Geo-electric resistivity evidence for subsurface palaeochannel systems adjacent to Harappan sites in northwest India

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ABSTRACT

It has been proposed that a major palaeo-river channel course, the Ghaggar-Hakra, flowed in the interfluve between the modern Yamuna and Sutlej rivers in the western Ganges basin during the Late Quaternary. This palaeochannel course has been associated with extensive Bronze-age Harappan civilisation archaeological sites that are located with the channel. The abrupt abandonment of urban centres at ∼3500 BP has been explained as a consequence of river diversion, although alternative explanations for cultural decline have also been offered. A major problem with earlier interpretations has been that little information exists on the geology of the palaeochannel system. Electrical resistivity soundings were used to map the large-scale geometry and architecture of the palaeochannel system. A thick and extensive sand body is present in the subsurface in parts of north-western Rajasthan, Haryana and Punjab. The dimensions of the palaeochannel bodies imply that these are the deposits of a large river system, though detailed sedimentological analysis is necessary to validate this. Two of the resistivity transects are close to important Harappan sites, Kalibangan and Kunal, suggesting a possible link to archaeological site distribution. However, detailed chronological constraints are required to establish such links. Nevertheless, this study reports the first geophysical evidence for the subsurface geometry of the palaeo-Ghaggar-Hakra river system.

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1. Introduction

Two major river systems drain from the Himalaya into the Indo-Gangetic basin: the Indus river system, which flows southwest into the Arabian Sea, and the Ganges river system, which flows eastwards into the Bay of Bengal (Fig. 1). The vast tract of land that forms the drainage divide between these river networks is now semi-arid and/or desert and no major rivers currently flow there. However, for over 130 years, scholars have been aware of vestiges of a succession of putative palaeo-channels that flowed through this divide that have been traced from the Himalayan front to the Arabian Sea near the Rann of Kutch, and have been taken to be evidence of a 'lost river' that flowed for 1000 km parallel to the mighty Indus. The noted geologist RD Oldham was the first to record evidence of this 'lost river' in 1886, identifying a major dry riverbed, the Ghaggar or Hakra, kilometres-wide, winding through the desert sands in what is now northwest India and eastern

Pakistan (Oldham, 1886). He documented the course of this palaeochannel, considered its sources and discussed in a logical manner a variety of hypotheses to explain the demise of the river that formed it. Oldham (1874, 1893) examined the links of this putative river to the Vedic Sarasvati. The 'lost river' was subsequently explored by an Italian linguist, Tessitori, who discovered archaeological mounds associated with the palaeochannels, and boldly linked them to a pre-historic culture. Unfortunately, Tessitori died before his research was published. The famous explorer-archaeologist, Sir Mark Aurel Stein, in 1942–43, surveyed ancient sites along the course of the 'lost' river and for the first time recognised the links with the Harappan culture of the main Indus Valley (e.g. Harappa and Mohenjodaro). He was able to show the existence of literally hundreds of archaeological sites strung out along the course of dried-up Ghaggar-Hakra River. He commented: '*The width of the Ghaggar-Hakra is so great that even now local folklore believe in its having once been completely filled by a large river*' (Stein, 1942). Despite his survey, Stein was unable to add anything substantial to further the debate about the origin of the river. It was not until the 1980s that research on the 'lost river' took a dramatic turn. Using LANDSAT MSS satellite imagery, Yashpal

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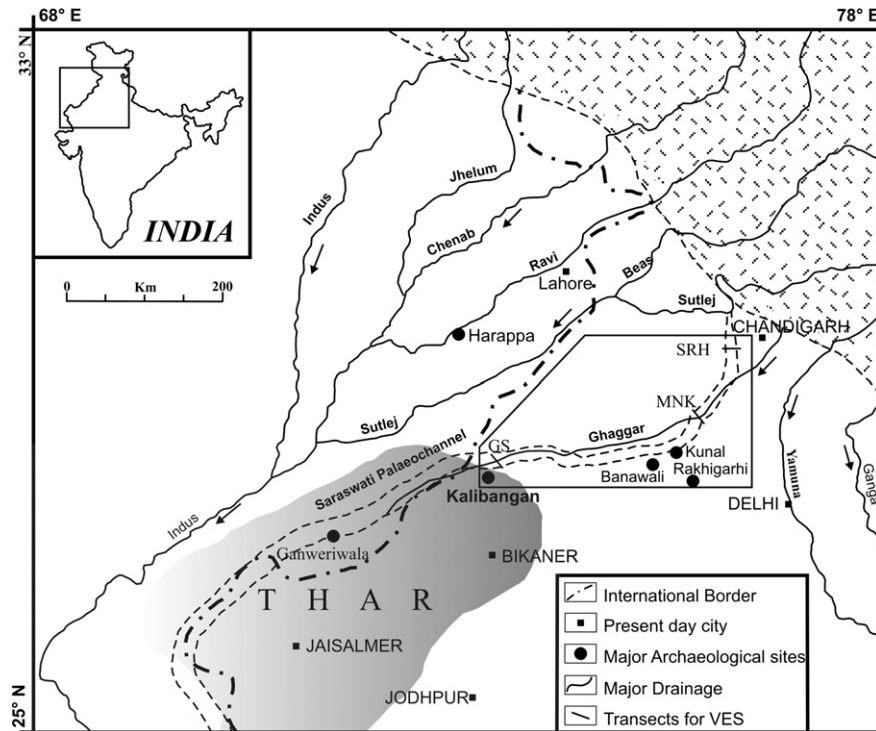*E-mail address:* rsinha@iitk.ac.in (R. Sinha).

Fig. 1. Location of the study area; the box shows the area of investigation which lies close to several important Harappan sites, Kalibangan, Kunal, Rakhigarhi, and Banawali, in northwestern Rajasthan. Three transects chosen for the resistivity surveys, GS, MNK and SRH are also shown.

et al. (1980) identified the course of the huge dry riverbed, up to 8 km in width and running over a distance of 400 km, which was coincident with the previously identified Ghaggar-Hakra channel. This was the most convincing evidence that a major river had perhaps once flowed through this now dry tract of land. Yashpal et al. (1980) suggested, on the basis of their image analysis, that it was perhaps possible to connect the trace of the Ghaggar north-westward to the Sutlej (now connected to the Beas) and north-eastward to the Yamuna. Ghose et al. (1979) extended the trace of the putative palaeochannel through LANDSAT image analysis. Thus, it appeared that major glacier-fed Himalayan Rivers might have fed the large palaeo-river systems, before a series of drainage diversion events caused its desiccation (Valdiya, 2002).

The great significance of these postulated palaeo-river systems is that archaeological evidence suggests that areas adjacent to the palaeochannel belt were intensively settled during the peak of the Harappan Civilisation (Stein, 1942; Indian Archaeology, 1963–64, 1966–67, 1980–81, 1987–88, 1997–98, 1998–99; Wilhelmy, 1969; Dikshit, 1977, 1979; Joshi et al., 1984; Gupta, 1996; Chakrabarti and Saini, 2009). The Bronze Age Harappan Civilisation (4800–3500 BP) was one of the world's first great complex socie-ties and attained its peak after 4400 BP with the development of a network of sophisticated urban centres spread over an extensive tract of NW India and Pakistan (Wright, 2010). Whilst the major sites of Harappa and Mohenjo-Daro are located along the Indus river system, the largest collection of Harappan archaeological sites is associated with the postulated surface trace of the Ghaggar-Hakra palaeochannel described above (Joshi et al., 1984; Mughal, 1997). It is generally believed that the river that formed this palaeochannel belt supported some of the major sites of this predominantly riverine civilisation. The abrupt abandonment of the Harappan civilization here at ∼3500 BP has often been linked to river diversion/drying (Stein, 1942; Singh, 1971; Singh et al., 1974; Mughal, 1997; Gupta, 2001; Lal, 2002; Valdiya, 2002; Lal et al.,

2003; Staubwasser et al., 2003; Tripathi et al., 2004; Sharma et al., 2005–06), but no sub-surface existence of such a river and its abandonment has been available. These ideas have remained speculative and subject to major discussion (Agrawal, 1964; Wilhelmy, 1969; Misra, 1984; Courty, 1995; Agrawal and Pande, 1977; Pande, 1977; Kenoyer, 1998; Sahai, 1991; Madella and Fuller, 2006) due to the lack of detailed subsurface data to confirm the subsurface continuity of the large palaeo-channel system inferred from satellite imagery.

A first step in the analysis and interpretation of the Ghaggar-Hakra palaeo-river system as inferred from satellite imagery is to obtain verification that a major palaeo-river sedimentary body does indeed exist in the subsurface corresponding to the trace of the channel in satellite imagery. Electrical resistivity is an important tool for mapping and reconstructing the sub-surface geometry of buried sand bodies, in particular, buried fluvial channels that are potential aquifers. The potential of resistivity methods for delin-eating aquifer heterogeneity as a function of stratigraphic units has recently been demonstrated in the Mississippi basin, USA (Bowling et al., 2005). In this example, stratigraphic units with distinct geoelectrical properties were interpreted as deposits of meandering rivers, braided rivers, fine-grained sand and a clay-rich interval, and a detailed alluvial architecture was presented. The application of resistivity methods in geoarchaeology has also been attempted. Buried channels of the Nile River in the Samannud area of the Nile Delta have been mapped using resistivity surveys (El Gamili et al., 1994; El Gamili et al., 2001) to test the relationship of some of the important archaeological sites related to ancient Egyptian history to Nile branches. Although the historical docu-ments suggested that the old settlements in this area had access to some of the branches of the Nile River, there were serious disagreements on this hypothesis. The resistivity surveys across the documented branches carried out by El Gamili and Ibrahim (2001) identified three geoelectric layers consisting of clays and silts,

saturated clay and a buried sand layer based on resistivity variations and representative borehole data. The buried sand layer was interpreted as the 'defunct' branches of the Nile river, in line with the historical and archaeological documentation that these are Bucolic and Sebennytic branches of the Neonile which were established at the end of Pleistocene (El Gamili and Ibrahim, 2001).

The electrical resistivity method was applied to reconstruct the subsurface stratigraphic geometry along three transects in northwest India. The southernmost transect (GS) is close to the major Harappan archaeological site of Kalibangan (Fig. 1). The second transect (MNK) is ~20 km north of Kunal archaeological site and the northernmost transect (SRH) is near Sirhind in Punjab. The resistivity survey for the GS and MNK transects was conducted with the overall aim of determining if the surface trace of the postulated Ghaggar-Hakra fluvial system as discerned from satellite imagery corresponds to a subsurface palaeofluvial sedimentary body. The SRH transect was designed to test the proposition by Yashpal et al. (1980) that a palaeochannel branch, possibly the palaeo-Sutlej, existed in northern Punjab and connected downstream to the Ghaggar-Hakra palaeochannel. The specific objectives were to: (a) map the subsurface sand body geometry, and (b) establish the edge of the palaeovalley. This paper presents the resistivity results and buried valley geometry interpretation, and discusses their geo-archaeological significance.

2. Study area description – the geoarchaeological context

Two transects, GS and MNK, in the study area lie in the western Haryana plains close to the important Harappan archaeological sites of Kalibangan and Kunal respectively (Lal et al., 2003). This area lies at the north-eastern edge of the Thar Desert with an annual precipitation of 300–450 mm/y falling during the monsoon months only, and therefore, a semi-arid climatic regime prevails in this region. At present, no major rivers flow through this area except for a minor drainage line of the seasonal Ghaggar River that originates in the Siwalik foothills of the Himalaya. However, the most enigmatic aspect of the Ghaggar River has been a very large palaeovalley (>3 km wide) observed on the satellite image that is not commensurate with the dimension of the modern Ghaggar river (less than 250 m wide). The modern Ghaggar River presently flows towards the southern end of the wide valley. Apart from this, several palaeochannel traces are visible in the desert area further to the west, which suggests that a denser drainage network previously existed in this region.

The existence of a large river in ancient times within this wide valley has remained speculative due to the lack of any reliable sub-surface data to confirm the sub-surface continuity of the large valley observed on the surface. The only exception is a recent study by Saini et al. (2009) who utilized shallow well sections (8 m) and groundwater well logs (>40 m deep) from an area south of the Ghaggar River and identified fluvial sand bodies inter-layered with aeolian sand, and brown silt and clay of floodplain deposits. Based on the spatial correlation of the litho-sections along two transects, the authors marked two major buried channels, south of modern Ghaggar river, for a length of ~250 km having fluvial sand bodies up to 30 m thick occurring 4–10 m below ground surface, and associated floodplain deposits up to 50 m thick. Saini et al. (2009) and Saini and Mujtaba (2010) also dated the top of the sand body to be 26 ± 2 to 21 ± 1 ka BP. The authors suggested that these buried channels were active around MIS 3 and went through a disorganization phase during the LGM. The aeolian sand overlying the buried channel was dated between ~20 and ~15 ka BP. They also mapped a few patches of a younger paleochannel that dated around 5.9 ± 0.3 and 2.9 ± 0.2 ka BP and considered them to be a part of the 'lost' Saraswati (Yashpal et al., 1980; Sahai, 1991).

This study has aimed at confirming the presence of the buried channel through resistivity surveys and drill cores and to establish its upstream connectivity. Two transects for resistivity soundings mapped the sub-surface lithology of the region close to Kalibangan (29°28′13.66″N, 76°07′49.06″E) and Kunal (29°37′41.18″N, 75°39′44.16″E) (Fig. 1) across the large valley partially occupied by the Ghaggar river channel at present. The third transect, SRH, was located across the trace of a palaeochannel near Sirhind (30°37′41.98″N, 76°23′10.98″E) in Punjab close to the Himalayan front; this was originally identified by Yashpal et al. (1980) as a possible former course of the Sutlej river. Although this area lies in the semi-humid, northern Indo-Gangetic plains with an average annual rainfall of 690 mm/year, there is no major surface drainage in this region. The modern Sutluj flows ~150 km west and the Yamuna flows ~150 km east of this transect. It has been suggested that the Sutluj flowed through this region before moving west (Yashpal et al., 1980) but there is no data to test if a palaeochannel is present in the subsurface in this region, which may have connected downstream with the Ghaggar palaeochannel.

3. Data acquisition and processing

3.1. Resistivity surveys and data interpretation

A Terrameter SAS 1000 (manufacturer; ABEM, Sweden) as well as an Aquameter CRM 500 (manufacturer; ANVIC systems) were used to conduct electrical resistivity survey for the transects, as described above. Vertical electrical soundings were taken at 14 locations along the GS transect and at 10 locations each along the MNK and SRH transects (Figs. 2, 4 and 6) to provide constraints about the spatial as well as vertical extent of the buried fluvial complex. The resistivity of the buried sand body is distinguishable on two accounts: (a) the overlying mud generally has a lower resistivity unless accompanied by concretions, and (b) the underlying sand/mud has a very low resistivity due to high salinity.

In this study, high-resolution electrical resistivity sounding data were obtained using a Schlumberger array applying small increments in the current electrode separations. Small increments of about 1.25 times were made in the successive current electrode separation (AB/2) to increase number of observations in a log cycle in order to map thin layers. Maximum separations (AB) ranging from 600 m to 1000 m were used depending upon the availability of space along the profile line.

The resistivity sounding data were interpreted first in terms of physical parameters, namely resistivity and thickness of the formations, and then these parameters were correlated with the available lithological data to interpret the subsurface stratigraphy. Various techniques are available for interpreting the resistivity sounding data. Kim et al. (2001) used statistical methods to interpret electrical resistivity data. Yadav et al. (2010) have discussed, in detail, the methodology and techniques used for the interpretation of geoelectrical sounding data for the alluvial plains in the Ganga basin. Most of the techniques for the interpretation of resistivity data are based on the assumption that the geoelectrical layers extend horizontally to infinity and are isotropic, homogeneous entities with distinct electrical resistivity contrast and thicknesses. Though all these conditions are seldom satisfied, these techniques are useful in inferring broad scale subsurface hydrogeological conditions.

The interpretation of resistivity sounding data was carried out in two stages. The first stage involved the interpretation purely on theoretical considerations in order to develop a basic geoelectrical model. In the second stage, the interpreted results were correlated with the available lithological information and validated accordingly to determine resistivity ranges for different lithological units.
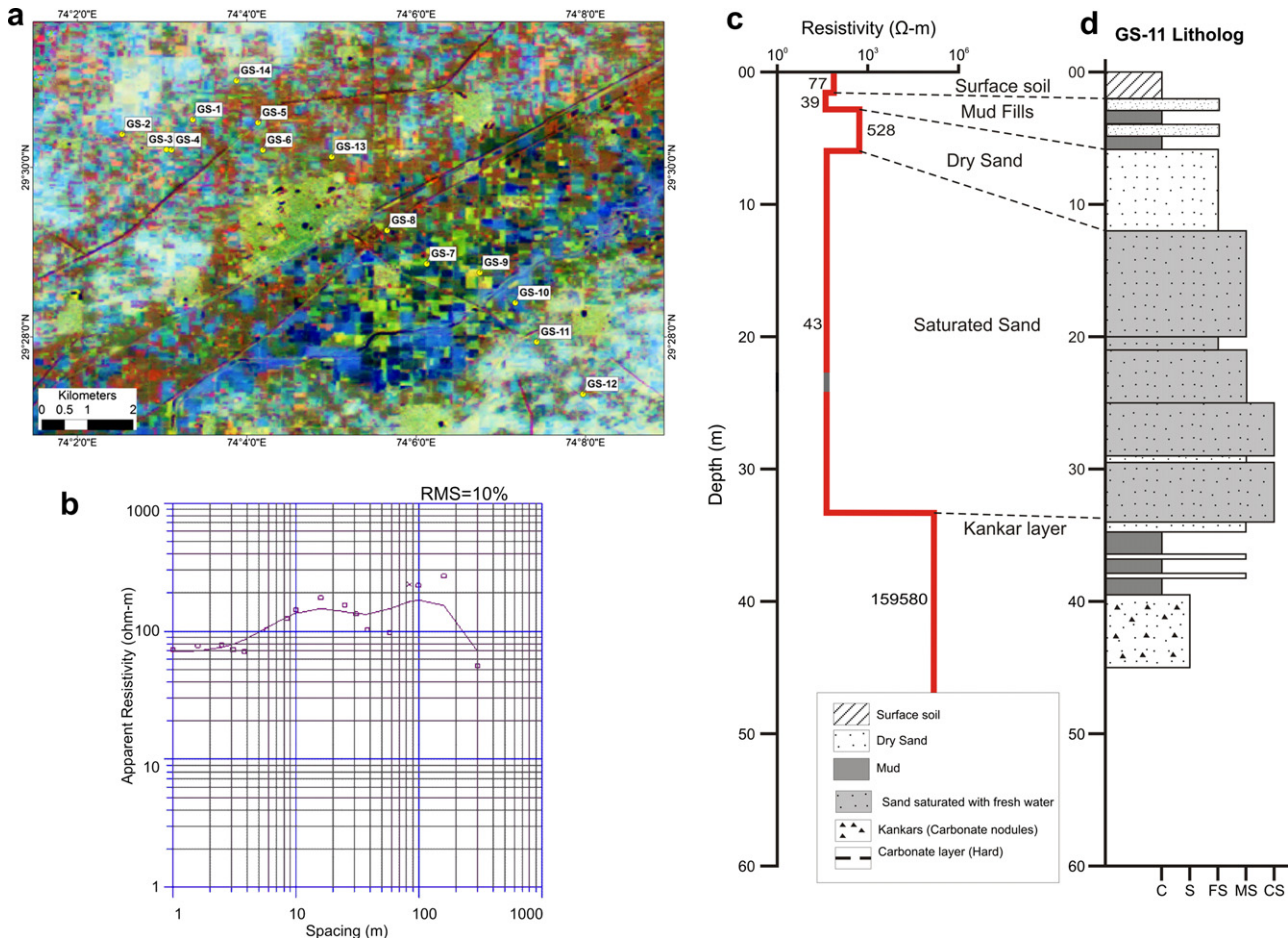
Fig. 2. (a) A Landsat image showing the transect for the resistivity survey across the modern Ghaggar channel. GS1…GS14 are the locations of resistivity soundings. (b) Apparent resistivity curve for sounding done at GS-11. (c) Interpreted resistivity model for this site shows 5 layers with a very high resistivity layer at the base. (d) Calibration of the resistivity data with the litholog of a drill core at this site. A thick sand body with fresh groundwater is clearly mapped in the resistivity data. The high resistivity layer at the base matches with the calcrete (kankar) layer which generally separates the fresh water aquifer from the saline water below.

Stratigraphic boundaries are not always associated with lithological variation and a good correlation may sometimes be difficult due to a variety of reasons viz. thin layers embedded in a thick layer of different material, variations in groundwater salinity. On the other hand, a single lithological unit may include a number of geo-electrical interfaces without any significant variation in its character.

The quantitative interpretation involved determination of the thickness of the different formations having different resistivities from the field sounding curves. Field curves were compared with the theoretically generated or available standard master curves for known layer parameters of two, three and four layers (Orellana and Mooney, 1966; Rijkswaterstaat, 1969). Initial layer parameters were obtained using partial curve matching technique with the help of master curves and auxiliary point charts (Ebert, 1943). Final layer parameters were obtained through inverse modelling for a known RMS error between the field curve and theoretically computed apparent resistivity curve.

3.2. Calibration of resistivity data with drill core

Fig. 2 shows the basis of interpretation of lithological layers based on the field resistivity curve. Field resistivity curve for one of the sites (GS-11) along the GS transect (Fig. 2a) is shown in Fig. 2b. The interpreted 6-layer resistivity model (Fig. 2c) with distinct variations in resistivity values. This model was calibrated against

a sediment core raised from this site which is ~40 m deep and contains most of the sedimentary lithologies typical of an amalgamated fluvial channel complex (Fig. 2d). Similar calibration of resistivity data was developed for MNK and SRH transects using drill core logs (see Figs. 4 and 6).

Based on the resistivity sounding, 4–6 layer models were developed for each site. Using the available lithologs from all transects, all resistivity models from all sites were compared and the range of resistivity values for different lithological units were determined (Table 1). Based on this data, different layers across different sites were correlated, and finally, simplified alluvial stratigraphic models across the different transects were generated (Figs. 3, 5 and 7).

4. Results and interpretation

The shallow subsurface stratigraphy for each of the three transects GS, MNK, and SRH is shown in Figs. 3, 5 and 7 respectively. The surface profile for each transect was constructed from a SRTM digital terrain model (90 m resolution) in the ESRI ArcGIS 10.0 environment. The surface profiles were smoothed for 5 point running average and interpreted resistivity values were plotted below the location of the VES station, for each transect, on their respective profiles. Different stratigraphic layers were marked in each transect following the different range of resistivity values, identified after data calibration (Table 1).
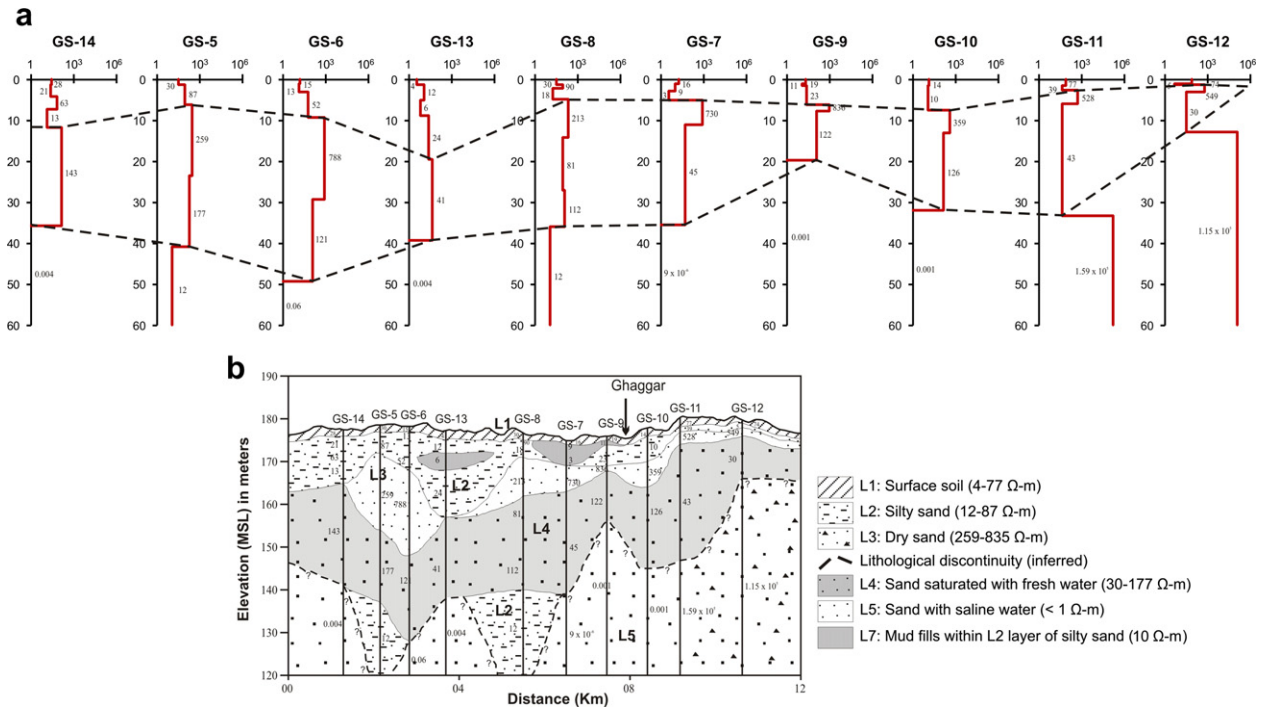
Fig. 3. (a) Resistivity sounding data for 10 sites across the palaeo-Ghaggar valley. The numbers indicate the values of the apparent resistivity for different layers. The dashed line indicates the interpreted sand body with fresh water. (b) Resistivity-based stratigraphic model for transect across the Palaeo-Ghaggar valley along the Gs transect. The buried channel body (sand with fresh groundwater) is distinctly mapped in the resistivity data. The lower bound of this sand body is marked by a sharp change in resistivity values, either too low (due to high salinity of groundwater) or too high (presence of calcrete layer). The sand body is overlain by dry sand layer with pockets of mud.

4.1. GS-transect

The roughly NW–SE trending GS transect running close to the Kalibangan Harappan site (Fig. 2) has a slope of ~0.1 m/km towards northwest and no clear surface topography is discernable. Five different lithological layers (L1–L5) were distinguished in the resistivity based stratigraphic reconstruction along a transect running at 90° to the postulated surface trace of the palaeo-Ghaggar channel (Fig. 3). The uppermost layer (L1) in all soundings has variable resistivity values with thickness varying between 1 and 5 m. This is interpreted as a topsoil layer, which is thickest around GS-10. This is close to the position of the modern Ghaggar river channel and may represent near-channel deposition by the modern river. Underlying L1, L2 shows resistivity values between 12 and 39 Ω-m and is fairly continuous across the profile. This is interpreted as a silty-sand layer with carbonate concretions (kankars or calcrete) based on correlations with core GS11 and local information. This layer is much thicker (>15 m at GS-13) towards the northern end of the profile with channel-form geometry. A similar geometry of this layer is also observed towards the southern end with a thickness of >6 m between GS-9 and GS-10 and this pinches out to less than 2 m towards the southern end of the profile. This layer is a channel fill deposit. This layer shows significant lateral variability in terms of resistivity values. For example, a pocket of slightly higher resistivity values (~90 Ω-m) capping this layer at GS-8 is interpreted as a minor sand lens embedded within the muddy matrix. A few patches of low resistivity values (3–11 Ω-m) are also noted within this layer, which are interpreted as lenses of clayey sediments.

Between ~5 and ~20 m depth, there is a layer L3 of high resistivity (213–835 Ω-m) which has a channel-form cross sectional geometry. This layer is interpreted as dry sand with kankars (carbonate nodules). This sand body is clearly segmented into two parts by a muddy layer around GS-13; it is thickest towards

north (>15 m around GS-5) and pinches out towards south with a thickness of <2 m.

Below L3 is L4, with moderate resistivity values (41–177 Ω-m) with a variable thickness ranging between 20 and 30 m. This layer is interpreted as sand saturated with fresh groundwater and has a distinct channel-form cross-sectional geometry. The maximum thicknesses of the buried sand body are recorded at GS-11 (~30 m) and at GS-8 (~20 m). The sand body shows some thinning on both sides but still maintains a thickness of 15–20 m at both ends. The resistivity values of this layer decreases towards the southern end that may be a manifestation of fining of sandy sediments. Local water wells indicate that this layer provides the most important source of fresh groundwater in this area. At GS-5 and GS-8, layers of lower resistivity values (12 Ω-m) may represent lenses of silty sand. The lower bound of the L4 sand body is generally a thin, hard concretion layer (based on local information on groundwater wells, not reflected in resistivity data except at GS-11 and GS-12).

Layer L5, which underlies L4, shows a drastic lowering of resistivity (<1 Ω-m). This is interpreted as an abrupt transition to a sand body containing saline pore water based on local water well information. This sand body with saline water occurs at a depth of >40 m towards the northern end of the profile but comes much closer to the surface (~10 m) at the southern end of the valley. In most cases, the base of this layer could not be mapped in the resistivity sounding data. Towards the southern end of transect, resistivity sounding data from GS-11 and GS-12 show very high resistivity values. This is a manifestation of the hard and compact kankar layer separating the fluvial and aeolian sands possibly with some mud as seen in GS-11 core. It is likely that this discontinuity exists at other sites as well but it may not be thick enough to be picked up in the resistivity soundings. This interpretation is based on (a) the abrupt change in resistivity, (b) an abrupt change in sedimentary facies in the core GS11, and (c) the occurrence of aeolian sand dunes at the southern margin of the Ghaggar palaeochannel.
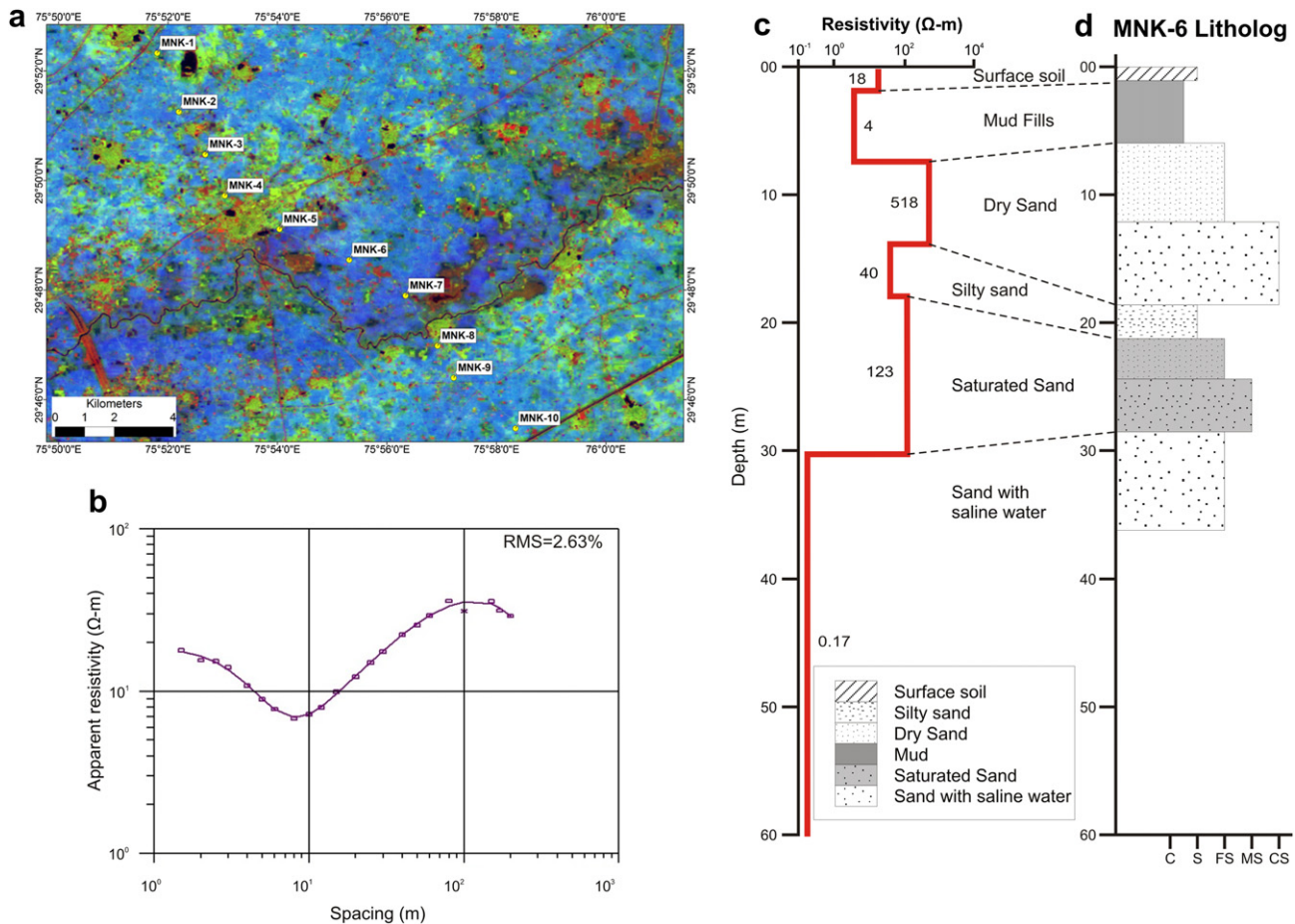
Fig. 4. (a) A Landsat image showing the MNK transect across the palaeo-Ghaggar valley; MNK1….MNK10 are the locations of resistivity soundings. The modern Ghaggar channel flows within this valley and swings from the northern to southern edge of the valley in this window. (b) Apparent resistivity curve for sounding done at MNK-6. (c) Interpreted resistivity model for this site shows 6 layers with a very low resistivity layer at the base. (d) Calibration of the resistivity data with the litholog of a drill core at this site. A thick sand body with fresh groundwater is clearly mapped in the resistivity data. Very low resistivity layer at the base is interpreted as sand layer with saline water.

4.2. MNK-transect

The MNK transect is ∼20 km long and runs close to the Kunal Harappan site and across the buried fluvial system, centred near Moonak (also known as Akalgarh) village (29° 49′16.36″N, 75°53′33.37″E). Presently, the modern Ghaggar River flows as a narrow and confined channel in this region. The roughly NW–SE oriented transect has a slope of about 0.34 m/km towards northwest. Ten resistivity sounding points (MNK-1 to MNK-10) almost evenly distributed along the length of transect (Fig. 4) and two drill cores at MNK-5 and MNK-6 were used to reconstruct the subsurface alluvial architecture along this transect (Fig. 5).

The topsoil layer shows variable thickness between ∼1 and 2.8 m, and consists of red silty clays, sometimes pedogenised with occasional presence of very small calcrete nodules. The topsoil layer, marked as L1, has resistivity values in the range of 18–90 Ω-m at different sounding points. This layer is unusually thick (∼9.5 m) at VES location MNK-9 that is located close to the present course of modern Ghaggar River. The underlying L2 layer, ∼3–10 m thick, is interpreted as a silty sand body with resistivity values between 12 and 50 Ω-m. A similar lithology is encountered again at deeper depths and at the margin of transect. The L3 layer, having a variable thickness of ∼1–10 m with resistivity values between 461 and 752 Ω-m, is fairly continuous throughout the transect. The underlying L4 layer is present mainly in the central part of transect, with a variable thickness of 5–20 m and resistivity values varying between

108 and 473 Ω-m. Both L3 and L4 layers represent sand bodies with the only difference that L3 is dry sand while L4 is saturated with fresh water. A dramatic drop in resistivity values (<<1 Ω-m) in layer L5 is interpreted due to the presence of saline water zone.

4.3. SRH-transect

The SRH represents a ∼20 km long transect close to Kunal Harappan site and across a buried channel centred near Sirhind village. Presently, this area is devoid of any major drainage. The roughly E–W transect has a ground slope of ∼0.57 m/km towards west. Ten resistivity sounding points (SRH-1 to SRH-10) along the length of transect (Fig. 6) and two drill cores at SRH-5 and SRH-6 were used to reconstruct the subsurface alluvial stratigraphy (Fig. 7) along this transect.

The topmost layer L1 consists of muddy and silty sediments with occasional presence of kankars due to which the resistivity values of this layer vary from 13 to 84 Ω-m. The underlying L2 layer in the eastern part of transect has a variable thickness of 2–10 m with resistivity values varying between 3 and 36 Ω-m. In the western part of the transect, the topsoil is underlain by a ∼2 m thick layer (L3a) of high resistivity (1729–7132 Ω-m) which is interpreted as dry sand with kankars. The underlying layer (L4) of variable thickness up to 30 m has a channel shaped geometry with resistivity values of 87–473 Ω-m and is interpreted as a wet or saturated sand layer. A 5–8 m thick mud-fill is also identified below
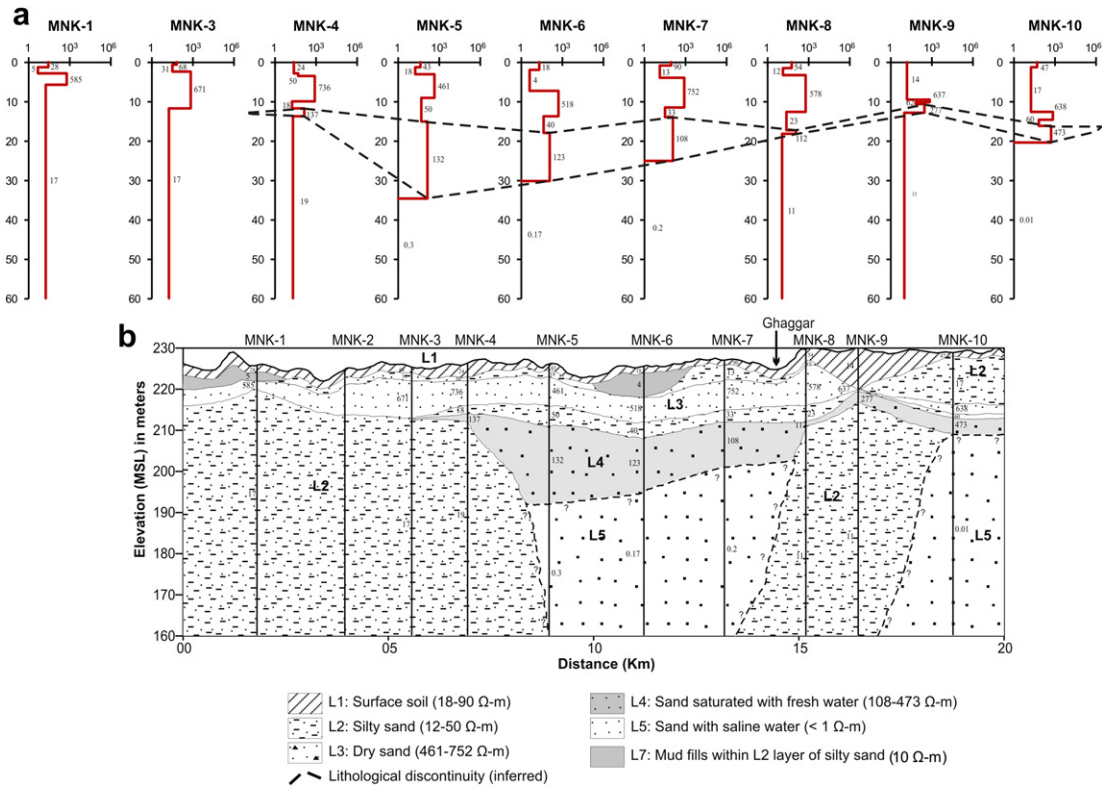
Fig. 5. (a) Resistivity sounding data for 9 sites along the MNK transect. The numbers indicate the values of the apparent resistivity for different layers. The dashed line indicates the interpreted sand body with fresh water. (b) Resistivity-based stratigraphic model for the MNK transect. The buried channel body (sand with fresh groundwater) is quite narrow along this transect and the lower bound of this sand body is marked by a sharp decrease in resistivity values due to high salinity of groundwater. The sand body is bounded laterally on both sides by silty sand and overlain by dry sand layer with kankars.
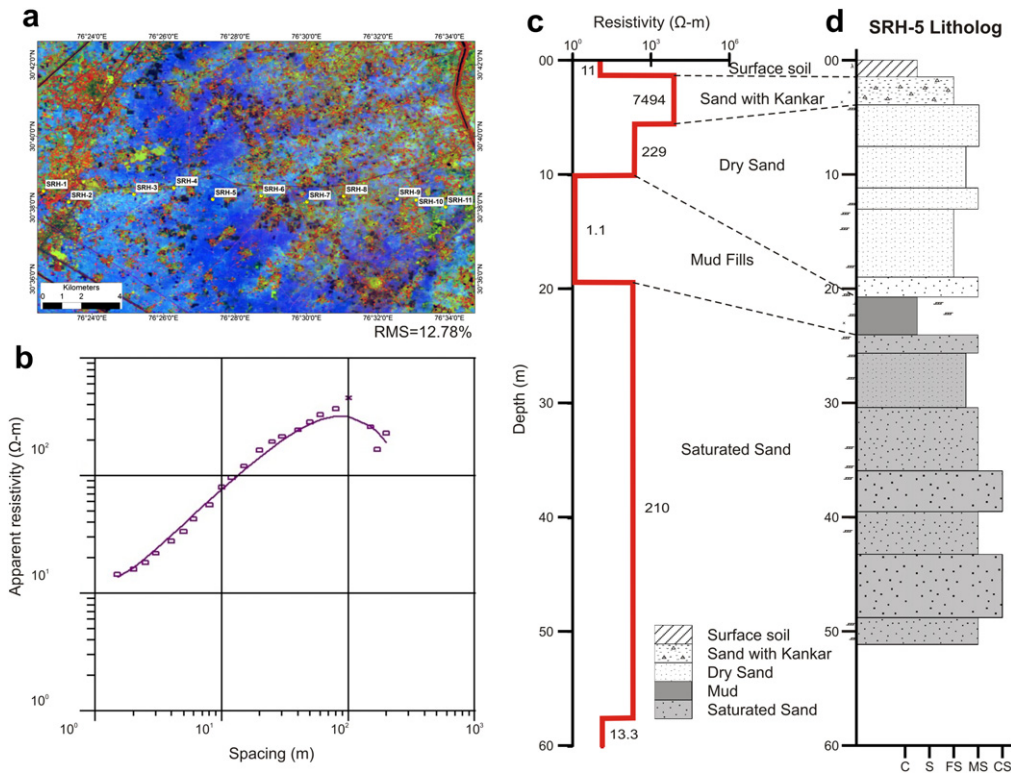

Fig. 6. (a) A Landsat image showing the SRH transect across the palaeo-Sutluj valley; SRH1….SRH11 are the locations of resistivity soundings. (b) Apparent resistivity curve for sounding done at SRH-5. (c) Interpreted resistivity model for this site shows 6 layers with a low resistivity layer at the base. (d) Calibration of the resistivity data with the litholog of a drill core at this site. A thick sand body with fresh groundwater is clearly mapped in the resistivity data. Low resistivity layer at the base is interpreted as muddy layer (not penetrated in the drill core).

Table 1
Range of resistivities for different lithological units.

Lithological units	Resistivity (Ω-m)
Top soil (L1)	4–90
Silty sand (L2)	12–87
Dry sand (L3)	259–835
Dry sand with carbonate concretions (kankars) (L3a)	1729–7132
Sand with fresh water (L4)	41–177
Sand with saline water (L5)	<1
Sand with gravels (L6)	>10,000
Minor mud fills (L7)	1–9

SRH-5 and SRH-6 that shows low resistivity values ($\sim 1.3–1.9$ Ω-m). The L2 layer repeats below the L4 layer for a large part of transect. A distinctive feature of this transect is the presence of a very high resistivity layer (L6) at the base which marks a lithological discontinuity between L5 and L6. None of the drill cores penetrated this layer, and it is tentatively interpreted as sand with gravels. This interpretation is based on the proximity of this transect to the mountain front and the limited field observations that gravels occur at shallow levels (<5 m) in most of the modern smaller tributaries around this latitude.

5. Discussion

Several previous studies have used satellite image analysis to document the surface trace of the postulated Ghaggar-Hakra palaeochannel based on contrast in reflectance characteristics as a function of the spectral character of vegetation cover (Yashpal et al., 1980; Gupta et al., 2011). This study provides the first confirmation that this postulated surface trace derived from satellite image analysis corresponds to a subsurface sand body,

reconstructing a detailed resistivity-based alluvial architecture below the plains.

Fig. 8 presents a summary of the sub-surface stratigraphy of this region available so far including the data published by Saini et al. (2009). Resistivity sounding data along the GS and MNK transects indicate a large composite sand body (L3 and L4) in the subsurface with complex internal architecture buried beneath aeolian cover. While the lower sand body L4 is saturated with fresh groundwater, the upper one (L3) is finer-grained and dry with dispersed kankars resulting in high resistivity values. The cores obtained from several locations confirm the presence of a sand body and also indicate an overall fining-upward trend. L3 and L4 together represent a composite sand body (>12 km wide and 30 m thick) that is an order of magnitude larger than the modern Ghaggar river channel (<500 m wide and <5 m deep). This composite sand body likely represents the localised amalgamation of multiple individual fluvial channel bodies. The amalgamated channel complex represents a river system that either formed in a more humid phase, or represents the palaeocourse of a large river that now flows elsewhere due to river diversion. In the GS and MNK transects, there is a layer of silty sand (L2) overlying the buried sand body which is fairly continuous and has a distinct channel cross sectional geometry. With a maximum thickness of ~ 10 m in the GS transect, this sandy layer appears to have incised the lower sand body (L3), and therefore, likely represents a younger phase of fluvial activity. The muddy layers encased in this sand body may represent channel fill deposits, which are in turn covered by modern deposits of the Ghaggar River and aeolian deposits. Both edges of the palaeochannel complex are very well marked by sharp changes in the resistivity values, both laterally and vertically, suggesting transition to aeolian sands or floodplain deposits. This is confirmed by
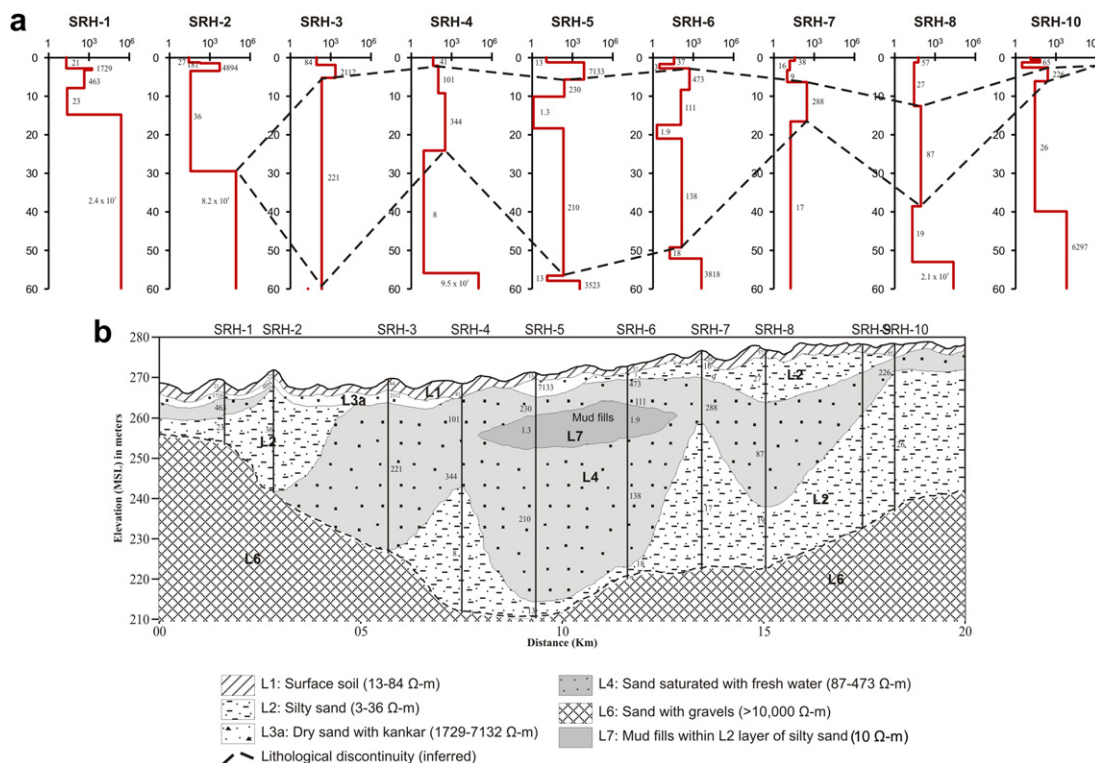

Fig. 7. (a) Resistivity sounding data for 9 sites along the SRH transect. The numbers indicate the values of the apparent resistivity for different layers. The dashed line indicates the interpreted sand body with fresh water. (b) Resistivity-based stratigraphic model for the SRH transect. The buried channel body (sand with fresh groundwater) is quite thick along this transect and the lower bound of this sand body is marked by a sharp increase in resistivity values due to the presence of gravelly bed. The sand body is overlain by dry and compact sand layer with kankars.
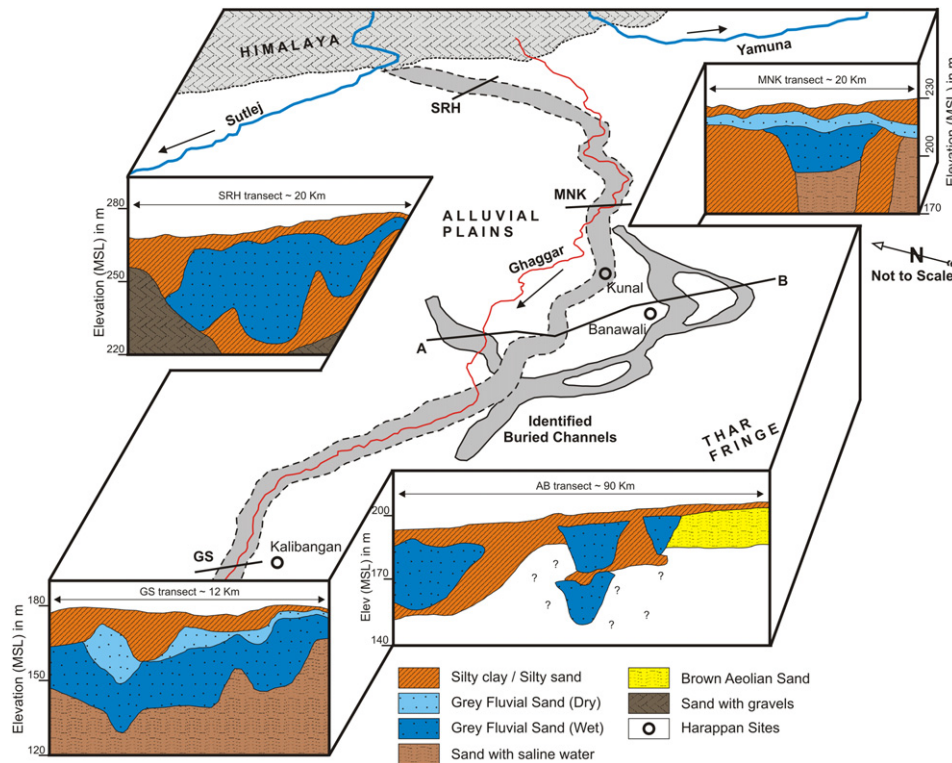
Fig. 8. Sub-surface stratigraphy of the Ghaggar and paleo-Sutluj valley based on the data presented in this paper and published by Saini et al. (2009).

the presence of aeolian mounds on either side of the palaeochannel complex around Kalibangan.

The SRH transect was primarily designed to track the subsurface existence of a palaeochannel complex in northern Punjab originally identified by Yashpal et al. (1980) as a possible tributary to the Ghaggar-Hakra palaeochannel. Resistivity data confirms a large sand body, 40–50 m thick, although there is no surface expression of this large valley. This sand body is covered with a hard and compact layer reflected by very high resistivity values. The sand body has a distinct channel-form geometry that is thickest in the centre of the transect and tapers on both sides. Unlike the GS and MNK transects, no layer with saline water was encountered along this transect in the upper 70 m of the strata represented by the resistivity data. A layer with very high resistivity value at the base is interpreted as a gravelly bed. This is attributed to the proximal position of this transect based on limited field observations.

Stratigraphic data from the GS and MNK transects compare well with that of the AB transect published by Saini et al. (2009) based on groundwater borehole data. The sand body thickness of the buried channel complex in all of these transects ranges between 25 and 30 m and is underlain by aeolian sand and covered with floodplain muds and aeolian silts. However, the buried channel separated by wide interfluves mapped along the AB transect is ~25 km south of the valley margin of the main channel complex. In the absence of intensive chronological data, it is difficult to comment if these buried channels co-existed or are time-separated. However, there are several examples in the Gangetic basin from where large-scale avulsions of large rivers and valley migration have been reported over time scales of 10^3–10^4 years (Gibling et al., 2005; Tandon et al., 2006; Sinha et al., 2007; Sinha, 2009). It has been suggested that the valley prominence may change with time and space as a function of climate and hydrological regime (Tandon et al., 2006) or

tectonics (Gupta, 1997). It is likely that the discovered buried channels so far are a part of a much large drainage network which has varied in time and space. A more detailed and intensive investigation of sub-surface stratigraphy is required to confirm these ideas.

These resistivity results represent the first stratigraphic evidence that a palaeochannel exists in the sub-surface alluvium both in the Ghaggar valley. The fact that the major urban sites of Kalibangan and Kunal lie adjacent to the newly discovered subsurface fluvial channel body along the GS and MNK transects suggests that there may be a spatial relationship between the Ghaggar-Hakra palaeochannel and Harappan site distribution. Detailed sedimentological analysis and dating of cores will in future provide the palaeoenvironmental and chronological constraints to test these important environment–archaeology relationships. Without this information, no further speculation is possible concerning hypotheses for why Kalibangan, Kunal and other Harappan sites are located along this buried channel trace.

6. Conclusions

This study has utilised resistivity sounding techniques to map the sub-surface existence of a large palaeo-river channel complex in an area of significance for Harappan archaeology in northwest India. There is a first order relationship between the postulated surface trace of a palaeochannel belt as observed in satellite imagery and the subsurface sand body. The sand body mapped by resistivity data has a clear channel-form cross-sectional geometry, which likely represents an amalgamated channel complex. The sand body appears to overlie aeolian dune sediments and is capped by thin topsoil formed in the modern semi-arid climate. The dimensions of the palaeochannel complex suggest a large, longlived fluvial system existed in this region, however, the timing and provenance of this system remains to be resolved.

Acknowledgements

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2012.08.002.

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