Rainwater harvesting as an adaptation to climate change

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Extreme climate events such as aridity, drought, flood, cyclone and stormy rainfall are expected to leave an impact on human society. They are also expected to generate widespread response to adapt and mitigate the sufferings associated with these extremes. Societal and cultural responses to prolonged drought include population dislocation, cultural separation, habitation abandonment, and societal collapse. A typical response to local aridity is the human migration to safer and productive areas. However, climate and culture can interact in numerous ways. We hypothesize that people may resort to modify dwelling environments by adapting new strategies to optimize the utility of available water by harvesting rain rather than migrating to newer areas. We review recent palaeoclimatological evidence for climate change during the Holocene, and match those data with archaeological and historical records to test our 'climate change–rainwater harvest' hypothesis. We find correlation between heightened historical human efforts for construction of rainwater harvesting structures across regions in response to abrupt climate fluctuations, like aridity and drought. Historical societal adaptations to climate fluctuations may provide insights on potential responses of modern societies to future climate change that has a bearing on water resources, food production and management of natural systems.

COMPLEX and extreme climate events such as aridity, drought, heat wave, flood, cyclone, stormy rainfall or hurricane are expected to leave a much greater impact on human society than gradual changes in climate. As culture and climate are interlinked, there is a general human response to adapt and mitigate the sufferings associated with such climate extremes. Societal and cultural responses to prolonged drought include population dislocation, dwelling abandonment, widespread migration and state collapse[1–3]. A documented and predictable response to local aridity is the human migration to safer and productive localities[4,5]. However, climate and culture can interact in many ways. Here, we propose that rather than migration, people may also resort to modify the dwelling environments by adapting strategies to optimize the utility of available water by harvesting rain[6].

Where there is water on earth, virtually no matter what the physical conditions, there is life[7]. Water has been important for the development of cultural complexity in human society during the Holocene and earlier. Human ancestors have always used aquatic resources to their benefit[8], as we see the earliest association of hominid ancestors with lakes and pools dating back to 6 and 7 m.y. ago (Upper Miocene) from northern Chad, central Africa[9]. The earliest known hominids, *Sahelanthropus tchadensis*, may have exploited a significant aquatic fauna such as fish, crocodiles and amphibious mammals, along with primates, rodents, elephants, equids and bovids associated with gallery forest and savannah[10].

Natural springs, river valleys and coasts have remained favoured locations for both hominids[11–13] and modern humans[14]. Particularly, aquatic and maritime adaptations such as coastal occupation, fishing and seafaring played a significant role in demographic as well as geographic expansion of modern humans after about 150,000 years ago[15].

A comprehensive knowledge of climate fluctuations and corresponding adaptation by human society is crucial for our progress towards sustainability. We review published archaeological and historical records of rainwater harvesting systems and water management worldwide to understand the climate–rainwater harvesting link. Since we expect that adaptation through rainwater collection may be particularly effective in tropical monsoon regions, where the seasonal cycle in rainfall is large, we specifically examined both sacred and secular ancient texts as well as published scientific work to infer the relationships of 'climate change–rainwater harvesting' in India. Taking water as a central issue, a chronological history of India beginning circa 4500 BC to the present was constructed from the available literature.

A review of high-resolution studies documenting the Holocene climate change from multi-proxy data helped us to examine the behaviour of past climate, including the monsoons. Additionally, in order to obtain the collateral evidence from primary data for climate change and fluctuating rainfall over India, we reconstructed the monsoon winds for the past 4500 years using fossil *Globigerina bulloides* abundance in box cores, RC 2730

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(ref. 16) and ODP Site 723 (ref. 17), from the Arabian Sea (see refs 16 and 17 for detailed methodology). Then, we compared the periods of climate fluctuations and historical human efforts for rainwater harvesting (Table 1).

Holocene climate variability

For a long time, climate of the Holocene epoch (~ 11 kyr BP to present), compared to last glacial period (widely accepted dates for the Last Glacial are ~ 74 kyr and 14 kyr ago as given by the Intergovernmental Panel on Climate Change)[18], was considered to be stable. But that belief has been broken as detailed and well-dated worldwide palaeoclimate records have provided evidence of climate variability and extreme climate events such as aridity, drought, flood, cyclone, stormy rainfall and millennial-scale variation in climate during the Holocene. The most recent of these events was the Little Ice Age (LIA), which occurred during 1300–1850, reducing the subtropical sea-surface temperatures by 3° to 4°C (ref. 19). Indeed, pace of the Holocene events and of abrupt climate shifts during the last glaciation has been suggested to be statistically the same; together, they make up a series of climate shifts with a cyclicity close to 1470 ± 500 years[20]. These changes may have influenced some of the most momentous revolutions – for instance, evolution of cultural diversity[21], domestication of medicinal plants[22], crops and animals[23–25], and adaptive innovations through socio-economic development – in human history during the Holocene.

Shifts in early Holocene atmospheric CO_2 concentration[26] and abrupt early to mid-Holocene climatic transition have been registered both at the equator and the poles[27]. Holocene climate fluctuations as inferred from proxy records worldwide, including North Atlantic[28], western Canada[29], southwest Ireland[30], North America[31] and elsewhere are now well established[32].

Records of sedimentation in Laguna Pallcacocha, southern Ecuador suggest El Nino/Southern Oscillation (ENSO) variability on millennial timescales throughout the Holocene[33]. It is notable that El Nino events influenced prehistoric cultural development in Peru. The onset of El Nino events at 5.8 kyr ago is coincident with the beginning of a monumental temple construction on the Peruvian coast, and the increase in El Nino frequency after 3.2–2.8 kyr ago correlates with the abandonment of monumental temples in the region[34].

In addition, several extreme arid events and droughts have been documented in Asia[35], Africa[36], North America[37], and South America[38]. These may represent individual episodes in a recurrent pattern of dry events, but some events may be consistent with greenhouse gas forcing. For instance, failure of the winter and spring rains and increased temperatures led to drought during 1998–2002 over the Northern Hemisphere mid-latitudes across the United States, the Mediterranean, southern Europe, and Southwest and Central Asia. These droughts were linked through a common oceanic influence and were consistent with greenhouse gas forcing[39].

Climate fluctuations that we review here are not necessarily anthropogenic. Some proxies representing local climate at different places across the world reveal that the 20th century is probably neither the warmest nor a uniquely extreme climatic period of the last millennium[40]. A variable sun through changes in solar irradiance and processes such as biological regime shifts[41] may have caused the observed climate variability[42] and climate fluctuations over much of the Holocene[43]. Indeed, geophysical, archaeological and historical evidences support a solar-output model for climate change[44] during a large part of the Holocene. As inferred from biological and geological proxies, terrestrial palaeotemperature may have been higher[45] due to natural variability.

Just before the Holocene, SSTs increased by 3.5–4.0°C during the last two glacial–interglacial transitions, synchronous with the global increase in atmospheric CO_2 and Antarctic warming, but the temperature increase occurred 2000–3000 years before the Northern Hemisphere ice sheets melted[46]. Deglaciation lagged the melting of ice sheets in the Northern Hemisphere by millennia and may still be under way, and may remain so in the future[47]. Thus, before the twentieth century anthropogenic climate change[48,49] and its impacts[50] that we are witnessing, the last truly global climate change[51] occurred between 20,000 and 10,000 years ago. At the last Glacial–Interglacial Transition rise in tropical temperature was felt first, for example in the Andes[52] and the Indo-Pacific warm pool (ref. 46), propagation of warming signal from the tropics to drive ice-sheet melting in the Northern Hemisphere 2000 to 3000 years later that resulted in global rise in sea level of 120 m. There was a rise of atmospheric CO_2 by nearly 90 parts per million (p.p.m.), from a low of about 180 p.p.m. in glacial times[53] and parts of the earth warmed up by 10–12°C (ref. 51).

Climate change and human migration

The archaeological and historical records show many instances of societal collapse, attributed to a combination of social, political and economic factors[54]. However, recent studies have implicated climate change and drought as the primary agent in human migration, cultural separation, population dislocation and the collapse of prehistoric and early historic societies (see refs 1–5). Human migration due to climate change and environmental stress is a well resolved survival strategy across continents, including Africa[55], Eurasia, South America and Australia (refs 1–5).

Ice cores from Kilimanjaro provide an ~ 11.7 kyr record of Holocene climate variability for eastern equatorial Africa[56]. The periods of abrupt climate change shown

Table 1. Rainwater harvesting in response to climate fluctuations in India

Timescale	Period of climate change and aridity	Adaptation response for rainwater harvesting
ca. 4500 BC	The southwest (sw) monsoon started weakening after its peak intensification during 10–8 Kyr BP.	Origin of simplest earthworks in Thar desert, Rajasthan.
2894–2643 BC	2000 BC to 500 BC active monsoon conditions in the Indus Valley.	Definite evidence of human presence in Thar desert during 2894–2643 BC, i.e. even before the Indus Valley Civilization.
ca. 2600 BC	Weakening of the southwest SW monsoon.	Dholavira (Harappan civilization) develops rainwater harvesting systems such as tanks.
ca. 2300–1750 BC		Urban Harappan civilization develops earliest wells of their kind in South Asia; a sound agricultural base thrived because of rainwater harvesting and collection systems.
ca. 1600–1400 BC		Inamgaon chalcolithic settlement, near Pune, Maharashtra, provides evidence of artificial farm irrigation.
ca. 1500–1000 BC	Major weakening of the SW monsoon, increased and persistent aridity.	*Rigvedic* pastoral economy thrived in the presence of natural sources of water for cattle as well as earthworks constructed by early settlers in India.
ca. 1000–600 BC		Migration of people from early settlements along Indus to Rajasthan, Ganga Plain and Ganga–Yamuna Doab. Intensification of earthwork (Khadin) construction for farming in dry areas of Rajasthan with prior human occupations.
ca. 900–800 BC		Discovery and spread of iron technology provided impetus for forest clearing and start of agriculture in the Ganga Plain region. Although early farms were designed for *in situ* moisture conservation by erecting small earthen embankments, the later period saw increasing sophistication in rainwater collection, storage and distribution for agriculture.
ca. 600 BC		The rise of the Magadha empire and construction of earthworks for agriculture, and cultivation of aquatic nuts (*Trapa* species) in artificial earthworks (ponds).
ca. 324–185 BC		Refinement in theory and practice of rainwater harvesting during the Maurya period led to rapid agricultural development and geographic expansion of the empire. A period of sound emphasis by the rulers on the construction and management of a diversity of hydraulic earthworks for rainwater harvesting throughout the empire.
ca. 300 BC		Development of sophisticated irrigation system of tanks and canals in ancient Vidisha close to Sanchi. A rock-cut tank, located near the largest surviving Buddhist Stupa in which relics of the Buddha are believed to be present, could be one of the two oldest surviving tanks, second only to a now ruined tank in Bharahut, Central India.
ca. 324–300 BC		During the reign of Chandragupta Maurya, the arid Kathiawad region saw the construction of a large reservoir named Sudarsana. Subsequently, Ashoka repaired the lake and water distribution system for agriculture.
ca. 268–231 BC		Reign of Ashoka the Great. Large-scale water harvesting structures built.
ca. 200 BC–AD 200		Hydraulic earthworks to store excess floodwaters of river Ganga develop near present-day Allahabad.
ca. 185 BC–AD 300		Plough cultivation spreads in India aided by decentralized farms and associated earthworks that helped seasonal collection of rainwater within farms. Subsistence farmers themselves made irrigation earthworks and streamside wells that supplied water to farms. Some large community wells fitted with water-wheel and pitchers too, came into being. Sacred as well as secular texts of the period document management of water.
ca. 150 BC–AD 200		Sangam literature of Tamil Nadu provides records of paddy cultivation, watered by river and tank irrigation.
ca. 80 BC		The kingdom of Maues, the first Shaka king in western India thrives on water harvesting.
ca. 30 BC		Kalinga ruler Kharvela extended the canal in Orissa.
ca. AD 50–95		Flood control embankments (~ 2720 km) constructed by Karikal Chola in South India.
ca. AD 150–151	Major weakening of the SW monsoon (AD 200–600)	Junagarh inscriptions document the repair of lake Sudarsana by Rudradaman, the Shaka king ruling in western India.
AD 319–320		Establishment of the Gupta dynasty.
ca. AD 455–456		The embankment of lake Sudarsana repaired again.
4–8th century AD		Water bodies such as Dasmati sagar of Titilagarh, Darpan sagar, Bhanu sagar, Ram sagar, Bhoj sagar and Hira sagar of Patna state and Krishna sagar of Mayurbhanja constructed.
AD 505–550	Severe monsoon failure	Birth of Varahamihira, author of the ancient text *Brihatsamhita* (AD 550) that contains the most detailed prescriptions for construction of tanks and ponds.
AD 570–1335		The Vijayanagar or Anagudi kings (AD 570–1335) constructed numerous reservoirs in dry Dharwad.

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(**Table 1.** *Contd*)

Timescale	Period of climate change and aridity	Adaptation response for rainwater harvesting
ca. 4–12th century AD		Creation of new settlements and renewed efforts on the part of common people resulted in several hydraulic earthworks for farming, fish-culture and groundwater recharge throughout the country.
ca. 7th century AD		As the surface water becomes further scarce, step-wells develop in Gujarat and Rajasthan.
AD 724–761		Although earthworks were largely the responsibility of the common people, state initiative to alleviate sufferings from the flood and store rainwater for dry period, as described in Kalhana's *Rajatarangini*, was not uncommon. King Lalitaditya Muktapida (AD 724–761) is credited with hydraulic earthworks in Kashmir. Several innovative water-harvesting systems developed in dry areas of western India (Gujarat and Rajasthan).
AD 750–1300	Medieval Warm Period, wet phase in several parts of India (AD 800–1200)	In Tirunelveli district of Tamil Nadu, irrigated agriculture using temporary diversion-weirs to push water into small channels grew steadily under the Pandyan rulers.
mid 8th century AD		Bapparawal, the legendary founder of the Sisodia dynasty receives Chittor as part of the last Solanki princess' dowry. The fort of Chittor has 84 artificial water bodies (22 major water bodies still survive), including talabs, kunds, baoris and wells.
AD 784		Baoris, older than large water bodies but younger than kunds in rural landscape, are built in Jodhpur where the famous Mandore baori is constructed. Beginning of the step-well era, starting with pre-Solanki period (8–11th century), Solanki period (11–12th century), Vaghela period (mid-13–end-14th century) and the subsequent period that extended the construction. Step-wells are the advanced form of scoop holes (virdas) of Maldharis in Gujarat. Virdas are also excavated by nomadic rabari people.
9th century AD		The Gond people, the great early empire builders of India, rule throughout the eastern region of Central India up to Sambalpur, hence the name Gondwanaland. Throughout the kingdom earthworks such as katas, mundas and bandhas develop as main source of irrigation.
		Tanks of early medieval Chola and Pallava kingdoms in Tamil Nadu came into being and continue to harvest rain since. Rulers not only encouraged building of tanks, they also laid down the basic principles of management of earthworks (for example, King Rajendra Chola, AD 1012–1044). The Nitimarga inscriptions of 9th century describe Arakere (mini tanks constructed exclusively for temples called Devikere).
AD 950		In southern Karnataka, a large tank of earlier time, Betha Mangala repaired by King Iriva Nolamba.
AD 997–1030		Raids by Mahmud of Ghazni in northwestern India, which had by this time become prosperous with large-scale farming in khadins.
AD 1010–1055		Paramara ruler Bhoj creates one of the largest lakes of its time at Bhopal.
AD 1011–1037		Viranam tank, the largest in South Arcot district of Tamil Nadu, is believed to have been built by the Chola ruler Rajendra Chola I. The tank was fed by the Vadavar channel from the lower anicut on the Kollidam river.
AD 1020		Tomar king Anangpal founded the city of Delhi close to Surajkund, an area that had an embankment to impound rainwater from Aravali watershed.
AD 1050		Between ~ 1050 and 1900, 2333 large embankments constructed, including Bisalya tank made by Bisaldeo Chauhan.
AD 1052		Qila Rai Pithora, the forest capital city of the Sultanate thrived because of rainwater harvest, as there was no other alternative source of water.
AD 1095		Betha Mangala tank in southern Karnataka, again repaired by Chokkimatya, a general of the Hoysala prince Vishnuvardham.
AD 1096		Inscriptions of this period refer to a system of tanks at Kattagiri in Chengalpattu district of Tamil Nadu and describe the practice of constructing tanks in a series at different levels of a watershed.
AD 11th century		The Gond kings build Jagannath Sagar at Jeypore, Damayanti Sagar at Kotpad, Bali Sagar at Malkangiri and perhaps Dev Sagar in eastern India. Chandraditya Samudra of the Bastar–Koraput region is built. The Sulekere tank in Shimoga district is built by damming the Haridra in a narrow george (South India).
AD 1126		Lake Balasamand, one of the five large reservoirs, around Jodhpur city is constructed.
AD 1130–1211		Profusion of cascading earthworks numbering more than 50,000 in Karnataka evolved, that are operational even today.
AD 1150		Aana Sagar lake of Ajmer is built.

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(**Table 1.** *Contd*)

Timescale	Period of climate change and aridity	Adaptation response for rainwater harvesting
AD 1300–1700	Modest rainfall failure in 1230s, 1280s (Little Ice Age – 1350–1850 AD, weak SW monsoon).	The Deccan capitals of the medieval period develop extensive urban water-supply systems. Monsoon being the only source of water in the Deccan, some of the most notable networks of earthworks known to humanity are built here.
AD 1148–1150		Kalhana describes (in ancient text *Rajatarangini*) ancient and contemporary earthworks and irrigation management in Kashmir.
AD 1210–1236		A large tank, Hauz-e-Sultani near Mehrauli (Delhi) is built.
AD 1303		Alauddin Khilji constructed a reservoir in the plains of Siri (Delhi).
AD 1325–1351	Modest rainfall failure in 1330s.	Mohammad-bin-Tughlaq constructed a dam towering 64.9 m above ground level (Delhi).
AD 1336		Founding of the kingdom of Vijayanagara, notable for developing rainwater harvesting systems in South India.
AD 1345		Founding of the Bahamani kingdom.
AD 1351–1388		Alauddin Khilji (AD 1296–1316) excavated the Hauz-e-Khas at Delhi. Feroz Shah Tughlaq built five irrigation canals and several reservoirs and repaired earthworks of earlier times. Tughlaqs' period is particularly notable for building tanks, reservoirs and canals.
AD 1367		Gharsi Rawal builds the famous Gadisar tank in Jaisalmer. The Gadisar tank remained the chief source of water for Jaisalmer until 1965.
14th century AD		Nandyal tank was built by a Chola prince.
AD 1423–1474		Zain-ul-Abidin constructed/repaired canals and reservoirs (Delhi).
AD 1440–1518		The legendry poet Kabir writes extensively on sacredness of water.
AD 1451		Numerous reservoirs built in Ahmedabad, including the lake Kankariya by Sultan Kutub-ud-Din.
AD 1460		The oldest tank in Jodhpur, Ranisar constructed. Chand baori (and perhaps Bheru baori at Mandore, Jodhpur)
AD 1465		Jagu baori in Jodhpur built.
Late 14th century AD		The lake Pichola in Udaipur built.
AD 1489		The city of Bikaner was founded by Rao Bika. The choice of site was influenced by the availability of mudiya kankar, which has excellent runoff characteristics facilitating the harvesting of rainwater through an elaborate network of 40 tanks built by Rao Bika with more tanks being and added by every subsequent ruler.
AD 1490		Idgah baori in Jodhpur built.
AD 1495	Modest rainfall failure in 1530s and 1590s.	The modern city of Jodhpur was founded by Rao Jodha. While selecting the location of the city, the strategic potential of rainwater harvest seems to be the prime factor. Rao Jodha built the present Jodhpur fort with elaborate water-harvesting systems. Soon after 1460 (?), Ranisar lake was constructed by Rani Jasmeda. Padamsar was constructed by Baldia Seth in the memory of his father Padma in 1515. Rao Gangoji constructed Gangelao for the use of people residing around the fort, and in 1608 Raja Soor Singh laid the foundation stone of Soorsagar tank near Raoti. Balsamand lake, which had been constructed much earlier in 1159 by the banjara king, Raja Balkaran Parihar, was further extended by Maharaja Soor Singh ~ 1611, and again extended by Maharaja Jaswant Singh, in whose reign (1638–1678) several other water bodies were also constructed.
15th century AD		The founder of modern Bangalore (King Kempe Gowda) promotes a series of tanks in Bangalore.
AD 1500 onwards		Construction of tanks, wells and bawadis in urban areas of Kota and Bundi in Rajasthan. Both rulers and people constructed and repaired tanks in ~ 3000 villages in eastern Rajasthan.
AD 1509		Rana Sanga of Mewar built baoris, tanks and ponds.
AD 1509–1530		Krishna Deva Raya, the great emperor of the Vijayanagar empire: his fundamental principle for water management suggests that the tanks and embankments alone can enhance the prosperity of a small kingdom. This was also the main period of tank construction in Andhra Pradesh and neighbouring areas of Karnataka (more than 58,000 tanks still survive in 2002).
AD 1520		First recorded masonry nadi was constructed near Jodhpur during the regime of Rao Jodhaji. Most villages had their own nadis. Padamsar tank constructed in AD 1520 continues to serve the people of contemporary Jodhpur.
AD 1559–1565		Rana Udai Singh builds Udaisagar lake with annual irrigation capacity of 607.5 ha.
AD 1575		The Hussainsagar lake in Hyderabad is built by Sultan Ibrahim Kutub Shah.
16th century	Monsoonal activity increases, yet AD 1600 onwards droughts become more frequent	The Timmanayapet tank was built by Pemmasani Timma Nayadu, the Governor of Gandikota in southern India.

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Timescale	Period of climate change and aridity	Adaptation response for rainwater harvesting
AD 1607		First record (but not the record of first existence) of construction of Kund in Jodhpur by Raja Surajsingh in village Vadi-ka-Melan.
AD 1627		The Kasar lake at Pen (Konkan) is built.
AD 1627–1658	Modest rainfall failure in 1640s (the SW monsoon shows increased strength since ~ AD 1600).	The city of Delhi shifted from Aravali hills to the plains of the river Yamuna. Red Fort (AD 1639–1640) is built during the reign of Shahjahan; waters of Yamuna brought to Delhi through elaborate engineering arrangements.
AD 1633		Numerous canals (e.g. Badshahi Nahar) constructed under the instructions of the Mugal Emperor Shahjahan, including Hasli canal, which was later repaired to feed the sacred tank of Amritsar. Two reservoirs in Mamdapur (Bijapur) constructed.
AD 1643		Mardan Ali Khan begins the construction of Rohtak canal by diverting waters to Delhi from the old channel constructed for the irrigation of the hunting ground of Hissar Firoza.
AD 1662–1676		Rajsamand in Rajasthan built by Rana Raj Singh in the famine relief work with just 15 lakh rupees.
AD 1685–1691		The Dheber lake or Jaisamand lake built by Rana Jai Singh II. The lake irrigated 4860 ha.
AD 1698–1728		Reign of Kanhoji, the Raja of Konkan; the Pathardi reservoir excavated.
AD 1740–1820		Canal flowing through Chandini Chowk (Delhi) was revived repeatedly by the rulers. Finally in 1890, the canal was closed in the walled city.
AD 1750		Reservoirs such as Akshi, Khavandal and Chamber are built in Konkan area. Puthen dam in Kerala built to raise the waters of Paralayar up to 6 m from the bed of the river. This is the principle source of water supply to present-day Kalkulam taluka.
AD 1759		Kund in Mehrangarh Fort in Jodhpur constructed during the reign of Udai Singh.
AD 1756–1763		The urbanization of Deeg, the erstwhile capital of the Jat rulers of Bharatpur, started by Raja Badan Singh; palace constructed during the time of his son Surajmal had elaborate arrangements for rainwater harvesting.
AD 1773		Raja Raghoji Angaria builds the Shree Nageswar reservoir at Nagaon in Konkan.
AD 1775–1780	Severe monsoon failure in 1790s resulted in exceptional aridity.	The field embankments locally known as Shilotris are an integral feature of agriculture in Colaba and Thane districts, made to keep out the tidal waters. In Colaba district, most of the embankments have been built during this period by Angaris and partly by Shilotridars (dam keepers).
AD 1780–1877		Five major tanks of Jodhpur were built: Fatehsagar, 1780; Gulabsagar 1794; Baiji-ka-talab, 1877; Mansagar 1870; Paota, 1887.
AD 1796–1818		Ashtami lake, Sangada, Vasi and Vadav reservoirs and the stone pond at Medha are built during the reign of Peshwa Bajirao.
Early- and mid-1800s AD	A pause in the SW monsoon during ~ 1800 to 1900.	A number of anicuts to divert water into irrigation channels across rivers are constructed in South Arcot district of Tamil Nadu, though some of them were of considerable antiquity.
AD 1800		Lalsagar, one of the five large reservoirs around Jodhpur city, constructed.
AD 1856–1885		The technique of constructing pucca tanks with ornamental designs is found in profusion. Jaswantnagar talab located outside the city boundary of Jodhpur, the youngest in a series of 46 tanks in Jodhpur was built.
AD 1866	The great famine of 1870 in India is reflected in palaeoclimatic records	The year of Orissa Famine
AD 1872		Kailana, one of the five large reservoirs around Jodhpur city, constructed.
AD 1873–1874		The year of Bihar Famine.
AD 1874		By this time, Konkan had numerous artificial lakes and reservoirs, built by old Hindu rulers. Kulava had 15 large reservoirs. A masonry dam is built to carry water for irrigation.
AD 1876–1877	Severe SW monsoon failure in 1876–1877; exceptional aridity.	Great impetus was given to water-supply schemes during the reign of Maharaja Jaswant Singh II (1872–1895), when Kailana was constructed in a famine year. Ranisar and Balsamand embankments were erected and canals constructed to feed the city tanks.
AD 1877–1879		Droughts of 1877–1879 triggered the adaptation responses among rulers and common people who not only undertook large-scale efforts in repair of rainwater-harvesting systems built earlier, but also invested resources in new ones throughout the country.
AD 1877–1880		The main tanks in Jammu city were built.

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Timescale	Period of climate change and aridity	Adaptation response for rainwater harvesting
AD 1880		Shiv baori, perhaps the youngest among baoris in Jodhpur, built.
AD 1884–1886		Rajsamand, built earlier in the famine relief work in 1662–1676, now gets canals to irrigate farmlands.
AD 1885		Jaswantsagar talab in Jodhpur, built.
AD 1895–96		Great famine in Jodhpur, large-scale construction of kunds follows. A single village, for example, Jalwali (situated between Bikaner and Anupgarh) has nearly 300 kunds.
AD 1896–1897		The year of Bihar Famine. Interestingly, Gaya district did not require any relief work because of the elaborate, traditional rainwater harvesting systems.
AD 1897		The worst drought and famine of 19th century; Sambalpur remains unaffected because of the early earthworks of Gond chiefs.
19th century AD		The Katte system of artificially created embankments for storage of water in Karnataka develops. A series of tanks built earlier in Karnataka were found functional.
AD 1931		Ummedsagar, one of the five large reservoirs surrounding Jodhpur city, constructed.
AD 1932		Takhatsagar, one of the five large reservoirs around Jodhpur city, constructed.
AD 1999	Hottest summer of the 20th century over northwest and central India that surpassed the records of warm summers in 1892, 1921, 1931, 1941, 1958, 1973, 1980 and 1988.	Bhopal lake suffered one of the lowest water stands. Bhoj Wetland Project commenced moving unprecedented quantity of silt from the impounding area to the upper hill areas. In Central India, a massive administrative programme of rainwater harvesting resulted in desilting of more than 50,000 village ponds and tanks.

Source: Constructed from the references (palaeclimatological, archaeological and historical sources) cited in the text.

in ice cores include ~ 8.3, ~ 5.2 kyr ago, and a third period, ~ 4 kyr ago coinciding with the 'First Dark Age' known for the most severe drought in tropical Africa. In a more recent history, effects of variable precipitation and drought in equatorial east Africa during the past 1100 years bear links with climate change and cultural effects[57]. Oral traditions as well as scientific evidence both indicate drought-induced famine, political unrest and large-scale migration of native population, and establish strong connection between cultural development, climate change and water stress (see ref. 57).

Recently, a robust study by Nunez *et al.*[4] found widespread evidence for human occupation influenced by water availability in the Atacama desert in northern Chile from 13,000 calibrated ^{14}C years before the present (cal yr BP) to 9500 cal yr BP, and again after 4500 cal yr BP. Initial human occupation coincided with a change from very dry phase to a humid phase. Archaic open campsites at elevations above 3600 m show that humans lived around late Glacial/early Holocene palaeolakes on the Altiplano. Human use of these sites was terminated between 9500 and 4500 cal yr BP due to drying of the lakes. The fact that climate change was instrumental for human occupation and abandonment of the area also provides support to proposition that early people in the Atacama region focused on favourable, humid habitats such as lakes, springs and streams[58].

Climate change and rainwater harvesting

We now turn to our proposed hypothesis that in a changing climate people may resort to rainwater harvesting and continue to occupy homelands rather than migration. History tells us that cultures do not give up until they have exhausted options for survival over the area they occupied for longer period. Before we explore widespread evidence of rainwater harvesting as an adaptation to climate change in India, we briefly explore global evidence for possible correlation between heightened historical human efforts for construction of rainwater harvesting structures across cultural landscapes throughout the human history in response to aridity and drought conditions.

South America

Several studies note climate variability over the continent[59]. A 10,000-year simulation study over Mexico suggests that a 'megadrought' and thirteen other devastating droughts lasting over a decade resulted in 20 to 40% reduction in rainfall and occurred with a return period of less than 1000 years[60].

The Mayan civilization is a case in point, which developed around 3000 years ago in Mesoamerica[61], and faced recurrent droughts due to solar forcing[62] before it collapsed due to climate deterioration towards the end of the Classic Period. A recent study[63] has shown that the collapse of the Mayan civilization in the Terminal Classic Period occurred during a spatio-temporally extensive dry period in the region, interspersed by more severe droughts centred at about AD 810, 860, and 910. What was the Mayan response to these oscillations before collapse? Indeed, a water storage adaptation in the Mayan region[64].

Ancient reservoir technology developed by the Mayan people in the seasonally dry tropics of southern Maya lowlands reveals that rainwater storage was a major source of water supply during the dry season. Reservoirs were constructed, for example, in Tikal to cope with seasonal scarcity of water. There were at least three distinct types of reservoirs as documented by Scarborough and Gallopin[64]: centrally located reservoirs, residential reservoirs and margin reservoirs. The nomenclature is essentially based on location of the reservoir and the differential capacity to store water. Similar water collection and storage have been documented in other areas of South America[65–68] as well.

Ancient man-made earthworks of Bolivian Amazon are another example of adaptation. The crucial factor that facilitated early domestication of palms and harvest of fish was construction of large-scale earthworks such as documented by Erickson[68] in the Bolivian Amazon. A complex man-made network of hydraulic systems and fish weirs covering 525 km^2 in the ancient landscape of Baures region of Bolivia is a classic example of rainwater collection that provided sufficient animal protein and palm fruits to feed large and dense populations in an arid savanna.

North America

There are numerous studies that have documented abrupt climate change[69], extreme drought conditions[70] and storminess[71] over North America during the Holocene. The 'Dust Bowl' drought severely impacted USA during 1934, 1936, and 1939–40. Recent studies of longer term US Great Plains drought variability over the past 2000 years with the use of palaeoclimatic data imply that no droughts as severe as those of the 1930s have occurred since the 1700s (ref. 72). A particularly notable example[70], supported by tree-ring climatic data, is the Lost Colony of Roanoke Island, which disappeared during the most extreme drought in 800 years (AD 1587–89). The appalling human deaths and the near abandonment of Jamestown Colony occurred during the driest 7-year episode in 770 years (1606–12).

In agreement with our hypothesis, existence of more than 2.6 million small, man-made water bodies accounting for ~ 20% of the standing water area in USA[73] may be the result of adaptation response to climate fluctuations. In addition, on the Southern High Plains, when surface water sources dried up due to most intense drought, substantial adaptive strategies, including well-digging[74] were employed by human society during the Holocene. Indeed, the discovery of a prehistoric well excavated in response to drought during the Pleistocene–Holocene transition by the Clovis people around 11,500 BC is the oldest prehistoric well in America[75]. The Clovis well is also among the first evidence of water harvesting–groundwater in this case–as an adaptation to climate change. The excavation of wells near regions which had surface water shortly before has been posited as the evidence for drought during the Pleistocene–Holocene transition[75].

Arabian Peninsula

Increasing depth of wells through time found at archaeological sites in Hili near Al Ain, United Arab Emirates, is in concordance with increasing aridity and consequent decline in groundwater levels for the past 4500 years[76]. In southern Arabia's highland Southern Jol, McCorriston and Oches[77] have documented and dated early water impounding structures, with important implications for prehistoric Arabian resource management and food production. In the Wadi Sana and its Wadi Shumlya tributary, checkdams (water-impounding structures) have been discovered buried in silts deposited 13,000–5000 years ago. While use of checkdams for agricultural activities in this region cannot be ruled out, the Wadi Sana archaeological remains of water storage adaptation are older than known ancient Arabian agriculture. Other purposes for which they might have been built could be flood control (another example of adaptation to extreme climate event), enhancement of pastures and promoting vegetation growth.

Climate fluctuations and rainwater harvest in India

Holocene climate fluctuations, including large spatial variation in Holocene monsoon and temperature over India are now well-resolved from various climate change proxies (refs 78–85; see also ref. 86).

Folk sayings such as 'capture rain where it rains' may have originated in response to increased aridity in the Indian region over the last few millennia. Such climate fluctuations may have given rise to traditional village tanks, ponds and earthen embankments numbering more than 1.5 million, that still harvest rainwater in 660,000 villages in India (ref. 6) and encourage growth of vegetation in commons and agroecosystems.

A somewhat coherent, although unresolved, picture that emerges for India is as follows: as the aridity increased in the region as is evident from palaeoclimatic studies[87–91], people intensified rainwater harvesting as is seen from archaeological and historical evidences[92–94] (see Table 1). Indeed, a specific emphasis through the long sweep of history on management of rainwater harvesting systems in ancient texts, such as *Rigveda* (1500 BC), *Atharva Veda* (800 BC), Kautilya's *Arthasastra* (300 BC), Varahamihira's *Brihatsamhita* (AD 550), and Kalhana's *Rajatarangini* (AD 1148–1150) may document adaptation to fluctuating climate (see Figure 1). We expect documentations in ancient texts of other continents as well, though we do not probe that in any detail.

In the Indian subcontinent, climate change in western India has been studied in relatively greater detail than in other parts. Detailed chronology of the Thar desert in western India based on lacustrine deposits[95] suggests that the climate for the past 5000 ^{14}C years has remained dry. Yet, humans were present in the region during 4230 ± 55 years BP (2894–2643 BC) even before the Indus Valley Civilization (4100 to 3500 ^{14}C yr BP or 2600 to 2000 BC).

The antiquity of human occupation of Thar desert goes back to late Pleistocene as indicated by the discovery of hand axe from Late Acheulian site and microlithic site with pottery of early- to mid-Holocene (i.e. between 7 and 6 kyr ago)[96]. Even after the disappearance of river Saraswati[97,98] due to drainage disorganization[99] and subsequent increase in aridity[100], people continued to occupy the region by adapting to climate change through rainwater harvesting. Indeed, the post-Saraswati society that developed in the Thar desert is essentially a rain-harvesting society. For instance, archaeological evidence indicates presence of ponds, tanks and step-wells in several areas once occupied by the people of Indus-Saraswati civilization (Table 1). Today, Thar is the most densely populated desert in the world and every settlement there has often more than one water collection pond and numerous earthworks to harvest rain developed over the last 5500 years of continuous and dynamic adaptation to climate change.

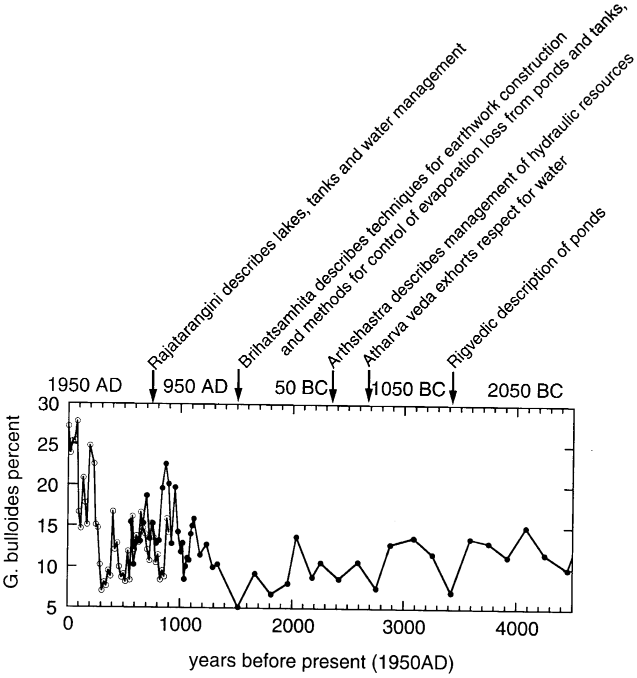

Figure 1. Monsoon winds reconstructed for the past 4500 years using per cent fossil *Globigerina bulloides* in Arabian Sea Box core RC 2730 (open circle)[16] and ODP 723 (solid circle)[17]. Weak summer monsoon winds are indicated by low abundances of the plankton *G. bulloides* in the Arabian Sea. Arid episodes correlate well with ancient Indian texts composed during those times containing descriptions of earthworks that may document aridity prevailing then: *Rigveda* (BC 1500, although dating of text is still unresolved), *Atharva Veda* (BC 800), Kautilya's *Arthasastra* (BC 300), Varahamihira's *Brihatsamhita* (AD 550), Kalhana's *Rajatarangini* (AD 1148–1150).

There is other evidence to support our climate change–rainwater harvesting hypothesis. Himalayan ice core data (ref. 82) suggest several periods of drought in the South Asian region. Many of these were with modest rainfall failures (1230s, 1280s, 1330s, 1530s, 1590s and 1640s), but two (1790s and 1876–77) were the most severe with exceptional aridity in the last 1500 years. Consequential cultural response to such a fluctuating climate is reflected in archaeological and historical records of heightened activity of widespread earthwork construction for rainwater harvesting across social strata (Table 1). Majority of palaces and forts (perhaps all) constructed during the 13–18th century developed elaborate water-harvesting systems. A spurt in activity is also evident in large-scale efforts for repair of ancient earthworks, particularly during late 17th and 18th century (Table 1).

During the Neolithic period (5000–3000 BP), people in the Deccan Plateau were just starting pastoralism and settled agriculture (ref. 89); it was also the time when aridity had started to set in during 5–2 kyr BP (ref. 90). No wonder then, as we list in Table 1, people in the Deccan Peninsula developed some of the most extensive and intricate rainwater harvesting systems known to humankind.

Contemporary relevance of rainwater harvesting

As a sound adaptation, why does rainwater harvesting matter more today than any other time in the Holocene? There are several reasons, as Jackson *et al.*[101] note: (1) over half of the accessible freshwater runoff globally is already appropriated for human use; (2) more than 1×10^9 people currently lack access to clean drinking water and almost 3×10^9 people lack basic sanitation services; (3) because the human population will grow faster than increases in the amount of accessible freshwater, per capita availability of freshwater will decrease in the coming century; (4) climate change will cause a general intensification of the earth's hydrological cycle in the next 100 years, with generally increased precipitation, evapotranspiration, occurrence of storms and significant changes in biogeochemical processes influencing water quality. Humanity now uses 26% of the total terrestrial evapotranspiration and 54% of the runoff that is geographically and temporally accessible. New dam construction could increase accessible runoff by about 10% over the next 30 years, whereas the population is projected to increase by more than 45% during that period[102]. Under such circumstances, harvesting rain shall be crucial.

Furthermore, as mentioned earlier, the climate fluctuations which we review here are not essentially anthropogenic. However, in future the case may likely be driven perhaps more by humans than nature. Burning of the fossil-fuel and deforestation have emerged as principal anthropogenic sources of rising atmospheric CO_2 and consequential global warming observed in late 20th century. Recent anomalies in temperature, precipitation, snow cover, sea level and extreme weather conditions provide collateral evidence of anthropogenic global climate change. Particularly, now globally coherent fingerprints of global warming and climate-change impacts across natural systems are becoming clearly visible[103,104]. With more than 99.9% confidence level, it can now be said that the rate of annual warming for global land areas over the period 1901–2000 was 0.07°C per decade[105]. As summers get hotter and hotter[106], and anthropogenic climate changes exert further strain on economic, social and natural systems[107,108], water scarcity is likely to grow in India and elsewhere. Addressing water problem holds the promise in future for a world compounded by climate change, growing population[109] and decreasing water-impounding area of traditional tanks due to urbanization[110].

In addition, extreme climate events are registering an increasing trend. A significant proportion of the global land area has been increasingly affected by a significant change in climatic extremes during the second half of the 20th century[111]. In India, wintertime rainfall may decline by 5 to 25% and may lead to droughts during the dry summer months in coming decades[112]. Thus, we will have to take into account the large-scale, natural climate variations as well as human-induced climate change in the management of natural, social and economic systems. If extreme climate events increase in future due to climate change, human society will use different means of adaptation. Additionally, regardless of climate fluctuations, population growth will put extra stress on natural resources.

Alternative to ecologically damaging, socially intrusive and capital-intensive water management projects that fail to deliver their desired benefits, it would be useful investing in decentralized facilities, efficient technologies and policies, and human capital to improve overall productivity rather than to find new sources of water supply[113,114]. Such efforts would need to be encouraged with innovative policy regimes that concurrently promote rainwater harvesting.

Traditionally, such systems have been integrated with agroforestry and ethnoforestry practices, and remain useful in contemporary conservation and ecological restoration of degraded ecosystems[115,116]. A systematic support to local innovations on rainwater harvesting could provide substantial amounts of water. For example, a hectare of land in an arid region with just 100 mm of rainfall annually, could theoretically yield 1 million litres of water per year from harvesting rainwater. Simple local techniques such as ponds and earthen embankments that we have reviewed here can help in harvesting and storage of rain (see Figure 2).

Rural and urban water use, restoration of streams for recreation, freshwater fisheries, and protection of natural ecosystems are all competing for water resources earlier dedicated to food production[117]. Under such circumstances, decentralized rainwater harvesting adaptations prove efficient. For instance, in the Negev Desert, decentralized harvesting of water in microcatchments from rain falling over a 1 ha watershed yielded 95,000 l of water per hectare per year, whereas collection efforts from a single large unit of a 345 ha watershed yielded only 24,000 l per hectare per year. Thus, 75% of the collectible water was lost as a result of the longer distance of runoff[6,118].

Traditional systems would become more efficient if scientific attempts are combined to enhance the productivity of local knowledge[115], as has been attempted in China[119]. But some local technologies may already be at par with scientific attempts. For instance, the indigenous *teras* water-harvesting system in Sudan offers agricultural production security and also raises the nutrient-limited yield from ~ 150–250 to ~ 650 kg ha^{-1} through its nutrient-harvesting effects[120].

Widespread arsenic poisoning[121–127] is another case in point where rainwater harvesting has great potential as a possible solution. In West Bengal and Bangladesh, alluvial Ganges aquifers used for public water supply are polluted with naturally-occurring arsenic, which adversely affects the health of millions of people by causing arsenicosis[128] and increasing the risk of cancer. Millions of people are at risk in Bangladesh alone[129]. Arsenic mobilization is associated with the advent of massive irrigation pumping that draws relatively young water directly into the aquifer[130]. Deep wells are being advocated as a remedy, that may provide a source of clean water; but the solution is only a provisional one. Rainwater harvesting is a better option to provide arsenic-free, safe water in a cost-effective and accessible manner, particularly for drinking and food preparation.

We must, however, address several challenges effectively to make rainwater harvesting efficient, particularly treatment of harvested rainwater in areas where pollution is rampant[131]. For instance, it is now possible to use nanofiltration for the removal of hardness, natural organic material, micropollutants such as pesticides, viruses and bacteria, salinity, nitrates and arsenic[132]. With an insightful policy, rainwater harvesting can be promoted as a core adaptation strategy for achieving the global security and sustainability of water resources in an era of anthropogenic climate change.

Conclusions and the way forward

Clearly, over thousands of years, people living in various geographical and climatic regions of the world have evolved diverse, indigenous rainwater harvesting and management regimes as an adaptation to climate change. Some of these practices continue to remain in use, particularly in South Asia. Rainwater harvesting in South Asia differs from that in many parts of the world – it has a history of continuous practice for at least the last 8000 years. As we noted, although hydraulic earthworks are known to have occurred in ancient landscapes in many regions, they are no longer operational systems among the masses in the same proportion as in South Asia.

The antiquity of rainwater harvesting as an adaptation to climate change in India is deep. In a fluctuating Holocene climate, rainwater harvesting by early farmers may have been pivotal for emergence and diversification of food production. Future studies should concentrate on cultural responses to climate change with economic implications, such as the role of rainwater harvesting in plant and animal domestication that may have shaped the evolution of cultural landscapes, agroecosystems and early agriculture. Construction of early rainwater harvesting systems required simple scooping of the earth and putting up embankments or erecting elongated soil heaps along farm boundaries. But, the benefits of such innovations for early farmers may have been substantial.

Earliest examples of rainwater systems in India include the havelis of Jabalpur, bandh and bandhulia of Satna, virda of Gujarat, khadins of Rajasthan, ahar-pynes of Bihar, eri of Tamil Nadu, dhora of Aravalis and similar other earthworks throughout the country. As these earthworks still continue to survive and serve society, scientific studies such as ^{14}C dating of sediment cores of ponds, tanks and lakes would be useful to understand the dynamics of rainwater harvesting and climate relationship in diverse geographic regions across India.

Rainwater harvesting in response to climate extremes enhances the resilience of human society. In a world confronting local and global changes, building resilience of human society to absorb shock, learn and develop[133,134] would depend on sound knowledge of the historical adaptive processes that are still functional.

An integrated perspective of traditional knowledge on adaptation strategies, such as the rainwater harvesting system, is particularly useful to comprehend vulnerability and adaptation to environmental stresses at the local scale. Local studies on risk management and decision-making can complement global climate modelling exercises in order to fully capture the complexities of real life[135,136].

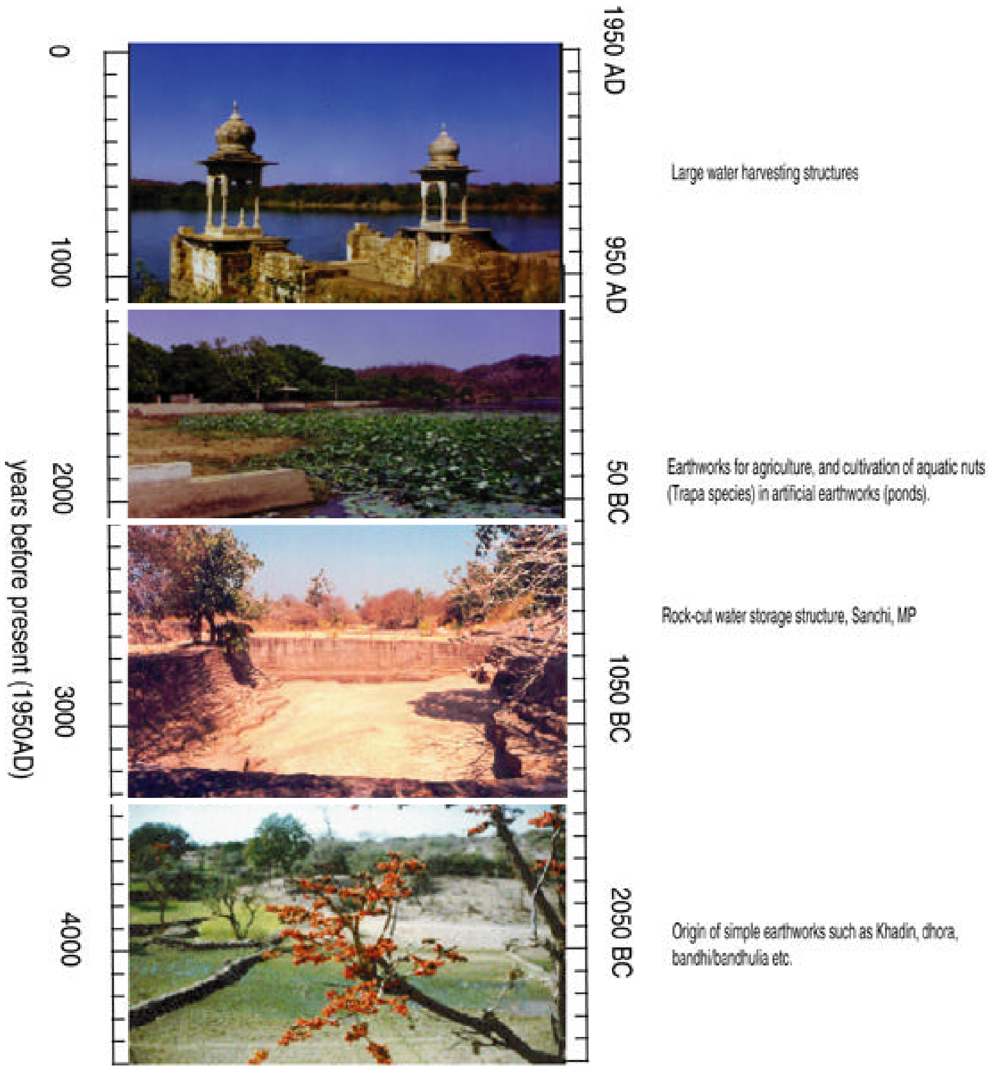

Figure 2. Schematic representation of increasing complexity of rainwater harvesting in India as an adaptation to climate change.

Although rainwater harvesting continues to be practised globally, and there is renewed interest in its revival, the system nonetheless has fallen to disrepair. It would be worthwhile to investigate whether declining interest in this time-tested adaptation, in India for example, is due to economic reasons or a climatic response to increasing strength of southwest monsoon during the past 400 years. Whatever the case, climate policy and water policy would require to be streamlined to promote rainwater harvesting in the water-stressed regions of the world. We believe that neither the water policy nor the climate policy discussions seem to notice the worth of rainwater harvesting as an adaptation to climate change, especially in urban areas where water resources are fast depleting due to rapid increase in population and unrestricted use of water. Studies of historical societal adaptations to climate fluctuations provide insights into possible responses of modern societies to future climate change and sustainable management of water resources.

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