated from 1907 to 1909). In two cases the only map sheets available were produced during the Second World War (1944).

The maps were georeferenced using the standard georeferencing tool in QGIS and following the criteria described in previous works [17–20]. Infrastructure such as railroads, roads, and canals provide reliable Ground Control Points (GCP) for georeferencing, since most of these structures persist today. This is particularly true for the 1930s editions. The pre-First World War editions provide fewer potential GCPs, since part of these networks were not yet built. The most problematic areas for identifying GCPs are the active floodplains of the main rivers, where continuous movements in the river courses have transformed the area beyond recognition. Except along the course of the Ravi, Sultej and Chennab, where the georeferenciation must be considered less accurate, around 20–30 GCPs were selected for each map, given an average RMSE value of approximately 30 m.

(See figure on next page.)

Fig. 4 Examples of the features of interest identified in the Survey of India historical maps, as they appear in the different examples and editions of the SoI historical maps that cover the study area. Mound features appears as contours (**A**) and hachures (**B**) in the 1900s editions and as form-lines (**C**, **D**) in 1930s and 1940s editions. Automated detection has been applied to 1900s and 1930s editions, but not to 1940s, due to the limited number of maps. Specially in the 1930s editions, small form-line features were used to represent barren lands and small outcrops (**G**), which introduces false positives that needed to be filtered. Limited false positives (**E**–**F**) can be induced by the similarity of certain features. Some missing elements have been also detected in the manual inspection (**H**). For more details see Garcia-Molsosa et al. [22] and Table 1. Features related to the hydrographic dynamics are also represented in the historical Survey of India maps, though their aspect differs a bit in the different editions. Here we have delimited the active floodplains (**I**, **J**), disconnected channels (**K**, **L**), and dry or intermittent channels oxbows and isolated meanders (**M**, **N**)

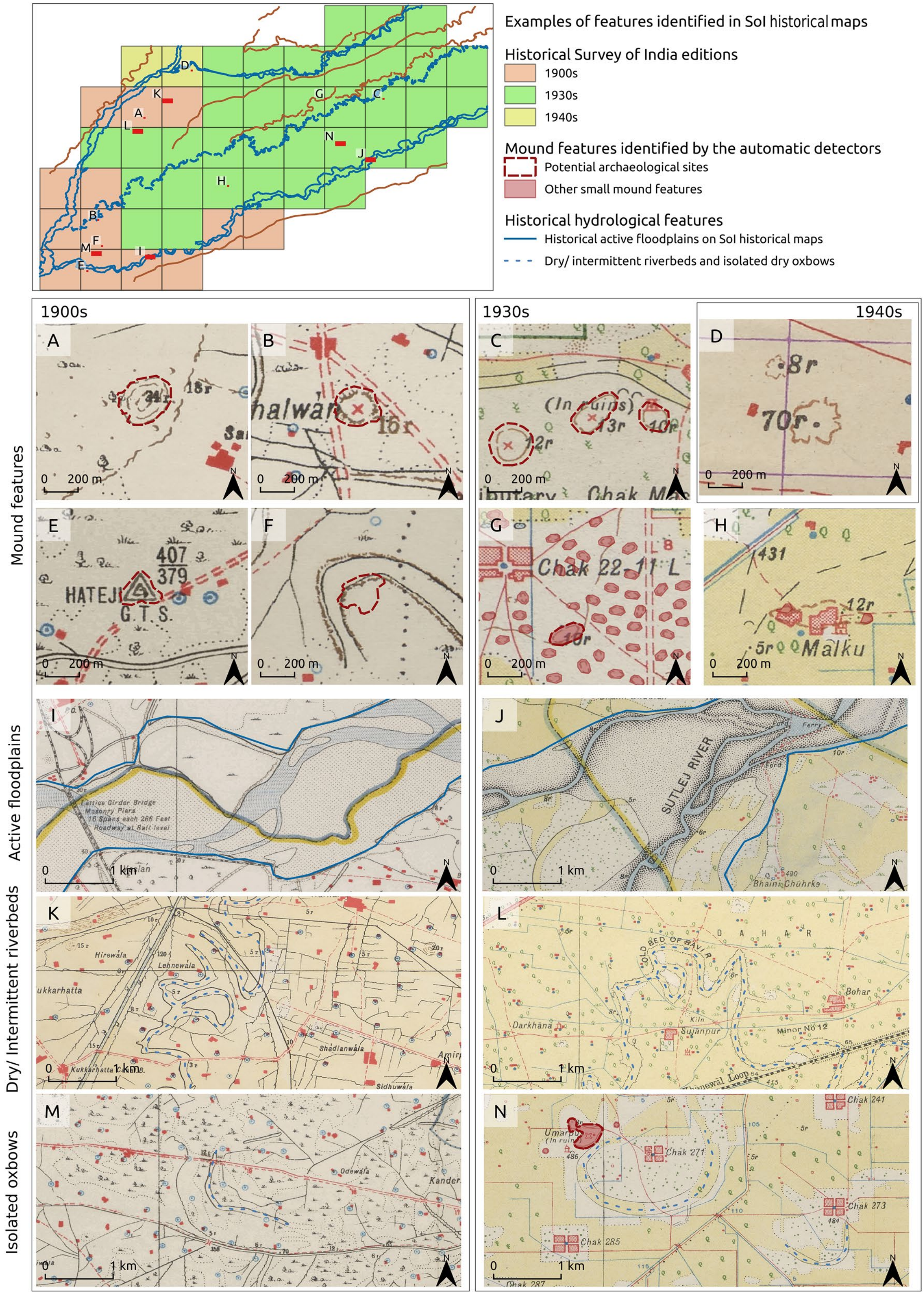


Fig. 4 (See legend on previous page.)

Mound extraction

A new workflow for automatic extraction of potential mound features have been successfully tested on these georeferenced maps. The method is described in detail in a previous publication [22]. Its implementation was based on the training of three detectors based on a U-Net architecture: two were tested for contour and hachure features in 1900s maps and a third one for form-lines in 1930s maps (Fig. 4A–H). Size filters have been applied to eliminate noise and small features that could correspond to small elevations such as dunes and other features with little probability of corresponding to archaeological sites. The experience gained from the work in Haryana, where an extensive ground-truthing archaeological survey have been carried on, showed that those features drawn as contours, hachures and form-lines larger than 2 ha in the maps are significantly more likely to correspond to archaeological sites [20].

The results of the automated method were tested and validated manually by an expert. That process has made it possible to correct most false positive and include some of the features missed by the detector.

River extraction

It is clear that the historic Survey of India maps contain valuable information about rivers and palaeochannels (Fig. 4I–N). Their production in parallel to the development of the canal colonies system explains why the hydrography was one of the main foci of the topographers. Active floodplains are represented on the maps with a main channel and secondary paleochannels physically linked to it both being depicted. On the recent and sub-recent floodplains, potential paleochannels can be identified as channels disconnected from the active floodplains or topographic features recognised by their morphology, which are strongly influenced by the formation of meanders and oxbows. Active floodplains have been identified by their more evident borders. Potential paleochannels and other hydrological features have been extracted as polylines.

Satellite imagery-based analyses

Earth Observation products have the potential to provide information about topographic variability and the distribution of and change in vegetation, and both can be combined to identify palaeorelief and archaeological features. In this study, two types of EO derived products (Fig. 5) have been obtained following techniques originally developed for the analysis of similar landscapes, specifically:

(1) Multi-Scale Relief Model (MSRM) [78], which allows the documentation of small and variable topographical changes over large areas. MSRM is particularly useful for the detection of palaeorivers, levees and related hydrological features. The MSRM analysis presented here has employed a TanDEM-X Digital Surface Model (DSM) of the study area. With 12 m/pixel this is the higher resolution and most accurate Global DSM available.
(2) Seasonal Multi-Temporal Vegetation Indices (SMTVI) [25], employ seasonal averages of Enhanced Vegetation Indices of multispectral imagery for a set of given years. The resulting composite image displays long-term trends in seasonal vegetation health, and these indices have proven useful in identifying relict channels and evidence of the shifting course of the Indus River [18].
(3) Spectral decomposition techniques (PCA and Tasselled Cap Transformation) [25] provide improved visualisation of long-term trends in the multispectral dataset averaged for wet and dry months.

Both SMTVI and the spectral decomposition techniques have been applied to full datasets of both Landsat 5 and Sentinel 2 imagery for the study area. While Landsat 5 imagery offer much deeper multitemporal depth than Sentinel 2 (28/7 years), Sentinel 2 offer much higher spatial resolution (30/10–20 m. per pixel) and spectral resolution. The algorithms for these applications adapted to the AOI are provided as supplementary information and can be implemented in the Google Earth Engine platform [82].

Results

Mounds of archaeological interest

The automated extraction from the SoI historical maps identified 13,130 features that could correspond to

(See figure on next page.)

Fig. 5 Representative example of the extraction of features related to the historical hydrological networks. In these images it is possible to identify the old Beas dry course (1), which is drawn in the historical SoI maps and is still visible in RS imagery (1: **B**–**H**). Three other paleochannels (2, 3 and 4), are also drawn on the SoI map (2–4: **C**), but are not visible in nowadays aerial imagery (2–4: **B**). Finally, a large trace of a disconnected oxbow was not drawn on the SoI maps (5: **C**) and is not visible in the aerial imagery (5: **B**). Those features are present and detectable in modern topography, and local relief-based visualization techniques such as MSRM (**D**) are very useful in rendering them visible. These features can be also intuited examining vegetation indices, but they are much more subtle and difficult to interpret. In the study area the longer series of Landsat 5 images (**E**) have been more useful than Sentinel 2 (**F**), even with the difference in resolution. In the latter case, Spectral Decomposition techniques (PCA) based on the wet periods is giving slightly better results (**G**, **H**)

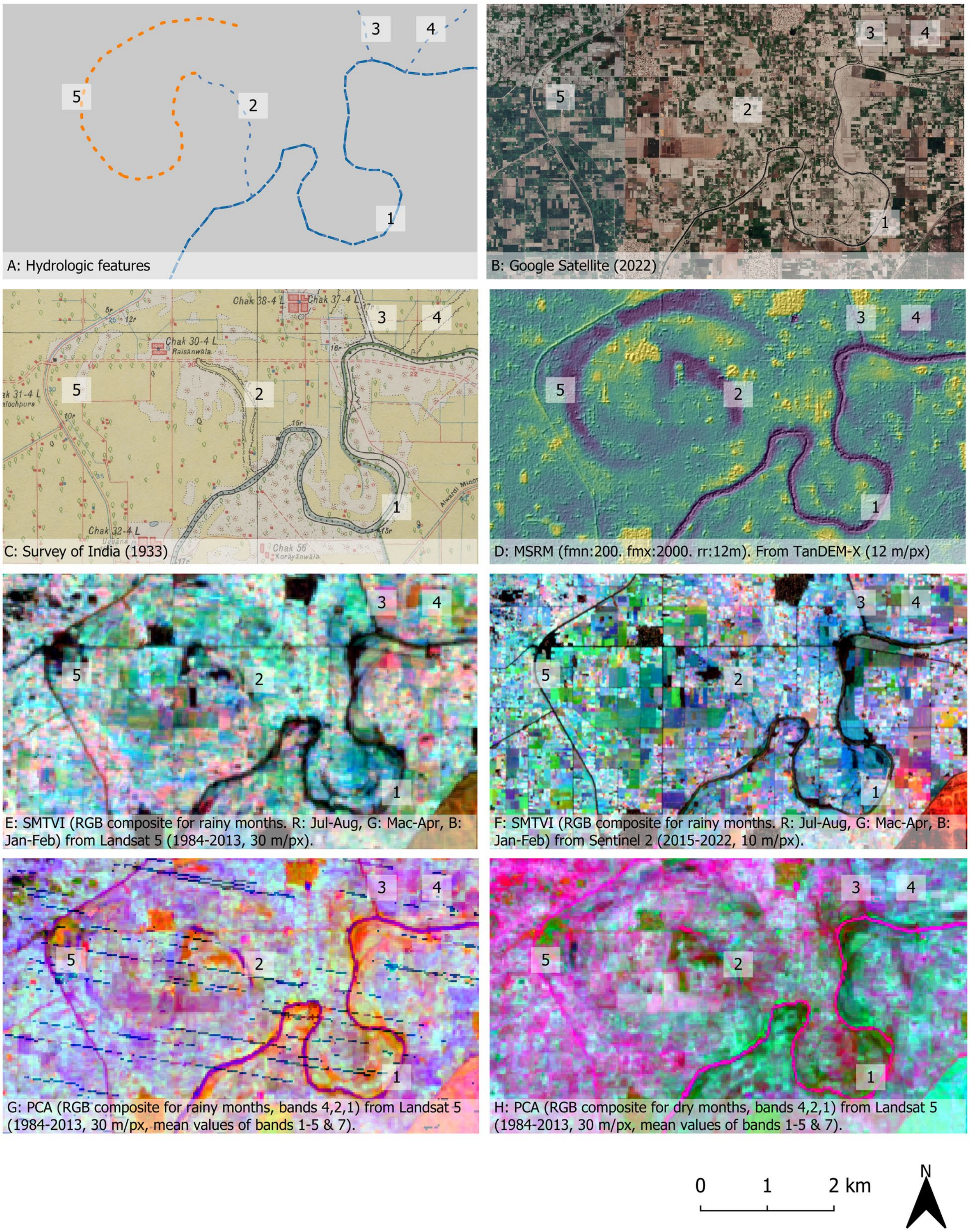


Fig. 5 (See legend on previous page.)

mounds (Table 1; Fig. 6). After the 2 ha threshold was applied, 638 features were considered to have a high probability of corresponding to archaeological sites according to the observations in Haryana [20]. The corrections introduced by the manual revision, increased this number to 646 potential remains of ancient settlements in the AOI.

Palaeohydrography

Excluding the main courses of the Sultej, Ravi and Chennab and the multiple channels visible in each of their active floodplains, a total of 6974 km of palaeochannel traces have been identified across the AOI (Fig. 7A). The active floodplains varied from 5 to 10 km in width for the Sultej and Chennab at some points and 1–2 km width for the Ravi. Despite some variations, the active floodplains tend to follow the broad floodplains as they appear in the SOI maps (Fig. 1), which suggests that the recent and sub-recent floodplains pre-date the twentieth century at the least. The effects of the construction of dams and barrages to manage the flow of water are likely to have contributed to a lack of channel movement since the start of the twentieth century [83, 84].

Beyond the active floodplains, recent and sub-recent channels are evident in various areas, including the dry courses of the Beas and older channels of the Ravi and Sultej. Other courses labelled as nalas on the maps are dry and/or seasonal watercourses that were historically used as inundation channels [37, 48]. In proximity to the more continuous courses, many isolated traces were also recorded in the historical maps. The documentation of this quantity of channels represents a significant enhancement of the findings of Smith [37], which were made using the more limited and lower-resolution data sets available at that time.

Table 1 Results of the automatic detection

Map edition	Num of maps	Automatic detection				Manual revision
		Targeted features	Features detected	> 2 ha	False positives	
1900s	13	Hachures and contours	322	162	n. 19 (12%)	155
	(7)	(Only contours)	(214)	(125)	(n. 5 (4%))	(126)
1930s	34	Form-lines	12,808	476	n. 16 (3%)	475
1940s	2	Form-lines	–	–	–	16
Total	49		13,130	638	35 (5%)	646

For more detail see Garcia-Molsosa et al. [22]

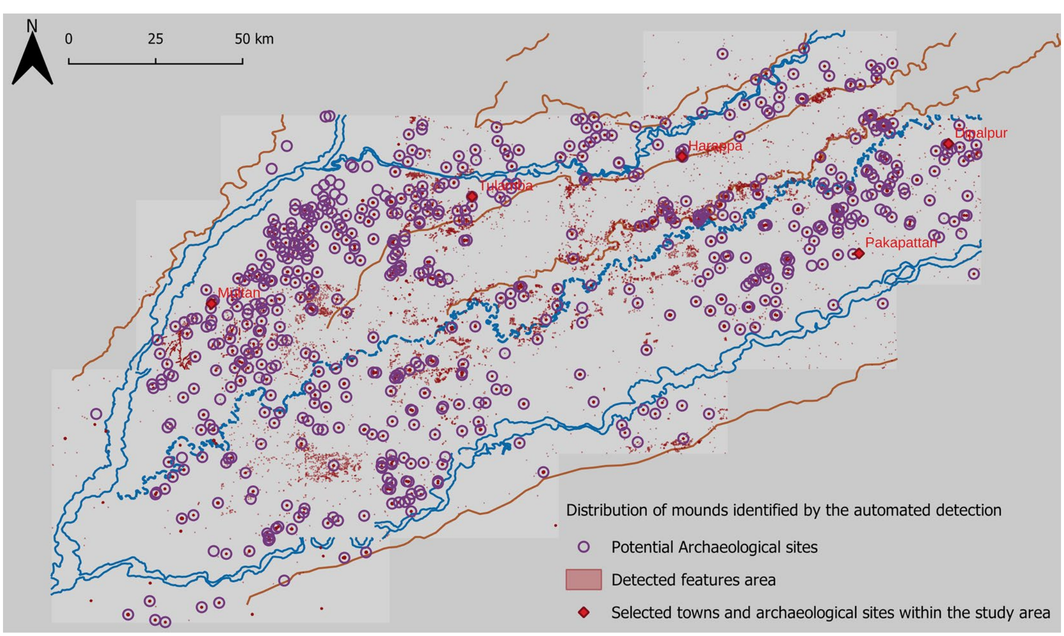


Fig. 6 Features identified as mounds and filtered as potential archaeological sites. Including the areas of the total of features detected and the selection of potential archaeological sites after the filtering by size and manual revision (see Table 1)

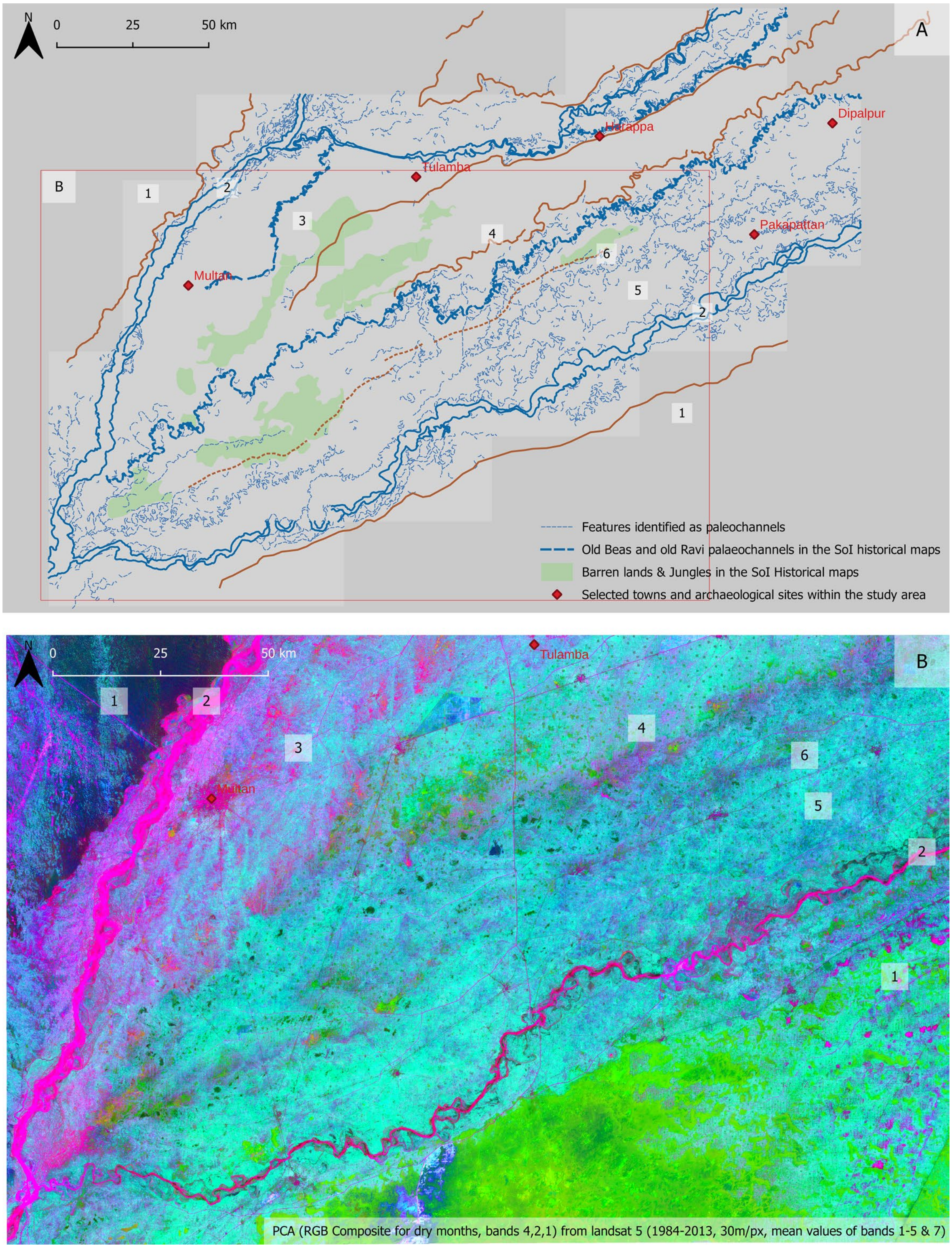


Fig. 7 Features identified as palaeochannels (**A**). A complementary interest of the vegetation indices (**B**) is that they help to distinguish the different geomorphological units (see Fig. 1), including the limits between the deserts and floodplains (1), the modern active riverbeds (2), the multan plain (3), the Ganji bar (4), and the old floodplains of the Ravi and Suletj (5). In the middle of the area (6), traces of an ancient bluff-line separating the Beas and Sultej old floodplains can be seen in some images (particularly in the combinations based in the dry months)

The river courses reported on the SOI historical maps are also clearly visible in the processed microrelief imagery, which are generated by the MSRM analysis. When the MSRM is compared with the maps, the maps show an excellent accuracy and precision in documenting channel traces, such that the traces extracted directly from the maps perfectly match the present-day landforms. However, the enhanced multi-spectral images show that some of this micro-reliefs can affect the humidity variability at small-scale, making visible landforms related to old watercourses that are not visible on the historical maps (Fig. 7B; see also Fig. 5).

The distribution of channels presents significant patterns in the different geomorphological sectors of the AOI. The channels recorded traverse the recent and sub-recent plains of the Ravi and Beas-Sultej, but they are notably absent in the Ganji Bar (Fig. 7A). In the lower part of the Bari Doab appear extensive "interfluvial" spaces occupied by "Jangals", where no courses were drawn by early twentieth century surveyors. Traces of the separation between the Beas and Sultej ancient floodplains can be seen in that area, only in some combinations of vegetation indices. An old bed of the Ravi is intermittently documented in the central part of the Multan plain by the cartography, and the micro-relief makes it possible to connect the different traces, although the marks are not always evident. The traces of the Ravi disappear east of the old town of Multan, at the point where modern suburbs make it impossible to follow the traces. It is notable here that, besides that one, palaeoriver traces are not evident in the plain around Multan.

Discussion

Archaeological map assessment

The analysis of the historical maps presented here has resulted in the identification of 646 mounds of archaeological interest, complemented by 186 other features such forts, toponymies of interest or abandoned villages. At one level, this list of potential sites represents a pre-exploratory resource that can be used to guide both research on the ground and heritage management planning. To get the most of these data field validation will need to be undertaken by heritage agencies and/or research groups. Although such analysis has not been attempted as part of this research, there is scope to carry out additional analyses to extract relevant information on site distribution from the dataset in advance of any ground-truthing.

It is possible to interrogate the features digitised off the SoI maps by comparing them to three types of data: (1) the results of historic map mound feature ground-truthing fieldwork assessment in Haryana [20]; (2) the distribution of known archaeological sites in the AOI [34]; and (3) the analysis of the present-day context of these locations in recent aerial and satellite imagery.

(1) Based on extensive ground-truthing campaigns directed at assessing mounds represented in SoI Maps [80, 81, 85, 86], Green et al. [20] analysed which types of map features were more likely to represent archaeological sites. Two main conclusions were drawn: first, mounds not represented as form-lines or hachures are not likely to present archaeological findings. That is particularly the case for reliefs represented as shaded features, which in the maps we examined represent "sand hills" or "stony wastes", according to the map legend. Secondly, the study outlined three categories based on the mound size as represented in the historical maps: size 1 (< 200 m diameter), size 2 (200–400 m diameter) and size 3 (> 400 m diameter). While size 2 and 3 mounds presented archaeological evidence in 60% of the cases when visited, only 25% of the smaller size 1 features contained archaeological material. The threshold used here, 2 ha—which approximates the area occupied by 200 m diameter sites—allowed us to discriminate those mounds with a higher probability of corresponding to archaeological sites (Fig. 4). Despite the fact that the maps of the area of Haryana correspond to the 1910–1920 editions, which present some differences with earlier and later editions used here, SOI maps were created following similar criteria in both areas. Also, the area explored in Haryana belongs to the same larger geomorphologic unit of the Punjab floodplains, and both regions have similar archaeological problematics. We have thus assumed that the data extracted from maps from both of these regions can be directly compared, with the caveat that this can only be confirmed by future fieldwork involving ground-truthing.

(2) We also compared the historical map mound features extracted from the SoI maps with the coordinates documented by the Punjab Archaeological Survey (PAS). The PAS [34] listed around 1000 sites and monuments across the whole Punjab, of which 301 are located in the AOI (Table 2; Fig. 8). If broad chronological periods are considered, the AOI contains a similar proportion (10%) of proto-historic sites to the general Punjab Archaeological Survey (PAS) area overall, with the exception of Cholistan where the proto-historic sites predominate [36]. Similar proportions of proto-historic sites were reported in field surveys in northwest India [20]. The rest of the PAS sites are Early Historic, Medieval, Mughal and/or later periods (from sixteenth

Table 2 Distribution of sites reported in the PAS by chronological phase

Sites and monuments per period	PAS (all Punjab Province)		PAS (AOI)		Mounds identified (AOI)	
	Sites (%)	Mon. (%)	Sites (%)	Mon. (%)	Sites (%)	%
Prehistory (Palaeolithic/mesolithic/neolithic)	19 (3%)	–	–	–	–	–
Protohistory (3300–600 BC, including PGW)	75 (10%)	–	24 (10%)	–	8 (7%)	33%
Early historic and medieval (5th BC–15th C.)	412 (57%)	39 (15%)	153 (64%)	14 (23%)	86 (70%)	56%
Mughal and later (16th C.–1947)	217 (30%)	213 (85%)	63 (26%)	47 (77%)	29 (23%)	46%
Totals	723 (100%)	252 (100%)	240 (100%)	61 (100%)	123 (100%)	51%

This compilation is based on the annexes included in Mughal et al. [34, Appendix I]. See also Fig. 8 for its geographical distribution

century onwards). Although similar numbers of features are reported, the later periods are represented mostly by standing monuments. Several studies have demonstrated the difficulty of finding matches between features visible on historic maps and/or remote sensing imagery and published site locations that were not determined through the use of GPS devices [21, 80, 81, 85–88]. This challenge also holds for the PAS data. The situation is also complicated by the fact that not all of the sites included in the PAS publication have co-ordinates. For the study presented here, we have only included the sites with co-ordinates [34], which makes it possible to cross-check them with the maps.

The comparison between PAS data and the mound features detected in the SoI Historical maps resulted in 123 positive identifications. That number represents sites that were located: (1) within the area of a mound feature; (2) close to a mound feature and/ or; (3) some toponymic indication helped to locate it in the map. For this analysis, we have preferred to be conservative and have not considered the cases where we had doubts about specific locations (Fig. 9).

These results indicate that 51% of the sites reported by the PAS can be linked to mound features in the SoI historical maps. In 12 cases, sites were associated to mound-features that fell below the 2 ha threshold. Although, there are potential issues with precision and accuracy in both the PAS-reported coordinates and the features documented on the maps we consider that the resulting data presented in Table 2 provide a good approximation for a first phase of remote assessment.

(3) Finally, we have also observed the current state of the areas occupied by mound features in the historical map, using up to date high-resolution aerial imagery (Google satellite in this case). The results of this component of the analysis (Table 3) can be divided in four groups: (1) mounds visible in present day imagery; (2) areas currently occupied by buildings, farms, cemeteries, and villages; (3) both mounds and buildings are present; and (4) agricultural fields.

Considering these three situations, we can extract some considerations:

As many as half of the sites reported by Mughal et al. [34] have not been identified in the old maps, and similar numbers were obtained from assessments of history satellite imagery [38]. A percentage of these may be related to imprecise coordinates. Nevertheless, without field assessment, it is impossible to know to what extent this percentage is reliable. Significantly, some of the 'missing' sites are depicted on the maps as abandoned villages, which were not automatically identified, or they occur in dune areas. Furthermore, relying on mound features means that it is not possible to detect sites that do not have the aspect of a mound.

Of the sites reported by PAS that were identified as mound features on the maps, almost all fall above the 2 ha threshold (sizes 2 and 3; [20]) and only a small number fall below it (equivalent to size 1; [20]). This correlation suggests that the pattern identified in Haryana is also valid in the AOI.

The mound-features identified as sites reported by PAS are mostly visible as mounds in present-day imagery (Table 3). Taking this correlation into account, we can infer that PAS surveyors documented mostly those mounds visible on the ground. Thus, the technique used here demonstrates the potential for identifying sites that were present at the start of the twentieth century and documented on historic maps, but which are no longer visible on the ground in the present-day and were not extant during the PAS. The existence of these mounds can thus only be inferred by the approach presented here.

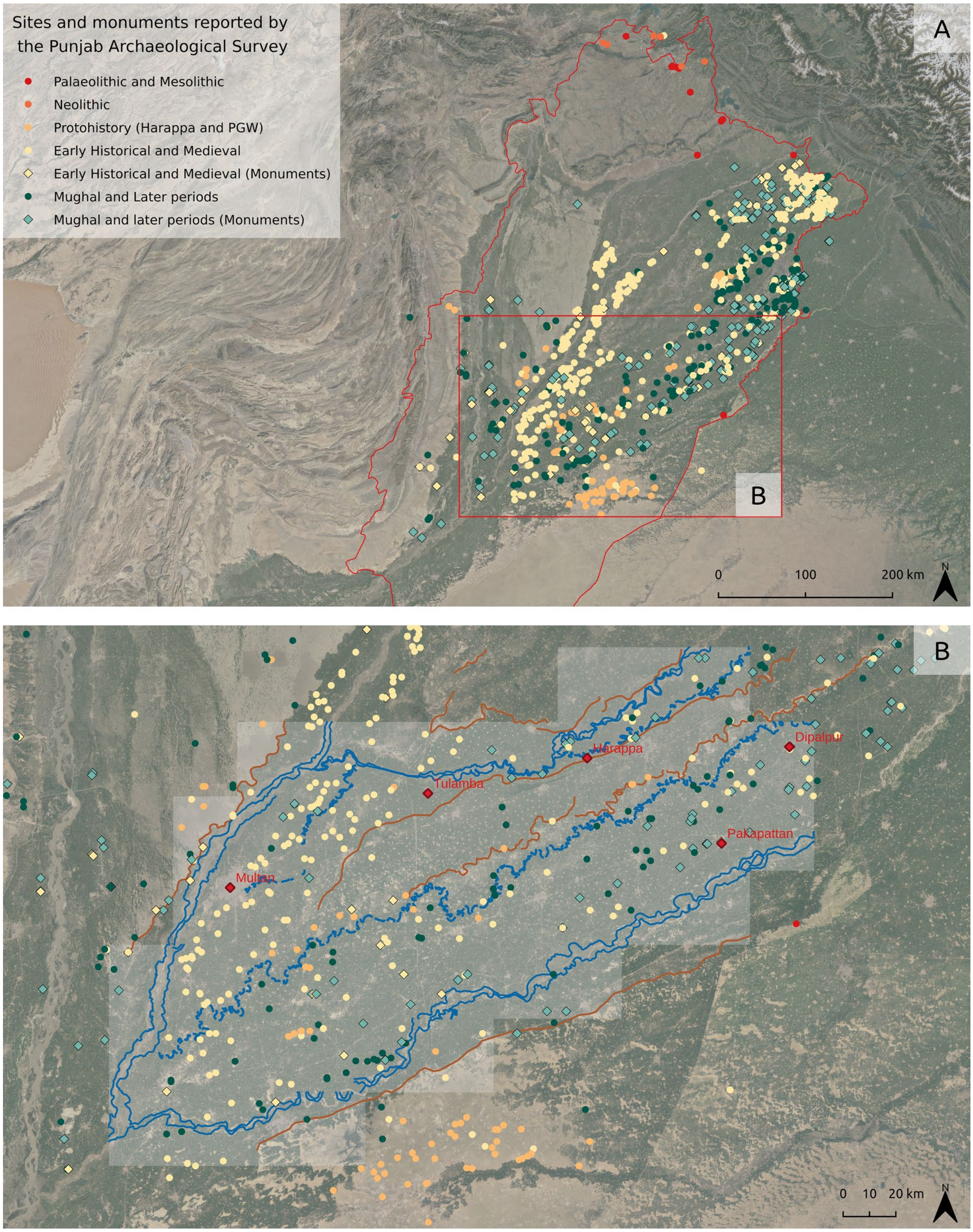


Fig. 8 **A** Map showing the geographical distribution of sites and monuments reported by the PAS. **B** Detail of the same data from the AOI. This compilation is based on the Annexes included in Mughal et al. [34, Appendix I]. See also Table 2

Around 70% of the historic map mound-features, both identified in the PAS and not, are occupied today by some type of building. It is interesting to note that in the historical maps, 15% of the mound-features already had cemeteries on top and 10% had abandoned villages, and occasionally, occupied villages were also depicted on top of mounds. It is now/was common for cemeteries and farms to cover the whole or at least part of a mound. In

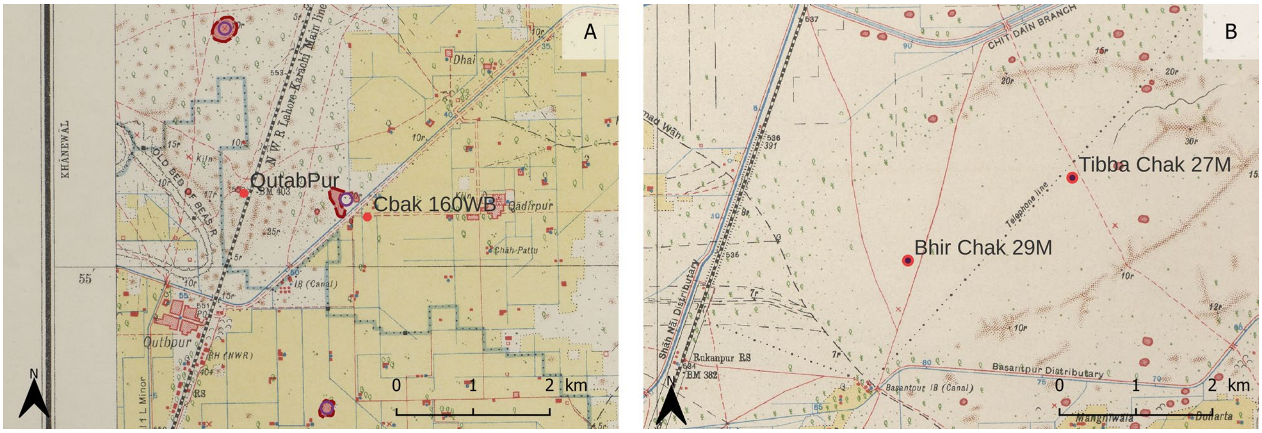


Fig. 9 Examples of challenges encountered while matching the location of the PAS sites: **A** one site (Chak 1600WB) can be identified with a mound feature in the SoI, while a second one (Qutabpur), though it indicates that the mound site must be around the town, it is not clear where. At least two mounds nearby might be the location, but it could also refer to a site located next to the town or in an abandoned village. **B** Shows two example of sites that could not be identified. Few small mound features and indications of abandoned villages are close to the reported location, and they could indicate the location

Table 3 Present-day context of the mounds identified in the SoI historical maps

Mound-features	Total	Mounds	Modern buildings	Modern buildings and mounds	Agricultural fields
Identified in PAS	123	23% (n29)	26% (n33)	42% (n52)	7% (n9)
Random sample > 2 ha	100	10%	30%	41%	19%
Random sample < 2 ha	100	5%	42%	11%	42%

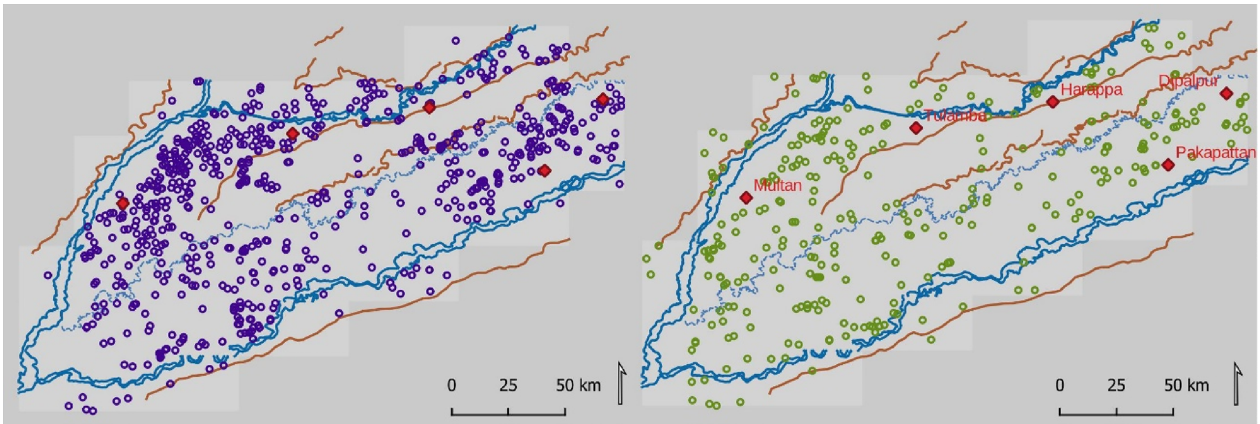
We have examined all mounds that could be related to sites reported in the PAS (see Table 2). From the rest, a random sample query has been applied to select 100 features across the AOI. A second random sample query has been done on the smaller "mound features", which provide interesting results to understand the specific problems of the small features represented in the SoI historical maps: in that case almost 90% are "not visible" Today, which confirms the low probability to be mounds, specially in the present landscape, but maybe also in the past. However, as happened in Haryana, still a small proportion correspond to mounds (16% here). That evidences that is a dataset not to be entirely dismissed, specially when working at micro-regional level

many of the remaining cases, recent urbanization has covered the area of mound features. That aspect highlights the importance to consider present occupation in the design of field approach, and also in the interpretation of settlement patterns. Seems probable that urban rescue archaeology has potential to play a major role in the future understanding of the archaeology of the area. On another side, the presence of cemeteries is a factor helping in the preservation of some mounds and future exploration will have to consider the cultural value of these spaces. In general, any strategy of heritage management in the area will have to acknowledge that a significant percentage of sites are located in currently inhabited areas. Local communities will necessarily need to play a central role in the protection of and research on the cultural heritage at local and regional levels.

The distribution of historic map mound-features has a similar pattern to that shown by the known archaeological sites documented by the PAS (Fig. 10). It is notable that few mound features have been identified on the Ganji bar or within any of the active floodplains. The absence of mound features in those areas is indicative of different factors, including: (1) a lower level of permanent occupation on the bars; (2) a combination of different cultural and geomorphological processes on the bars, that formed an archaeological record in which artificial mounds are not created and or preserved; and (3) active floodplains that tend to partly or completely erase settlement remains [18].

Most of the sites that have been identified are located on parts of the floodplain that have not been recently active and may not have been active for some time. This factor, combined with the absence of sites on the bars and within active floodplains, reinforces the idea that the mound-features correspond to sites, and that their distribution is archaeologically and historically significant. This observation also indicates that the dating of archaeological sites has the potential to reveal chronological information about morphodynamics.

The geographical pattern of ancient site distribution described above is a result of a combination of the different settlement patterns characteristic of the various



Sites

Mounds detected in Historical maps   Site & monuments reported by the PAS

Fig. 10 Mound features identified in the map (left) and archaeological sites according Mughal et al. [34] (right)

periods. A general pattern of intensive occupation of the areas where water can be accessed through inundation and/or wells can be inferred, and it is consistent with what have been observed for different historical periods [35, 38, 48, 50, 89]. The shifting of the rivers implies that the location of intensive occupation areas changed through time, impacting the settlement distribution in different periods. We will address some aspects of this process in detail in the next section. It is important to note here that from protohistory to the post-Medieval period, multiple technological, economical, socio-political and environmental factors influenced the settlement patterns, and the data provided here will need to be analysed in detail and contextualised in relation to the historical data in order to exploit its complete potential.

Beyond its role in settlement patterns, fluvial morphodynamics are responsible for the destruction of archaeological sites in the floodplains that have been active over time. Archaeological site distribution of the different periods cannot be explained without critically addressing the "empty" spaces on the map. For example, PAS [34] identified many more historical sites than protohistoric sites. That pattern should perhaps be expected in areas that have been continuously inhabited and where population has increased, but also where older sites have been impacted by the fluvial morphodynamics over a longer period. There is an inherent challenge to differentiate areas that were not occupied in the past from those where settlements were present, but have subsequently been erased by floodplain dynamics. It is particularly notable that there is a specific concentration of historic period sites around Multan, and it is important to acknowledge that similar patterns have been observed around important medieval sites in northwest India [20, 80, 81, 85, 86].

Approach to long-term river morphodynamics

Combining historical map and the MSRM analysis has proven to be an effective approach for extracting a detailed picture of the hydrographic network in the AOI. The Survey of India maps have proven to be detailed and accurate, matching the MSRM-based topographic analysis almost perfectly.

The resolution of the 12 m/px TanDEM-X, represents an important step forward compared to the 30 and 90 m/px DEM imagery that was previously the highest resolution dataset available for this area [37]. We have been able to extract information of a complex palimpsest of relict water-courses that criss-cross all the recent and sub-recent floodplains. Importantly, our work highlights that multi-spectral imagery alone does not provide a clear picture of the complex system of channels, though it does contribute to the understanding of the context of the different geomorphologic units. Importantly, the channel traces that are visible in modern microtopography were also evident to the early twentieth century surveyors. It is possible that these traces are the product of relatively recent events, but the chronology of the different palaeochannels will only be ascertained through a combination of geomorphology, geoarchaeology and absolute dating that will reveal their relative sequence.

Meanwhile, it is possible to combine the evidence for the distribution of historical map mound features and river channel tracing to develop an understanding of the long-term settlement dynamics of the study area. This type of approach has been considered in some detail in previous research investigating this region [37, 38, 44, 68, 72]. The data we provide here does not include any new absolute chronological information, as that will only come from future ground-based field assessments. In the following sections, we make use of the information from the published PAS dataset [34], which remains the only comprehensive dataset suitable for analysis of large-scale long-term settlement dynamics. Rather than an exhaustive interpretation of historical settlement and fluvial dynamics, we aim to illustrate how our new datasets can be used to further current knowledge, and inform future work directed to answer the multiple questions that still challenge the understanding of the long-term occupation of the Punjab floodplains. We present the following sections as an open interpretative tool, being conscious that future fieldwork and complementary analysis will enrich the discussion for each of the periods considered here.

Mughal period and the settlement patterns in the old Beas

The most recent avulsion of the Beas was the consequence of its capture by the Sultej in the late eighteenth century, which was reported by mid-nineteenth century sources [55, 56]. Indeed, the analysis presented here reveals multiple traces of features through the Beas-Sultej interfluve, crossing from one river-course to the other (Fig. 7). The complexity of the channel traces suggests that the shifting of the Beas in the late eighteenth century was the last of a series of recurrent episodes. In that sense, the picture obtained here is consistent with nineteenth century reports and also an eighteenth-century map produced by the Mughal administration that shows multiple connections between the two river systems [37, 90].

The archaeological dataset shows a close spatial relationship between Post-Medieval sites (fifteenth to nineteenth centuries) and many of the relict watercourses of the Beas-Sultej floodplains (Figs. 11 and 12). 90% of 63 post-medieval sites in the AOI recorded by the PAS, are located in the Beas-Sultej interfluve. In contrast, archaeological information for these periods is virtually absent from the Multan plain, with only two sites being recorded. The remaining sites are distributed in both the Beas-Sultej and Ravi floodplains. This pattern matches the historically known dynamics of the rivers, which indicate the avulsion of the Beas in the late eighteenth century that caused the abandonment of settlements along its course. The establishment of the canal colonies created a new settlement pattern that further contributed to the abandonment of the older settlements of the area. The inactivity of the rivers in this area since the late eighteenth century would have contributed to the conservation of sites preserved at that moment, thus explaining the abundance of Mughal period sites identified in the Beas-Sultej interfluve.

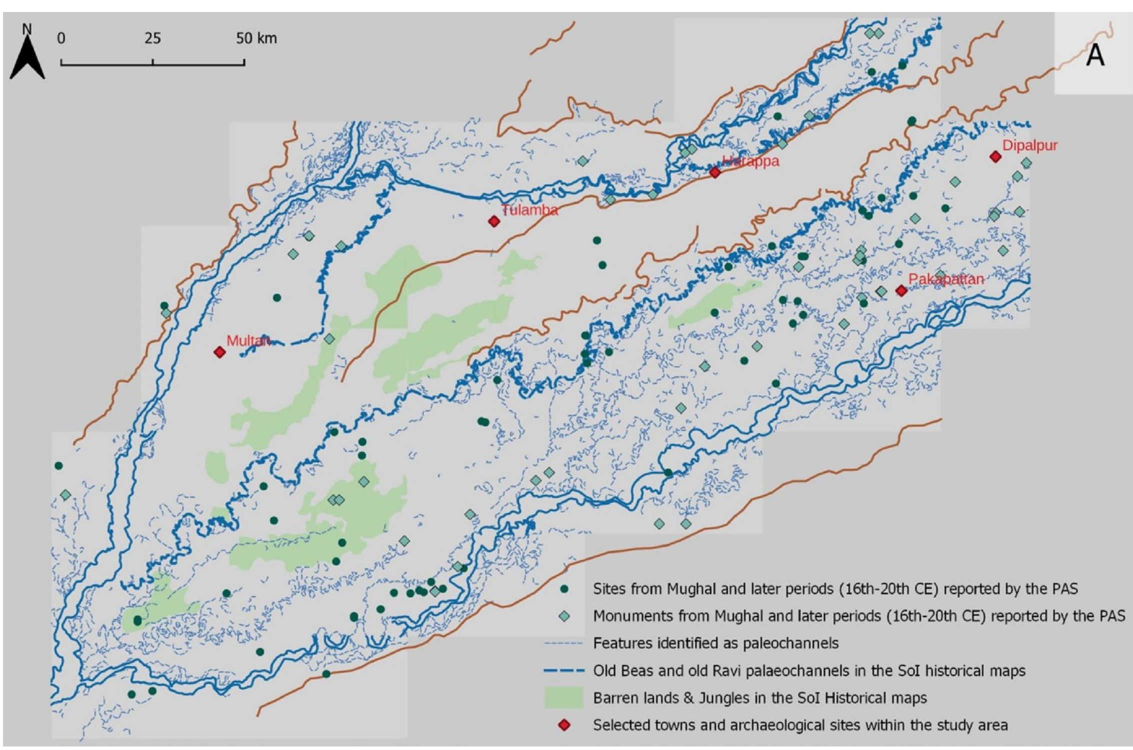


Fig. 11 Distribution of post-medieval (sixteenth century onwards) sites and monuments identified by the PAS

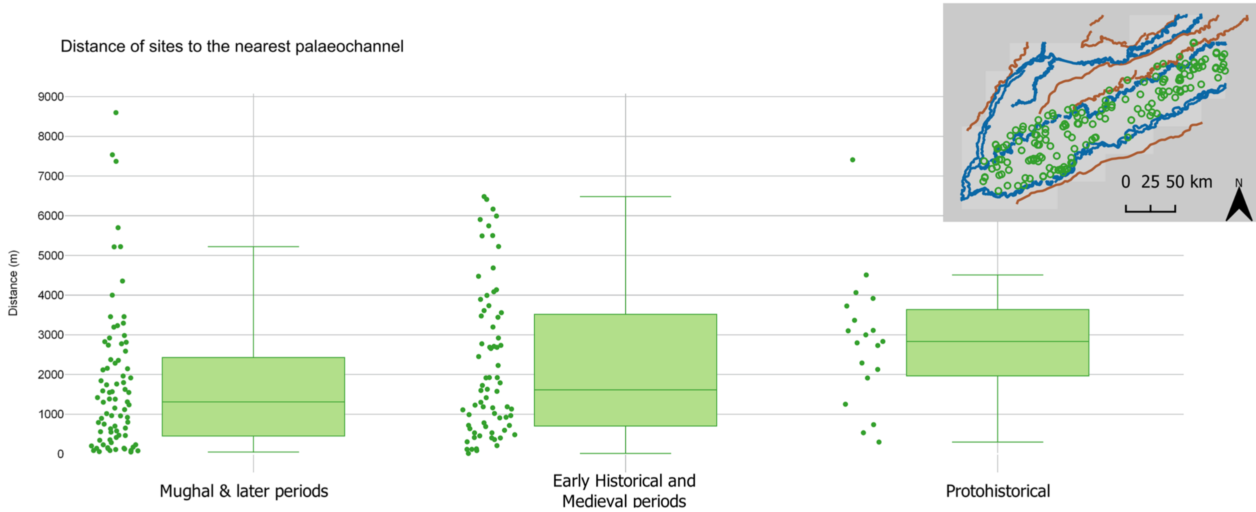


Fig. 12 Graph representing the PAS sites (Fig. 8) situated in the Beas-Sultej floodplain (**A**), distributed by chronologies and the distance to the closest identified paleochannel. It illustrates the trend of later sites to be closer to the relict hydrographical network

It is interesting to see how the course of the old Beas River corresponds nowadays with an area of highly salinized aquifers [91] (Fig. 13), which illustrate a significant aspect for understanding the relationship between river morphodynamics, settlement and agriculture in the area. When they are cut off from the recharging water of the river courses, aquifers tend towards salinization, which causes problems for agriculture irrigation [48, 50, 91, 92]. That process seems to have impacted the old Beas area when its water was diverted towards the Sultej.

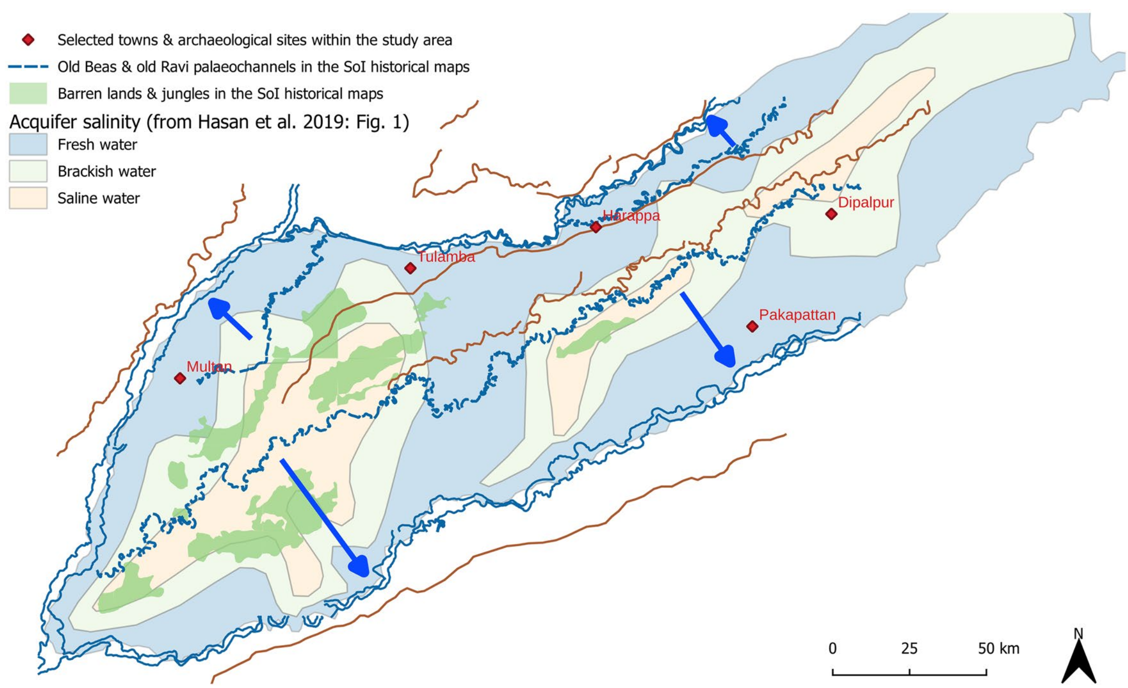


Fig. 13 In this image, the traces of the old Beas and old Ravi courses are superimposed over the hydrogeological map published by Muhammad Hasan et al. [91, Fig. 1]. This map shows the old course of the Beas in the centre of the saline aquifers. The presence of saline aquifers also correlates with the areas that in the early Survey of India Maps are defined as barren lands and "jangals" (green areas in the image)

It is difficult to assess the past dynamics of the Sultej in the study area. The general trend in the PAS data was for fewer sites to be documented in areas close to the Sultej, and it is particularly notable that almost no pre-Medieval sites are known in the area. If at some point the water of the Sutlej was flowing into the Hakra palaeochannel zone or even the Beas dry-course [64], the southern strip of the study area might have reflected a similar situation to that of the nineteenth century dry-course of the Beas. The future reconstruction of the Sutlej palaeo-hydrodynamics will be essential for explaining the absence of known sites earlier than the Medieval period in the vicinity of the Sutlej.

This pattern reinforces the suggestions that: (1) the course of the Beas was populated-continuously or at least repeatedly until the late eighteenth century; (2) the shift of the Beas towards the Sultej may have impacted negatively on the preservation of the archaeological sites along the course of the Sutlej and positively on the those along the Beas course.

The Ravi channels and Medieval and Early Historic period patterns of occupation

A similar situation to that we have described in the old Beas can be seen in the south-western section of the Ravi in the AOI. Here, the salinized aquifers extended towards old courses of the Ravi, which has tended to move towards the north, leaving relict canals (Fig. 13).

Along the Ravi floodplains and the Multan plain in particular, the PAS dataset identifies many sites dated on the Early Historic (eighth century BCE–eighth century CE) and Medieval (eighth–fifteenth centuries CE) periods. Early Historic and medieval sites represent almost 2/3 of the sites identified by PAS in the AOI (Table 2). They are present in all the sectors analysed here, but their distribution shows the reverse pattern to that seen for the Mughal period sites, with more sites in the Multan plain than in the rest of the areas, and numerous sites also being found in the Beas-Sultej interfluve (Fig. 14). The eighth century CE is considered a breaking point between the Early Historic and Medieval periods in the PAS dataset, as the authors describe most of the sites as

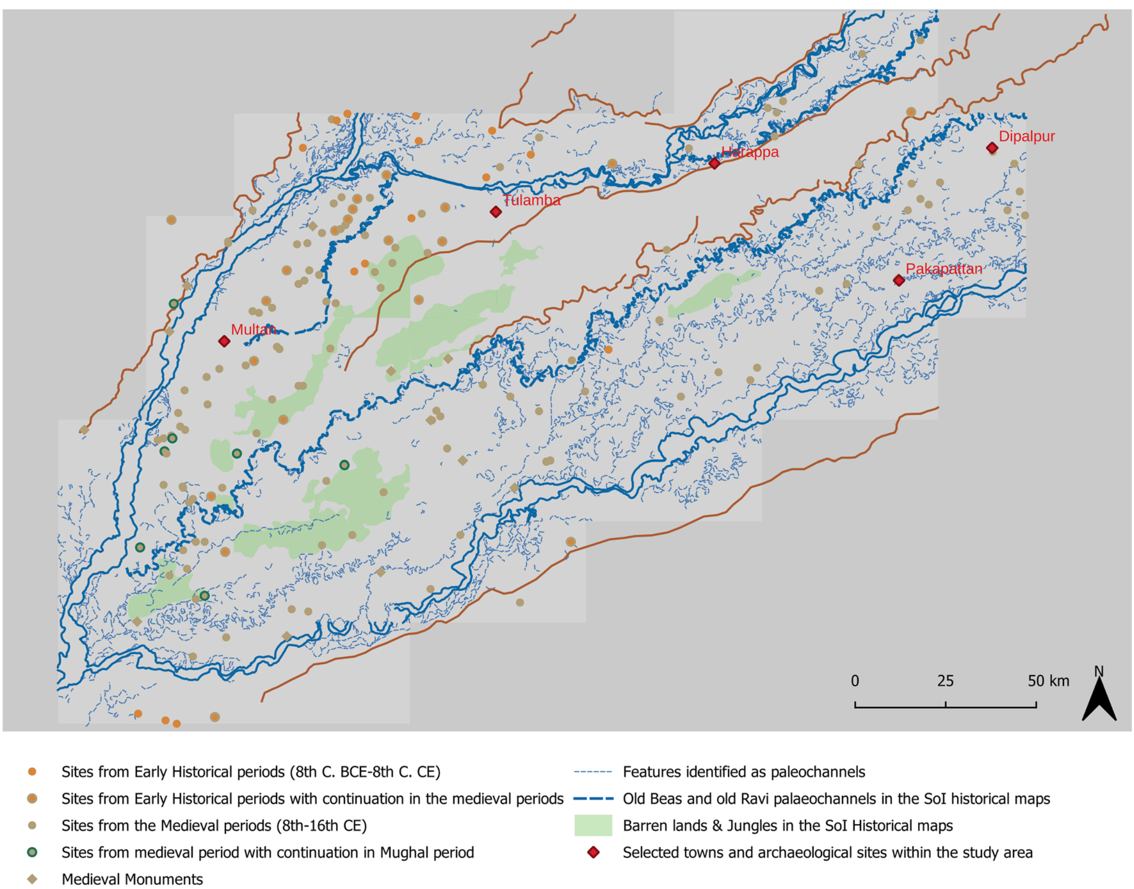


Fig. 14 Distribution of the sites and monuments identified by the PAS with occupation phases thorough Early Historical (eighth century BCE–eighth century CE) and Medieval (eighth–sixteenth centuries CE) periods

being either abandoned (Early Historical) or just stablished (Medieval) at this point in time [34], with some examples of continuous inhabitation.

Looking at the distribution of settlement in Punjab beyond the AOI (Fig. 8A), it is apparent that there is a significant concentration of PAS reported sites dating to the Early Historic period that lie between the Chenab and Ravi channels [34, 37, 38]. In the AOI (Figs. 8B, 14) we can observe an extension of this concentration towards the north section of the Multan plain, which was, in fact, part of the Rechna Doab before the shifting of the Ravi to the west. This movement of the Ravi left a relict channel that can be traced on the eastern side of the city. It appears to have been active at least during medieval times [37, 38], but it was drawn as a relict channel in the 1839 SDUK map [53]. On both sides of that channel, a complex system of what appear to be inundation canals is visible as linear microreliefs that appears to show the course of bunds or artificial embankments. These features extend to the south-east, where a strip of Jangal is delimitated along the Ganji bar and continues through the space that separates the old courses of the Ravi and the Beas (Fig. 15). A short distance towards the east, similar linear features with a different orientation can be seen to the west of the large site of Tulamba, which was occupied in the Early Historic and Medieval periods [73].

On the Multan plain, many of the preserved medieval sites clustered around the old course of the Ravi and its associated features. This would support the idea that this course was active during the Medieval period, when travellers described the Ravi as flowing to the east of Multan. Our data suggests that the post-Medieval shifting of the river prompted a restructuring of the settlement patterns and the abandonment of numerous medieval settlements in this area.

The small number of Mughal sites known in the Multan plain seems to contradict the historical evidence that, although Multan declined in importance as a main trade node, it remained a well-populated area with significant agricultural and commercial activity [93, 94]. Further, this area was not transformed by the canal colonization to the same degree than other parts of the Bari Doab [50]. The limited evidence for post-Medieval settlement suggest that the Mughal period settlements may well lie below present-day occupied villages.

Indus period patterns of occupation

Proto-historic period settlements are less well represented in the PAS database (Table 2). Most of the sites inside the AOI (14 out of 24) are part of a well-known ensemble of mounds situated on the Old Beas floodplain [34, 35, 38, 68, 76]. These sites are concentrated on the levee line of the Ganji Bar, at the limit with the Beas floodplain and at some distance of the known paleochannels (Fig. 16), though there are some exceptions where sites are located in the Beas-Sutlej interfluve itself. This pattern is different to that seen in the later periods, were known sites are located within the floodplain and the bar was the exception.

In general, Indus sites seem to be preserved in locations that are at the margins of the present river systems and in areas not affected by the movement of these rivers. Besides the sites situated on the Ganji bar, four other sites are located in the Thall and Cholistan deserts, in the margins of the AOI, and in a type of context we have addressed elsewhere [21]. Despite the presence of Harappa itself, there is only one other Indus site known on the Ravi floodplains. There is one unusual case of a group of four aligned Indus sites, which represents the only cluster of sites situated in the middle of the Bari Doab, and is visible to the lower left of Fig. 16. The group of sites is located in an area labelled as a jangal in the 1930s SoI historical maps, which is isolated in between paleochannels linked to the Beas to the north and the Sultej to the south. It was most probably situated at the margin of more recent avulsions of one or other of the rivers. In that sense, these four sites lie precisely in the area that separated the Beas and Sultej old floodplains, and it is likely that they lay at the limits of one of them—most probably the Sutlej.

It is notable that Early Historic and Medieval sites are also preserved in this part of the plain (Figs. 11, 14), which suggests that this area (and areas marked as barren soil, with the presence of elongated dunes on SoI maps) may represent sections of the Beas-Sultej interfluvial floodplain that have not been damaged by channel migration. This observation is significant, as remote sensing imagery has been used to identify a possible relict abandoned canal in this area, which the authors have suggested dates to the Indus period, based on the presence of Indus Civilisation settlements on its alignment [77]. Without ground-based observation and direct dating it is difficult to say much about the proposed canal. The presence of a potential canal does fits with the suggestion made here that ancient landscape elements could have been preserved in such areas. Casana and Wright identify potential relict levees in their Fig. 7, but it is important to note that research in northwest India has shown that such features are often traces of relict river channels, some of which are preferentially selected for establishing settlements [25, 95]. We do suggest that the hypothetical reconstruction of a Bronze Age vast canal system linked to either the modern Sutlej River channel or ancient Beas River—as presented in Casana and Wright's Fig. 10—should be treated with considerable caution, particularly as it is proposed to lie in a region that has seen the

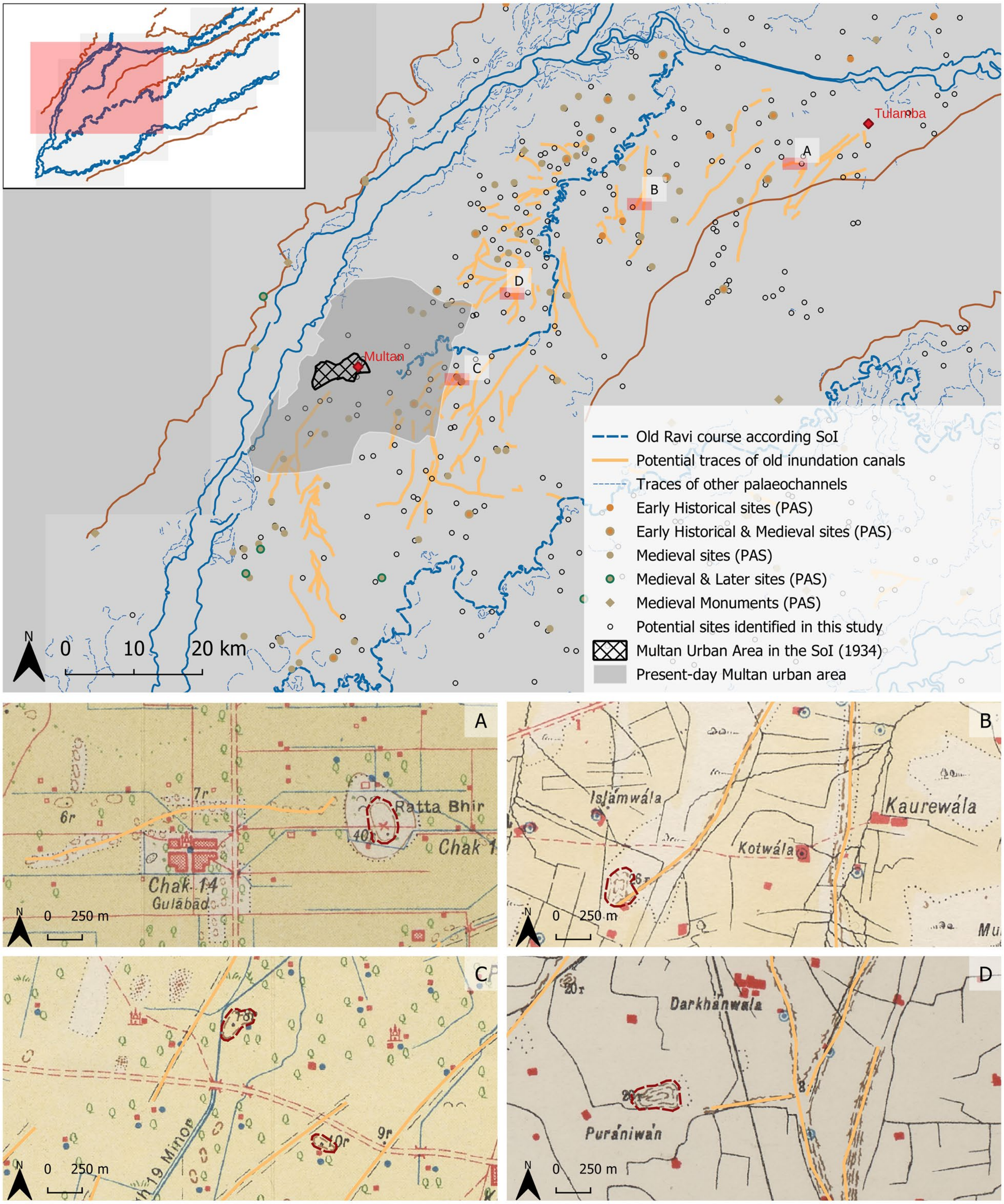


Fig. 15 Detail of the Multan plain, with the traces of the old Ravi course and the linear features identified as potential abandoned inundation canals. The detail images show how the features are represented as lines of small mounds (**A**), disused canals (**B**) or positive relief (**C**, **D**). Often the features show a close relationship with mounds identified as Early Historical or Medieval sites (in **A** Ratta Bhir, identified by the PAS as a site occupied between the first century BCE until twelfth century CE), Medieval sites (**B** two mounds identified by the PAS as medieval sites, eighth–fifteenth centuries CE)

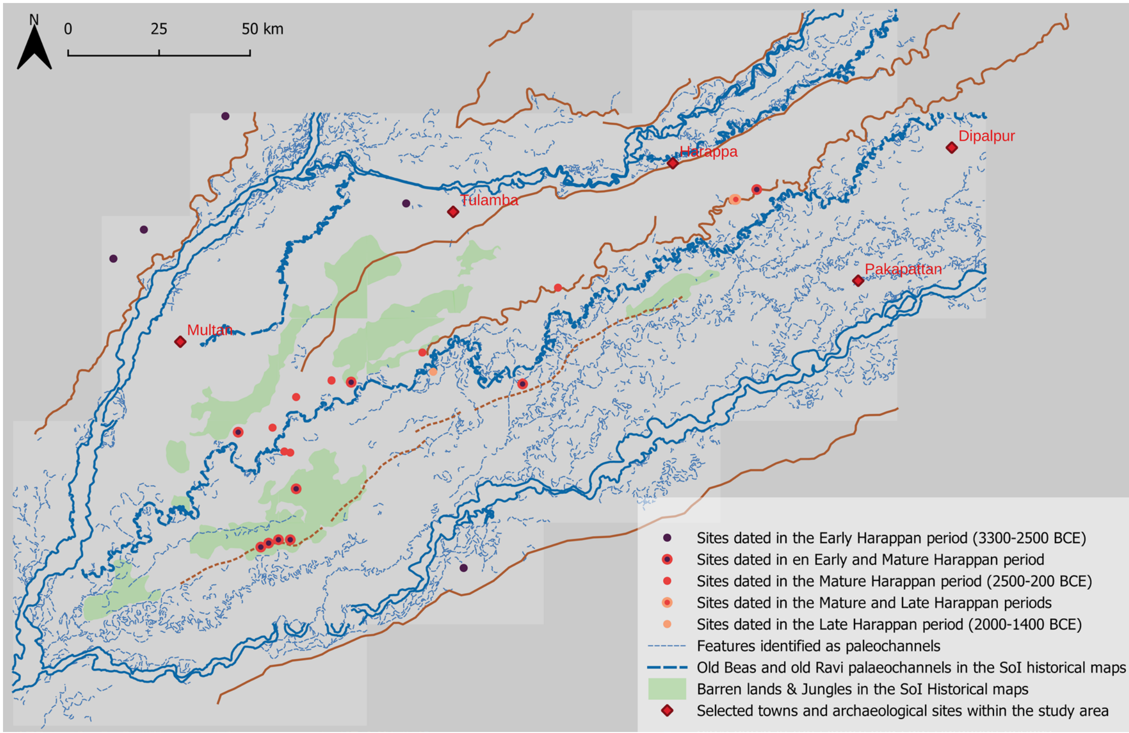


Fig. 16 Distribution of prehistorical and protohistorical sites identified by the PAS

construction of large-scale irrigation systems during the last centuries. The morphodynamic reconstruction of the floodplain presented in this paper suggests that these four mounds may once have been very close to the course of the Sutlej River, and any supply of water via a canal may only have needed to be relatively small scale.

Overall, the emerging picture is consistent with the results obtained by detailed studies around Harappa and other selected sites situated in the Ganji Bar [44, 67, 68, 96, 97]. In all cases, older alluvial deposits and palaeosoils have been documented under the archaeological deposits of Bronze Age settlements. These older deposits are cut and filled by younger alluvium deposits with no traces of Protohistoric archaeological material.

The distribution of known proto-historic sites suggests that the dynamics of the hydrological system has influenced the preservation of the oldest settlements in this part of Punjab. As we have seen in the Early Historic and Medieval periods, floodplains were densely occupied, and proto-historic sites are less represented but not entirely absent of those areas. In that context, substantial sites such as Harappa are likely to have fared better under the area's dynamic hydrology due to their very large size, but smaller settlements will have been more vulnerable to long-term processes of sediment deposition and erosion. The distribution of the earlier archaeological sites presents in consequence a more scattered pattern, and it is worth to note that they are largely disconnected from the visible relict channels (Fig. 12), which respond to later dynamics. This reconstruction is of course compatible with previous observations about the occupation along the floodplains of the Beas and the Ravi, though we have very few clues on the aspect of those during earlier periods.

Conclusions

The alluvial plains of Punjab are an outstanding example of the complexity of long-term settlement dynamics in riverine environments. Cumulative historical and geomorphological processes define the present-day character of the cultural landscape of Punjab and similar areas in South Asia and elsewhere. The study of the interactions between landscape, settlement and river morphodynamics, including the chronological dimensions, represents a major challenge for landscape archaeologists, which we have addressed in this work.

The workflow presented here represents the first integrated application in a single study case area of an ensemble of methods developed by the authors [17, 18, 20, 22, 25, 78]. The region of southern Punjab was selected due to the range of previous research, which makes it possible to assess the interpretative potential of the approach. The different patterns of settlement in the post-Medieval, Medieval, Early historic and Proto-Historic periods and their associations with floodplains demonstrated that this multi-source and multi-scale approach is a useful tool for providing new insights into the historical processes of complex landscape systems, though we acknowledge that fieldwork validation is still required.

This workflow is based on well-established landscape archaeology approaches that can be replicated beyond this specific study case, totally or partially, in other areas of the Indus Basin, South Asia and worldwide. The workflow presented here is being further enhanced through the use of machine learning approaches [98] which we have already explored the potential of both within the study area and in other areas that also have collections of historical maps that can be used for detecting archaeological sites [22]. With appropriate modifications to suit local data sources and different research agendas, this workflow also has the potential to be applied to other types of features beyond artificial mounds and river palaeochannels.

Overall, the multi-scale approach implemented here has allowed us to map features of interest at a large regional scale using historical maps, RS imagery, and DEM data at a resolution not previously available. It has brought us closer to both regional and single site contexts, which is one of the main challenges for RS applications in archaeology.

On a quantitative level, we have located hundreds of potential archaeological sites and thousands of river paleochannels, using a workflow that incorporated filtered data to assess the degree of confidence. A significant proportion of the mound feature datasets represents potential site locations that were previously unknown, and comparison with previously published datasets shows the complementarity of our results with sources such the Punjab Archaeological Survey and surveys done elsewhere in the Indus River Basin. The same can be said for the continuous and discontinuous relict channel network, in which case the results obtained can be evaluated by future research in light of field-assessment and RS sources not attempted here. It has to be remembered that one of the challenges of the study area is the intensive land use, continuous occupation and large-scale transformation that has occurred from the late nineteenth century until the present. Even in that context, our approach has located many potential archaeological sites, including some that are hidden by land transformation processes.

From a more qualitative perspective, the work developed here allows us to advance some interpretative insights to contextualize the distribution patterns of human settlement and its relationship with geomorphological processes. In fact, the main geomorphological units (active floodplains, recent and sub-recent floodplains, and bars) present a very different archaeological record, with almost all known settlements concentrated in the recent and sub-recent floodplains and being absent in the other areas. The causes for this pattern can probably be found in a combination of diversified uses, hinted at by relatively late written sources, and taphonomic processes, but it remains an aspect to be explored by future research. In addition, another emerging significant factor is a landscape dynamism, in which processes are not static in time and space. We have evidence that active floodplains have moved repeatedly during the Holocene, creating, covering and/or erasing old floodplains and bars. Lastly, the landscape transformations set in motion during the period of British control and continued by modern global economic dynamics is a major factor to take into account, since these processes have introduced changes that dominate the present landscape and have obliterated previous settlement patterns. The consequence of these processes is that old settlement patterns appear patchy throughout the region, and reflect the geomorphological dynamics of the historical periods. The examples of the changes to the old Beas in late Mughal period and the Multan plains in the Medieval period illustrate that patterns emerge and are preserved circumstantially in particular sub-regional geographic areas. Whether these patterns correspond to single local phenomena or are part of wider dynamics will only be answered by future research. Exploring the links between multiple settlements and the alluvial environment in detail makes it possible to contextualise archaeological datasets associated with historical hydrological networks that can be reconstructed remotely using historical cartography and EO data.

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Author contributions
AGM conceived and developed the research, and prepared the original draft and figures. AGM and HAO defined the methods and wrote the associated code. CAP conceived and supervised the projects that funded the research. All authors reviewed and edited the manuscript.

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Availability of data and materials

This paper presents a combination of publicly accessible data on the location of archaeological sites, and data compiled from the analysis of: (i) historic Survey of India maps currently hosted in public libraries that are scheduled to be made open access in due course, (ii) publicly accessible remote sensing imagery, (iii) commercially available digital elevation data that is not publicly accessible, and (iv) the results of analysis that has been carried out using a combination of open access and proprietary computational algorithms.

The site location datasets included in this research paper were obtained from publicly accessible publications [33, 34, 99].

The historic Survey of India 1″ to 1-mile maps are currently held as hardcopies in the collections of the British Library and the Cambridge University Library. These maps are scheduled to become accessible via open access digital repositories hosted by each library.

The remote sensing imagery that has been used (NASA Landsat 5; European Space Agency Sentinel 2) is available Open Access and is accessible via Google Earth Engine and other platforms.

The TanDEMX digital elevation model data has been provided by the German Space Agency (Proposal ID: DEM_HYDR2712), and is not open access.

The SMTVI algorithm has been published in Orengo and Petrie 2017 [25] and is available Open Access. The modified versions used in this paper are available in the following links:

Landsat 5: https://github.com/ArnauArqueo/Orengo_Petrie_2017_RS/blob/patch-1/south_punjab_landsat5.

Sentinel 2: https://github.com/ArnauArqueo/Orengo_Petrie_2017_RS/blob/patch-1/south_punjab_sentinel2.

The MSRM algorithm has been published in Orengo and Petrie 2018 [78] and is available Open Access. The version created for this paper is available in the following link: https://github.com/ArnauArqueo/Orengo_Petrie_2018_MSRM/blob/patch-1/south_punjab_MSRM.

The detectors of mounds in historical maps are not Open Access, we refer to the original publication for more details [22].

The datasets that have been generated and/or analysed during the current study are being compiled in an Open Access Arches data repository as part of the Arcadia-funded Mapping Archaeological Heritage of South Asia (MAHSA) project (https://www.mahsa.arch.cam.ac.uk/), which is not yet publicly accessible.

Access to the datasets that have been compiled, generated and/or analysed during the current study that are not otherwise publicly accessible are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

Author details

[1]Landscape Archaeology Research Group, Catalan Institute of Classical Archaeology, Plaça Rovellat sn, 43003 Tarragona, Spain. [2]Department of Archaeology, McDonald Institute for Archaeological Research, University of Cambridge, Downing St., Cambridge CB2 3ER, UK. [3]Catalan Institution for Research and Advanced Studies, Passeig Lluís Companys, 23, 08010 Barcelona, Spain.

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