

# Fluvial landscapes of the Harappan civilization

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**The collapse of the Bronze Age Harappan, one of the earliest urban civilizations, remains an enigma. Urbanism flourished in the western region of the Indo-Gangetic Plain for approximately 600 y, but since approximately 3,900 y ago, the total settled area and settlement sizes declined, many sites were abandoned, and a significant shift in site numbers and density towards the east is recorded. We report morphologic and chronologic evidence indicating that fluvial landscapes in Harappan territory became remarkably stable during the late Holocene as aridification intensified in the region after approximately 5,000 BP. Upstream on the alluvial plain, the large Himalayan rivers in Punjab stopped incising, while downstream, sedimentation slowed on the distinctive mega-fluvial ridge, which the Indus built in Sindh. This fluvial quiescence suggests a gradual decrease in flood intensity that probably stimulated intensive agriculture initially and encouraged urbanization around 4,500 BP. However, further decline in monsoon precipitation led to conditions adverse to both inundation- and rain-based farming. Contrary to earlier assumptions that a large glacier-fed Himalayan river, identified by some with the mythical Sarasvati, watered the Harappan heartland on the interfluvium between the Indus and Ganges basins, we show that only monsoonal-fed rivers were active there during the Holocene. As the monsoon weakened, monsoonal rivers gradually dried or became seasonal, affecting habitability along their courses. Hydroclimatic stress increased the vulnerability of agricultural production supporting Harappan urbanism, leading to settlement downsizing, diversification of crops, and a drastic increase in settlements in the moister monsoon regions of the upper Punjab, Haryana, and Uttar Pradesh.**

Indus Valley | floods | droughts | climate change | archaeology

**T**he Harappan or Indus Civilization (1–8) developed at the arid outer edge of the monsoonal rain belt (9, Fig. 1) and largely depended on river water for agriculture (10). The Harappans settled the Indus plain over a territory larger than the contemporary extent of Egypt and Mesopotamia combined (Figs. 2 and 3). Between the Indus and Ganges watersheds, a now largely defunct smaller drainage system, the Ghaggar-Hakra, was also heavily populated during Harappan times (4, 5). Controlled by the Indian monsoon and the melting of Himalayan snow and glaciers (2, 11, 12), the highly variable hydrologic regime, with recurring droughts and floods, must have been a critical concern for Harappans, as it is today for almost a billion people living on the Indo-Gangetic Plain in Pakistan, northern India, and Bangladesh. In such challenging environmental conditions, both the development and the decline of the Harappan remain equally puzzling (13). We investigate how climate change affected this civilization by focusing on fluvial morphodynamics, which constitutes a critical gap in our current understanding of the Harappan in the way it affects habitability and human settlement patterns near rivers in arid regions.

## Brief Harappan History

The Harappan cultural tradition (2–4) evolved during an Early Phase (5,200–4,500 y ago) from antecedent agricultural communities of the hills bordering the Indus alluvial plain to the west and reached its urban peak (Mature Phase) between approximately 4,500 and 3,900 y ago. The Harappans were agrarian but developed large, architecturally complex urban centers and a sophisticated material culture coupled with a robust trade system. In contrast to the neighboring hydraulic civilization of Mesopotamia (14) and to Egypt (15), Harappans did not attempt to control water resources by large-scale canal irrigation (16). Deurbanization ensued after approximately 3,900 y ago and was characterized by the development of increasingly regional artefact styles and trading networks as well as the disappearance of the distinctive Harappan script (2–4; 17). While this is often referred to as “collapse,” archaeological evidence indicates a protracted and regionally varied process (2, 4, 17). Many settlements exhibit continuity, albeit with reduced size, whereas many other riverine sites are abandoned, especially along the lower Indus and the Ghaggar-Hakra course (3–5; *SI Text*). Between 3,900 and 3,000 y ago, there was a proliferation of smaller, village-type settlements (2–4, 6, 18), especially in the Himalayan foothills and the western part of the Ganges basin along the Yamuna River and on the Yamuna-Ganga interfluvium (Fig. 3B).

Socio-economic theories have been invoked to address the collapse of urban Harappan society, including foreign invasions, social instabilities, and decline in trade (4). Alternatively, environmental factors were suggested to play a decisive role in the decline (1, 2, 8); among these, regional aridification, hydrological changes such as the drying or capture of the Ghaggar-Hakra system (3, 4, 7, 19, 20), as well as human-induced environmental degradation (21) have been advanced. Despite almost a century of research, a clear perspective on the role played by fluvial dynamics in influencing the fate of the Harappan civilization has been hampered by a lack of high-resolution topographic data and sedimentary chronologies. Shuttle Radar Topography Mission (SRTM) data (22) combined with field surveys and radiocarbon and optically stimulated luminescence dating offer us a way to analyze fluvial landforms and date deposits of the Indo-Gangetic Plain. In this context, we reexamine archaeological site distribu-

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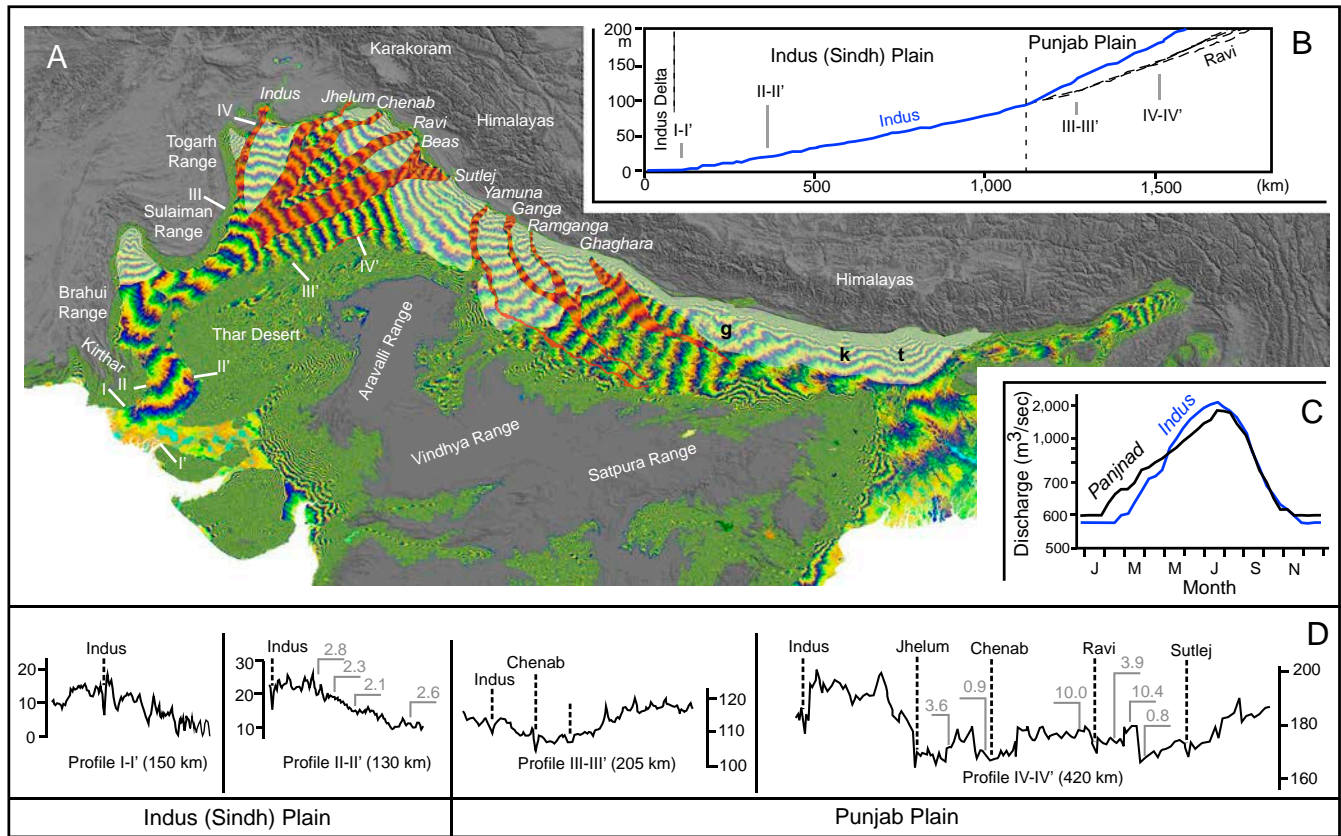
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**Fig. 1.** Large-scale morphology of the Indo-Gangetic Plain (for altitudes, pattern of colors repeats every 10 m to 300 m in height; higher landscape in gray). Convex downslope, aggradational landscapes (e.g., Tista = t; Kosi = k; Gandak = g) have a lighter mask, whereas incisional landscapes have a red mask. (B) Along-channel longitudinal profiles for the Indus and its Punjab tributaries. (C) Hydrographs for the Indus and confluent Punjab tributaries (Panjnad River). (D) Profiles across the extended Indus plain (in meters above sea level). River channel locations are identified on the profiles, as are locations and ages of studied fluvial sedimentary deposits in Sindh and Punjab (ages in thousands of years).

tion to understand how climate-controlled changes in river dynamics affected the Harappans (*SI Text*).

### Morphodynamics of the Indo-Gangetic Plain

The Indo-Gangetic Plain (Fig. 1) was built during the Cenozoic with sediments derived primarily from the Himalayas (23). Our digital elevation model shows a trend from aggradation in the eastern part of the Indo-Gangetic Plain toward incising rivers in the west (24), probably driven by the westward weakening of the monsoonal rains along the Himalayas (9, 25). In the eastern Indo-Gangetic Plain, alluvial megafans were actively built during the Holocene by rivers with large, highly seasonal sediment discharge and low stream power (25). In contrast, rivers in the western Indo-Gangetic Plain (Fig. 1) are largely degradational after emerging from the Himalayan foothills. Wide, shallowly incised valleys separated by interfluvies characterize the Indus and its tributaries in Punjab (26) as well as the Ganges and its westernmost tributaries (Fig. 1).

The Old Beas Survey (2, 27; 28) previously documented incision of the terminal Pleistocene sediments on the Beas-Ravi interfluvial at and near Harappa followed by stable conditions and occupation levels after approximately 7,700 y ago. On the interfluvies in Punjab, we dated the latest fluvial channel deposits to approximately 10,000 y ago (Fig. 2B; *SI Text*), confirming that large-scale fluvial sedimentation ceased at the beginning of the Holocene. Within the entrenched river valleys, we mapped abandoned river channel belts and terraces (26), which indicate periodic but progressive incision (29, 30). Our dates on incised valley deposits vary in age between 700 and 3,900 y (Fig. 2B; *SI Text*). Thus, rivers in Punjab started to incise after 10,000 y ago, but before 3,900 y ago. As documented along the Himalayan course

of the Sutlej River (12), the easternmost tributary of the Indus, century-long phases of sediment load decline caused by weak monsoons were responsible for incision, primarily in the early Holocene between approximately 10,000 and 8,700 y ago. The presence of Harappan and even earlier settlements within these incised valleys (*vide infra*) also argues for major incision predating the Harappan. During Harappan times, the alluvial landscape in Punjab offered suitable terrain for floodwater farming within incised valleys and important protection against large floods on interfluvies.

The similarity of incision profiles (29, 31) for Indus tributaries across Punjab (Fig. 1) reflects comparable hydrological histories during the Holocene (25). On the other hand, high water discharge and sediment load (29) explain the relatively steep longitudinal profile of the Indus. We note the sharp contrast between the degradational character of the tributaries of the Indus and the Ganges in the western Indo-Gangetic Plain and the lack of wide incision valleys along the Ghaggar-Hakra interfluvial (Figs. 1 and 24). Numerous speculations have advanced the idea that the Ghaggar-Hakra fluvial system, at times identified with the lost mythical river of Sarasvati (e.g., 4, 5, 7, 19), was a large glacier-fed Himalayan river. Potential sources for this river include the Yamuna River, the Sutlej River, or both rivers. However, the lack of large-scale incision on the interfluvial demonstrates that large, glacier-fed rivers did not flow across the Ghaggar-Hakra region during the Holocene. Existing chronologies (27, 28) and our own age on the bank of Sutlej (*SI Text*) identified deposits of Late Pleistocene age, indicating that the interfluvial formed instead during the last glacial period. Provenance detection (32) suggests that the Yamuna may have contributed sediment to this region









deposits at Fakirabad, among the dunes of the expanding desert, are even younger at approximately 3,350 y old. Further south, the Nara valley, which would be currently dry if not for modern irrigation, also had active fluvial sedimentation approximately 2,900 y ago (Fig. 2B; *SI Text*).

Downstream in the province of Sindh, the Indus River built a unique distributive-type fluvial system that we term the Indus fluvial mega-ridge (Fig. 1). The alluvial plain here is convex up (35–37), showing maximum aggradation near the modern channel belt and tapering out toward the plain edges (*SI Text*). The cross-sectional relief of the ridge is very subdued (over 100 km wide and 10–15 m high; Fig. 1) and the river is stable on its apex because the thalweg is incised as deep as the ridge. Fossil channel belts and associated crevasse splays occur on both sides of the modern Indus course (Fig. 24; *SI Text*). Radiocarbon-dated fluvial deposits of old channel belts in lower Sindh indicate that aggradation was minimal during the late Holocene (between 2.4 m/kyr near the mega-ridge top down to less than 1 m/kyr near its edge; Fig. 2B; *SI Text*). This relative stability of the late Holocene landscape suggests that large avulsions of the Indus were rare and distributary channels acted mainly as overflows, as documented for the historical period (38, 39). In contrast, at our Matli floodplain drill site on top of the Indus mega-ridge (Fig. 2B; *SI Text*), sedimentation rates were at least three times higher between approximately 7,200 and 2,700 y ago compared to the last approximately 2,700.

We speculate that the development of the Indus fluvial mega-ridge was also the direct consequence of late Holocene aridity (12, 40–42). Hydroclimate in the western Indo-Gangetic Plain is influenced by both the Indian summer monsoon system and westerly winter disturbances bringing humidity from the Mediterranean, Black, and Caspian Seas (9, 11). Most sediment is delivered to the Indus by floods after high-intensity monsoon storms (43), but the bulk of Indus water discharge is dependent on snow melt (11). The weakening of the monsoon after approximately 5,000 y ago compared to the slower decline in winter precipitation originating in western Asia (40, 42, 44, Fig. 4) must have resulted in a reduction in sediment load compared to water discharge, causing channel incision and stabilization (12; *SI Text*) and leading to longer intervals of decoupling between channels and the alluvial plain. The subdued relief of the fluvial ridge, resulting from less frequent breaches and overflows as well as cohesive banks (35), which are typical for arid regions, are not favorable to avulsions. Rarity of large scale avulsions reinforces deposition close to existing channel belts and allows for the slow growth of the mega-ridge. Within the deep active channels on top of the ridge, effective conveyance of sediments toward the coast for the build-up of a new deltaic depocenter in western lower Sindh (45, 46) must have diverted most of the sediment away from the Indus alluvial plain in the late Holocene.

Our analysis reveals a palimpsest of fluvial forms and deposits in the western region of the Indo-Gangetic Plain; however, one constant trait that is evident across the entire Harappan landscape is the change from a more energetic fluvial regime earlier in the Holocene (before approximately 5,000 y ago; Fig. 4) to increased stability of alluvial forms by Early Harappan times, and even drying up of some river channels during and after Harappan times.

### Settlement Dynamics in the Harappan Domain

The distribution of Harappan sites within the incised valleys of Punjab (Fig. 3A) provides clear evidence that rivers were already entrenched by 5,200 y ago or earlier (Fig. 2B). Numerous sites are present in the incised valley at the confluence zone of the Indus with the Punjab rivers. In this region of confluences, regardless of their past geometries, backwater flooding would have been common because the Indus and its tributaries in Punjab reach their flood stages asynchronously (Fig. 1). Settlements on

the Punjab interfluves, including Harappa, also tend to be located near their edges, close to the fertile, annually flooded areas in the incised valleys (Fig. 3A; 28). Farther to the east, Harappan sites have been reported along a network of smaller monsoon-fed rivers in the upper region of the Ghaggar-Hakra domain (i.e., Haryana and upper Punjab; 19, 47, 48) as well as along and within the incised valley of the Yamuna and the Yamuna-Ganga interfluve (49, 50). As the climate continued to become drier during late Harappan times (Fig. 4), the number of sites increased in the upper Punjab and Haryana, especially on interfluves near the Himalayan piedmont where monsoonal rains are more consistent (Fig. 3B).

The largest agglomeration of mature Harappan sites, including the urban Ganweriwala, occurs on the lowermost Ghaggar-Hakra interfluve (5, 49) in modern Cholistan. The proximity to both the Ghaggar-Hakra valley and the well-watered Indus-Punjab river confluence region provides the best explanation for the unusual continuity and high-density occupation of the lower Ghaggar-Hakra interfluve (Figs. 2 and 3). Recent Harappan discoveries in the Thar Desert adjacent and along the Nara valley (51) support our reconstructions of a better-watered past for this dry region as well. As channels of the Ghaggar-Hakra dried through the Late Harappan Phase, fewer sites occur on the lower part of the Sutlej-Yamuna interfluve (4, 5), with the notable exception of sites closest to the Indus where access to water remained somewhat reliable (Fig. 3B). In contrast, the number of sites in the upper region of the interfluve increased as they did beyond the Yamuna to the east (4, 18, 50; *SI Text*, Fig. 3B). Later, Painted Gray Ware sites were reestablished along the middle Ghaggar-Hakra course (Fig. 3B), suggesting a possible reinvigoration of seasonal river flows during the Iron Age (5). The lack of Painted Gray Ware sites at the distal end of the Ghaggar-Hakra system (4, 5), however, supports our chronostratigraphic evidence that river flow had become ephemeral and did not reach as far as the Indus.

In Sindh, in the southern part of the Harappan domain, many archaeological sites are found on landforms that were not affected by fluvial erosion or deposition, such as the western Pakistan ranges and bedrock inselbergs raised above the alluvial plain. However, in upper Sindh, good preservation of early and mature Harappan sites on the alluvial plain (45), including Mohenjo-Daro, suggests that the Indus mega-ridge has been relatively stable in that region since Harappan times. In contrast, in lower Sindh, just a few Harappan sites have been discovered on the eastern delta plain (52), supporting the idea of a switch of the fluvio-deltaic depocenter to the west (45, Figs. 2 and 3). Any settlement on the alluvial plain that may have existed in the southwestern part of Sindh is probably buried under later fluvial sediments. Sites in Kutch, a coastal region that was never dependent on flood agriculture but instead relied on trade, remained active into late Harappan times (4, Fig. 3B), when settlements were far fewer on the Indus plain.

Although erosion or burial of archaeological sites is an important process in fluvial environments, preservation of Harappan archaeological sites in potentially dynamic contexts such as entrenched valleys, river confluences, and accretionary distributive fluvial forms indicates relatively low fluvial activity across the wider alluvial plain since the time settlements were established. In this context, however, the preferential occurrence of Harappan urban sites on interfluves, but in close proximity to floodable, agriculturally viable land (20, 24), suggests awareness of devastating floods that can occur on Himalayan rivers. Settling of the Ghaggar-Hakra river system is the best example of an adaptation strategy that takes advantage of smaller floods along monsoonal rivers, where monsoon rains are not augmented by meltwater. However, most floods, whether in entrenched valleys in Punjab, along overflows in Sindh, or along the smaller rivers of the Ghaggar-Hakra system, must have been predominantly benign in character to be able to foster intensive agriculture and also regular enough not to require canal irrigation.

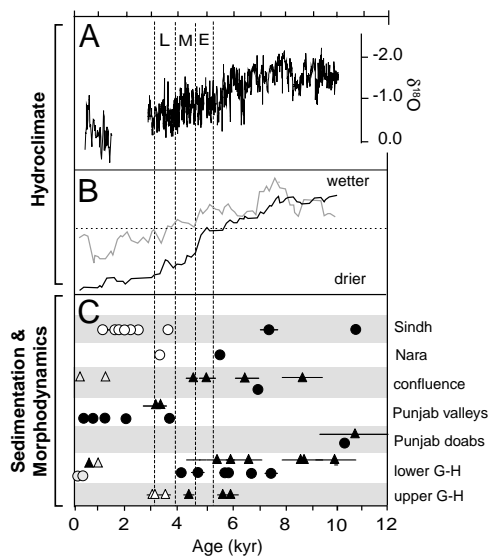
Diminished monsoon rains and less reliable flooding during late Harappan times could explain the expansion of settlements near the headwaters of the Ghaggar-Hakra system, where small-scale floods probably remained more dependable and where rains allowed summer-cropping on interflues. Agriculture, land development, and continuous habitation can skew the distribution of archaeological sites, but such biases should be minimal in desert areas like Cholistan. In upper Punjab, Haryana, and Uttar Pradesh, where historical and modern destruction of sites has been intensive, the increase in the number of sites during the late Harappan shows an unambiguous trend. In contrast, in lower Punjab and Sindh, regions of similarly intense history of human activities, the number of sites decreased over the same interval.

### Climate Change and the Harappans

For the arid Indus region, river floods have always been far more important and reliable for agriculture than rainfall. As during the Harappan era (7, 10, 20), inundation agriculture during the *Rabi* season (winter crops) was dominant along the Indus and its tributaries (10, 38, *SI Text*) prior to the development of the largest irrigation system in the world in 20th century Pakistan. Hydroclimate reconstructions for South and Central Asia (39–41) show that precipitation from both monsoon and westerly sources that feed rivers of the western Indo-Gangetic Plain (20) decreased since approximately 5,000 y ago, and was at its lowest after approximately 4,000 y BP (Fig. 4). This drying of the Indus region supports the hypothesis that adaptation to aridity contributed to social complexity and urbanization (1, 52). An intense drought period around 4,200 y ago, linked to major disruptions in Egypt and Mesopotamia (53–56), coincides instead with the flourishing of Harappan urbanism within the limits of available chronology. This event, recorded at the start of the aridification process in

South Asia, had affected the total Indus discharge (57), but aridification may have diminished the intensity of floods and allowed inundation agriculture to expand along the Indus and its tributaries (20). However, our analysis of fluvial landscapes suggests that further drying was detrimental for the Harappans, who relied on annual floods to sustain their economy. Good preservation of numerous archaeological sites at locations seemingly vulnerable to flooding, erosion, or burial suggest that, as aridity intensified, monsoon-augmented floods became less frequent and/or less intense. The most spectacular case of climate-controlled landscape transformation is the Ghaggar-Hakra system, which became ephemeral and was largely abandoned.

Settlements of the posturban period are preferentially located near the easily flooded region at the confluence of the Indus with rivers in Punjab or in eastern regions with more reliable monsoon rains. Diversification of agriculture towards *Kharif* (summer) rain-based crops and the increase in drought-tolerant crops like millets (*SI Text*) at the end of the urban phase (58) reveal intense efforts to adapt to hydroclimatic stress at the arid outer edge of the monsoonal rain belt. The climate-controlled decline in floods concurrent with the reduction of monsoon rains probably led to a decrease in surpluses for supporting that part of the population that was not involved directly in agriculture, which in turn led to diminished social complexity. Although snowmelt continued to regularly provide water to the Indus and its Himalayan tributaries (57), the Harappans did not develop canal irrigation. In contrast to inhabitants of Mesopotamia and Egypt, which were surrounded by arid lands, the Harappans had the option to migrate east toward more humid regions of the Indo-Gangetic Plain. Migration toward the periphery could have contributed to reduced population in the core region of the Harappan domain and the decline of urban centers. The unprecedented scale of hydroclimatic stresses must have increased the vulnerability of Harappan society, but does not provide a simple, deterministic explanation for the transformations in site size, distribution, and interrelationships across the whole civilization area (2, 4, 6, 17, 59). The longevity of the decentralized late Harappan phase and continued habitation documented in places in Sindh and lower Punjab suggests that the perennial flows of the Indus and its Himalayan tributaries still flooded agriculturally viable lands, albeit less extensively than earlier. As a lesson from the past, the possible return to stronger monsoon-augmented floods (60), similar to the disastrous events of 2010 in Pakistan, may render current flood controls and irrigation systems vulnerable and require the large-scale adaptation of modern society in the western Indo-Gangetic Plain.



**Fig. 4.** Palaeo-hydroclimate reconstructions and sedimentary activity chronology for the Harappan domain. (A) Indian monsoon precipitation reconstruction (35). (B) Synthetic reconstructions for the Indian monsoon domain (black) and westerly precipitation (37) (gray). (C) Sedimentation ages for fluvial forms in: Sindh (i.e., Indus fluvial mega-ridge); Nara Valley; Indus-Panjinad-Ghaggar-Hakra confluence; Punjab incised valleys; Punjab interflues (doabs); and the lower and upper Ghaggar-Hakra (G-H) system regions, respectively. OSL dates are represented by triangles and calibrated AMS radiocarbon dates by circles; error bars are shown if larger than the symbol size. Fluvial deposits are shown in black- and white-filled symbols (for high vs. low sedimentation rate deposits, respectively), whereas dunes are represented by gray-filled symbols. Ages for the upper Ghaggar-Hakra system are from Saini et al. (33). The temporal extent of each Harappan phase is indicated by vertical dashed lines (E = early; M = mature; L = late).

### Methods

We used SRTM (22) data to map the Indo-Gangetic Plain, focusing on its western region (see *SI Text* for full methods). We identified active and abandoned river courses, incised valleys and interflues, terraces, fluvial ridges, alluvial fans, piedmonts, and dune fields. To avoid misinterpreting the morphology due to post-Harappan alterations of the Indo-Gangetic Plain via natural and anthropogenic processes, especially over the past century, we only interpreted features that retain a clear, large-scale SRTM topographical expression. Using SRTM-based digital elevation models, satellite photography, and geological maps, we selected key locations in Sindh and Punjab (Pakistan) to investigate the stratigraphy of the uppermost Indo-Gangetic Plain fill. Chronologies for fluvial and aeolian deposits in newly collected cores, trenches, and large-scale exposures in sand quarries were constructed based on accelerator mass spectrometry (AMS) radiocarbon and optically stimulated luminescence dating (*SI Text*). Location and age estimates of archaeological sites (*SI Text*) provided additional chronological information to assess the dynamics of fluvial environments.

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