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An interdisciplinary framework for using archaeology, history and collective action to enhance India's agricultural resilience and sustainability

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Abstract

South Asia has a deep history of agriculture that includes a range of past farming systems in different climatic zones. Many of these farming systems were resilient to changes in climate and sustainable over long periods of time. India's present agricultural systems are facing serious challenges, as they have become increasingly reliant on the unsustainable extraction of groundwater for irrigation. This paper outlines an interdisciplinary framework for drawing on patterns from the past to guide interventions in the present. It compares past and present strategies for water management and use in semi-arid and temperate Punjab with equatorial Telangana. Structural differences in water use in these two regions suggest that a range of interventions should be adopted to expand the overall availability of surface water for agricultural systems in India, in combination with empowering local communities to create their own water management rules. Active interventions focus on the efficient use of water supplies, and increasing surface water availability through renovation of collective ponds and reservoirs. We argue that this conceptual framework has significant potential for guiding agronomic and economic interventions in the future.

1. Introduction

Water-stress is a global problem that is exacerbated by unsustainable irrigation practices. This problem is particularly acute in India, where water availability per person is low in some regions (e.g. Chellaney 2011), but irrigated land area has increased substantially since 1950 as part of the Green Revolution (figure 1) (Shah 2009, Government of India 2013 irrigation). Increased irrigated land area was designed to boost agricultural yields, but also required increasing the number of bore wells that bring groundwater from the aquifers into fields (e.g. Zaveri *et al* 2016). This atomized water management strategy is now used to grow the water-intensive crops favored by state level policies, such as minimum support prices and irrigation subsidies, which over-exploits aquifers that are slow to recharge (Mishra *et al* 2018, Vatta *et al* 2018, Sarkar 2020). In addition to generating environmental challenges, the use of groundwater in agriculture has fueled disparities in regional development (e.g. Pingali *et al* 2019). It has long been argued that South Asia's past farming systems incorporated diverse cropping strategies (e.g. Petrie and Bates 2017) and water management strategies (e.g. Bardhan 2000, 2001) that were more sustainable. The goal of this paper is to present an interdisciplinary framework for using these patterns from the past to offer insights into how interventions might increase sustainable water management in India today.

The deep history of agriculture in South Asia suggests that a range of water management strategies were sustainable in the past. South Asian agriculture began more than 5000 years ago (e.g. Fuller 2006), and since its beginning in periods long pre-dating written records, it has incorporated a wide array of

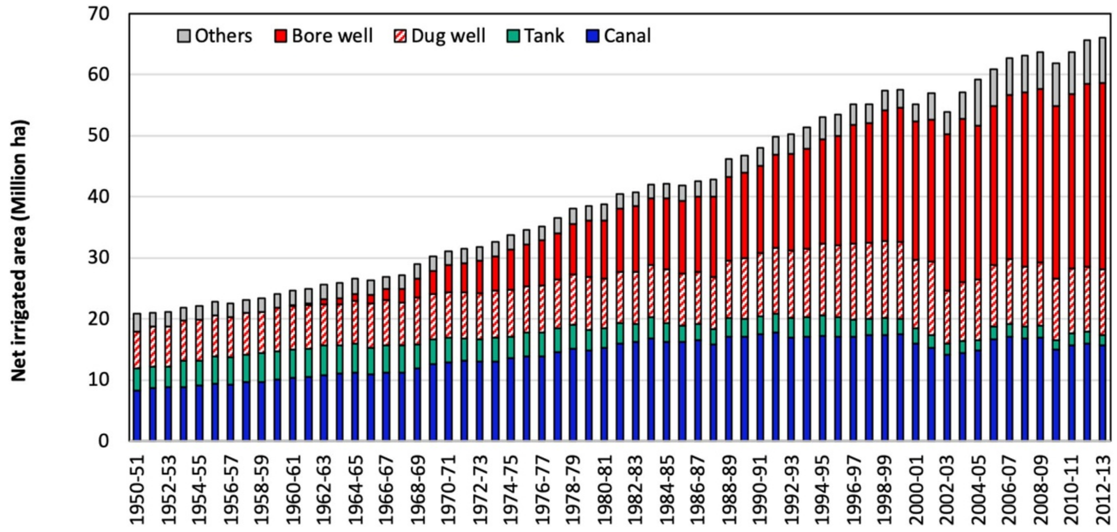

Figure 1. Source wise irrigated area between 1950 and 2012 in India (Government of India).

water management strategies (e.g. Miller 2015, 2006, Bauer and Morrison 2008, Morrison 2009). Most focused on the use of surface water, derived primarily from precipitation that either charged hydrological systems or filled open reservoirs such as ponds, lakes, or anthropogenic 'tanks' (Reddy *et al* 2018). This water was then used to grow a diverse range of crops. The institutional arrangements, social relations, rules and infrastructure of these past water management and use systems have the potential to inform contemporary agriculture. As such, water management and use practices from the past comprise an under-explored heritage that can contribute to a sustainable future (e.g. Koohafkan and Altieri 2011, Winter 2013, Harrison 2015, Harvey 2015).

2. An interdisciplinary framework for looking to the past to enhance India's agricultural resilience and sustainability

The deep past can be used to identify lessons for interventions designed to increase the sustainability of water management in Indian agriculture. Toward this end, the TIGR^{2}ESS Project, a collaborative international agriculture project that seeks to improve water use and management in India's changing monsoon climate, has developed an interdisciplinary framework designed to connect patterns from the past with interventions in the present (figure 2). This framework incorporates collective action theory (e.g. Ostrom 1990), which considers how people engage in the collective management of a common resource, to investigate the broader social and environmental contexts of water management and use, asking at which scale decisions are made. We also incorporate lessons from long-term patterns of social and environmental sustainability in past water management. The resulting framework links patterns from the past to interventions in the present, considering the implications of contrasting past water management practices of different regions, past collective water management strategies that have the potential to offer advantages over present atomized water management strategies; and local-level cooperation in water management that have the potential to facilitate sustainable surface water use in both semi-arid/temperate and equatorial settings. We argue that to improve the long-term resilience and sustainability of Indian farming systems, we should aim to revive surface water supplies from the past, reduce demand on those water supplies, and increase the efficiency of their use by empowering their local management, monitoring, and distribution.

3. Dangers to the sustainability of India's agriculture

There are contradictions within India's present agricultural system. South Asia is characterized by contrasting climate zones, which have a profound impact on water availability during winter (*rabi*) and summer (*kharif*) growing seasons. Winter precipitation largely falls in the Himalayas, charging the hydrological system of northern South Asia by filling its rivers and watercourses. In contrast, the Indian summer monsoon increases the availability of precipitation during the summer months, and falls across south, central and western India in addition to the Himalayas. Different crops are appropriate in each season, and in the past it has often been possible to produce multiple crops inside a single year (Devendra and Thomas 2002, Petrie and Bates 2017). For example, wheat and barley thrive in the *rabi* season (around October–March), and thus make the most of winter rains, and rice and millets are better suited to the

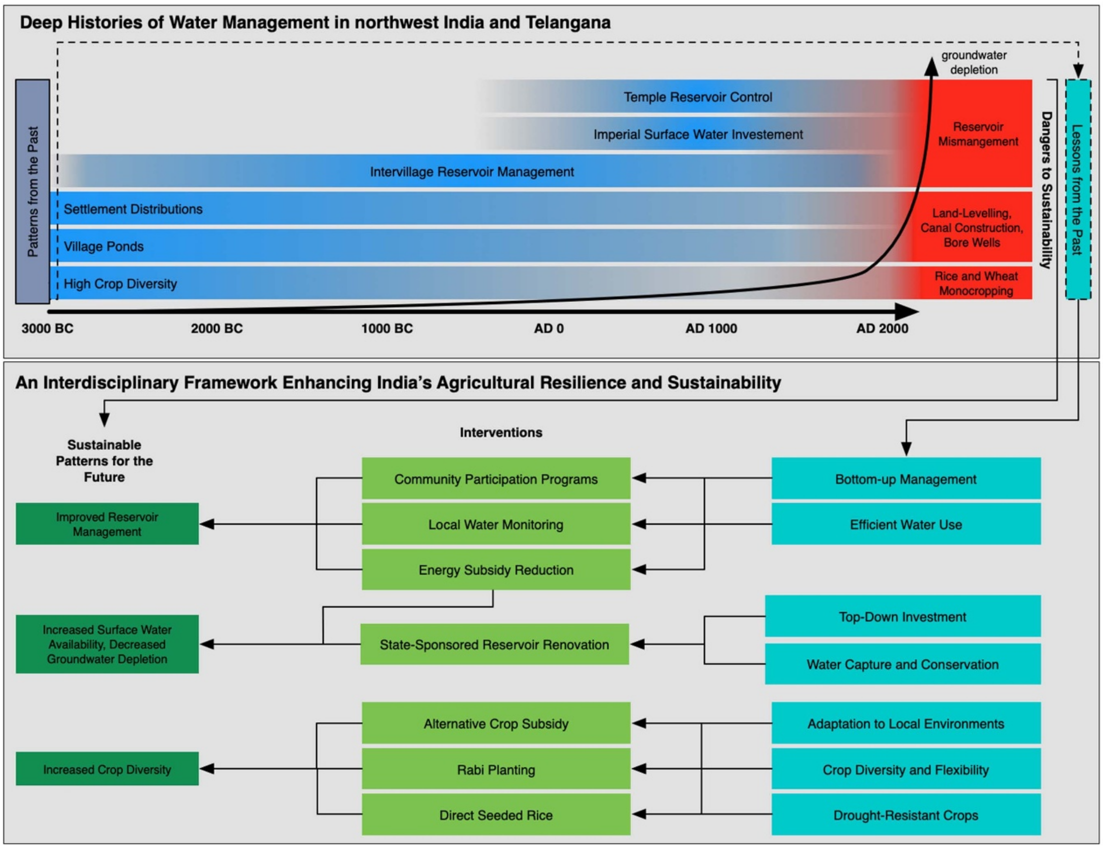

Figure 2. Schematic of the proposed interdisciplinary framework for improving interventions by drawing upon patterns from the past. The top register summarizes patterns from the past, which have been curtailed in recent decades by dangers to sustainability contributing to increased groundwater depletion. These have been used to identify lessons from the past in the below register, which can enhance interventions to bring about sustainable patterns for the future.

kharif season (around June–October). In the semi-arid and temperate zones that stretch across the northwestern part of India, winter rain was and is the primary surface water source, which is distributed widely via large-scale canal-based irrigation systems and sometimes stored in village ponds. In the equatorial zones that transverse the Indian peninsula eastward from the Western Ghats, reservoir (tank-based) farming systems that rely on monsoonal rains have been more important. Despite these differences in water management, thirsty and inundation-dependent paddy rice, which has a water footprint 2–3 times greater than other cereals (e.g. Bouman *et al* 2002, Yao *et al* 2017), is now the primary cereal grown throughout India (figure 3). Paddy rice is often grown in addition to thirsty winter crops such as wheat, superseding more water efficient crops like millet and barley. The predominance of this form of water-intensive Indian agriculture increased considerably beginning in the 1960s, largely the result of the 'Green Revolution' (Nair and Singh 2016). These practices were contingent on an increase in the number of pump operated bore wells, which have now and partly overtaken canal and tank water management. The number of bore wells throughout India increased from one million in 1960 to 20 million in 2009 and annual groundwater withdrawal increased from 25 to 300 km^3 (Shah 2009). Bore wells are generally controlled by individual farmers, though they are powered by electricity supplied and often subsidized by state authorities.

In Punjab, the production of paddy rice uses approximately 1500 mm of water (Vatta and Taneja 2018), a significantly higher quantity than any alternative summer crop. To facilitate its growth, India has made major public investments in large-scale water infrastructure, constructing multipurpose dams that increased canal-based irrigated area from 10 to 18 million hectares by the 1990s (figure 4). The canals were built before Indian independence to increase the agricultural activity in the region, enhance productivity and ensure viability of farming which was the livelihood of the majority of rural households (e.g. Bhattacharya 2019), and canal construction continued through the 1970s and 1980s as part of the Green Revolution (e.g. Amrith 2018). These brick canals are cleaned and maintained by state authorities, and form a vast network that consolidates water

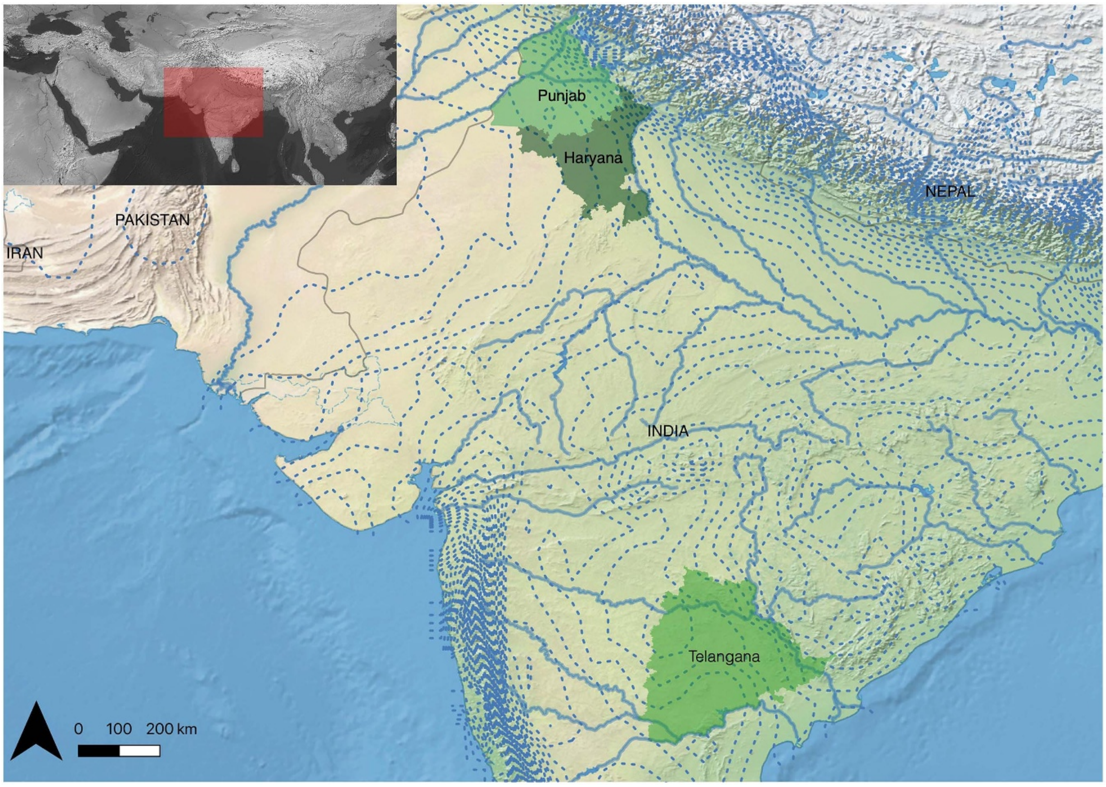

Figure 3. Study states considered in the text and precipitation isohyets. Basemap from Natural Earth (naturalearthdata.com), and precipitation data compiled from (Giesche *et al* 2019). Map prepared in QGIS 3.12 (www.qgis.org).

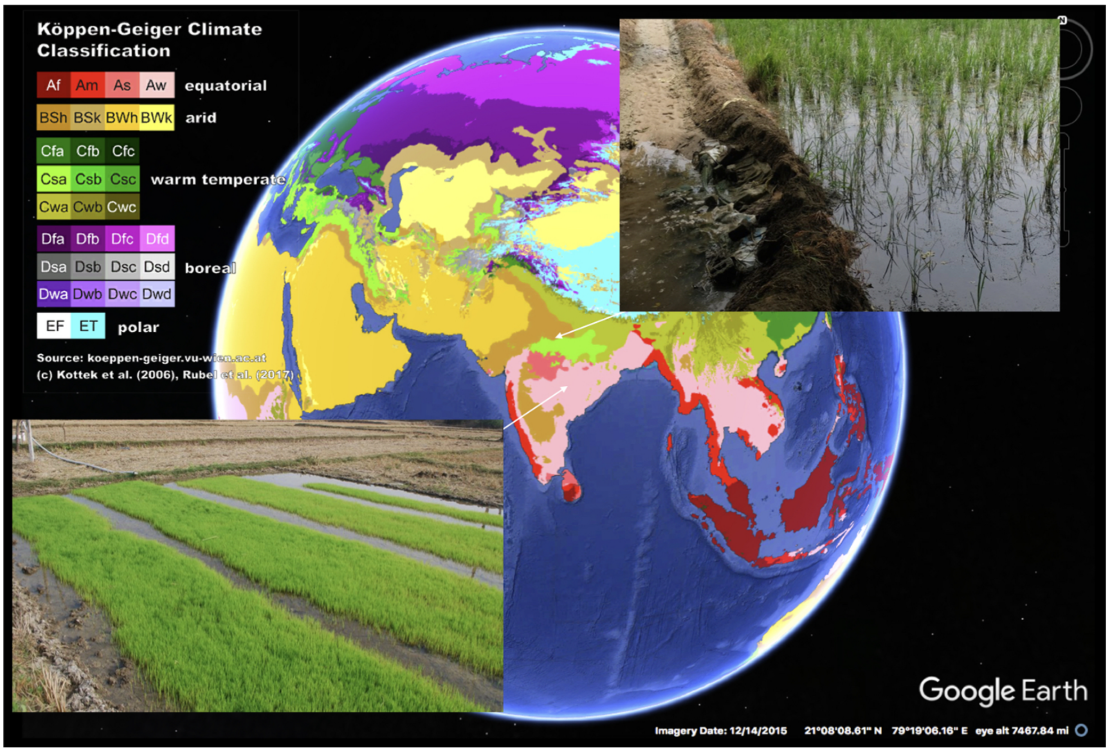

Figure 4. Farming systems found in South Asia's contrasting Koppen-Geiger climate zones. Photos taken by Adam S Green in 2019. Basemap Data ©2020 Google and data from http://koeppen-geiger.vu-wien.acat.

from the Ghaggar, Yamuna, and Indus River tributaries. Important examples in northwest India include the Indira Gandhi Canal and the Sharda Canal.

Canals have not been able to meet the water demanded by paddy rice cultivation. In the states of Haryana and Punjab, where canal irrigation is significant, the area of canal irrigation is only between 29% and 39% of total irrigated area (Government of India 2018). Poor canal management has been a factor, and the shortfall in water availability has been made up by increased small-scale private investments in drilling and pumping technologies, and free or subsidized energy since the 1990s has increased the extraction of groundwater through wells (Singh 1962, Sarkar and Das 2014, Vatta and Taneja 2018). The number of tube wells in Punjab more than doubled between 1981 and 2016 (Ghuman 2018). These wells are now the main source of water for agriculture, an atomized water management strategy that contrasts with historic collective surface-water management strategies represented by canals and ponds (Zaveri *et al* 2016b).

In contrast with Punjab, the large-scale water infrastructure in the south Indian state of Telangana in equatorial India are reservoir-based irrigation systems, which account for 35.6% of the total area under cultivation (Government of India 2018) (figure 5). These reservoirs involve significant collective labor investment, and can measure hundreds of hectares in area and provide water to farmers in multiple villages. When water is plentiful, farmers prioritize rice, producing multiple crops within a year by inundating the fields closest to the tanks. Unfortunately, there is evidence that the performance of Telangana's reservoirs has been deteriorating, in part because of a decline in community participation in their management (Falk *et al* 2019). The decrease in reservoir use may be due to a range of factors including changes in land ownership patterns, caste, and class, and there are reports in other parts of India that the village institutions that had managed the tanks are no longer present (e.g. Reyes-García *et al* 2011, Reddy *et al* 2018, Meter *et al* 2016). As a result, decisions about when to open sluice gates are made outside of farmer communities, often by state-level departments of irrigation. As the availability of surface water is outstripped by use, groundwater has been used to make up the shortfall, and bore wells are now the most utilized water source in Telangana, which has also impacted the capacity of existing tanks, furthering the decline of tank management.

The prevalence of bore wells in both northwest and south India creates numerous environmental problems. In northwest India, as the groundwater level decreases every year, the cost of re-boring and maintenance has increased (Vatta and Taneja 2018). The consumption of electricity in agriculture, which is provided free to farmers by the state government in Punjab, has increased nearly 70% between 1975 and 2016 (Ghuman 2018). As farmers are inclined to saturate their fields, water use often exceeds the needs of a specific crop and overdraws groundwater. Although the state maintains high levels of wheat and rice productivity, the consumption of water to produce one kilogram of rice in Punjab is 5337 l as compared to the all-India average of 3875 l (Ghuman 2018). As a consequence, much of Punjab has been categorized as a 'dark zone', with over-exploited, critical or semi-critical groundwater resources (Central Ground Water Board 2019). While aquifer depletion has not reached the same levels in Telangana, it is associated with similar challenges as in Punjab, and is reducing the base flow to defunct tank ecosystems.

4. Developing lessons from the past

It is frequently argued that patterns from the past can inform the present (e.g. Kintigh *et al* 2014). This is particularly true with respect to the study of long-term socio-environmental interaction in archaeology, a subject that is most often oriented to identifying what makes societies 'resilient' and 'sustainable' (Miller 2011, Marston 2012, 2015, Lane 2015, Hegmon 2017, Petrie *et al* 2017, Bradtmöller *et al* 2017, van der Leeuw 2019, Green *et al* 2020). These concepts are often adapted from the general study of social and ecological systems (e.g. Gunderson and Holling 2002), with resilience referring to the capacity to adapt to change and sustainability referring to the degree to which things can continue without degrading their underlying conditions. Comparing long-term patterns in socio-environmental interaction can reveal how societies increased their resilience and sustainability (Petrie *et al* 2017, Green *et al* 2020). For example, Marston (2012) has argued that village-level decision making can lead to more sustainable agriculture than imperial-level decision making. Likewise, the diversity of subsistence strategies and the distances across which agricultural communities interact shape a society's long-term resilience and sustainability (Green *et al* 2020).

Despite the growth of sustainability research in archaeology, insights from archaeology rarely contribute to interdisciplinary discourses with agronomists and economists that consider resilience and sustainability and have the potential to influence agricultural and economic policy. Governments and policy makers often struggle to see how a specific lesson from the past might interact with policies in the present. This is a problem with how heritage is perceived and valued—as while the past is often considered a resource that needs to be managed and preserved, its role in assembling a just and sustainable future (e.g. Winter 2013, Harrison 2015, Rizvi 2018) is often overlooked. We argue that an interdisciplinary framework that specifically connects a common set of concepts that have the potential to distill lessons from the past into policy objectives needs to be articulated. Present farming systems often have roots

Figure 5. Canal in northwest India. Photo taken by Adam S. Green in 2019.

deep in the past, and this agricultural heritage has the potential to be a core component of the interface between long-term trajectories of sustainability and resilience and current agricultural practice (e.g. Koohafkan and Altieri 2011). Agricultural heritage can also include a diverse range of farming practices, crop choices and approaches to water management that were resilient and sustainable. Many of these approaches have fallen out of use, but potentially should be revisited. To ensure such approaches are practicable, it is essential to characterize water management practices from the past using concepts and variables that can be applied to the present. Here, theories of collective action are key.

Theories of collective action focus on the conditions under which people engage in and sustain cooperation. Collective action is the joint endeavor of many different people or social groups to generate public goods or protect common resources (e.g. Olson 1965, Ostrom 1990). Building a canal, digging a reservoir, and distributing water across a network of fields are all examples of collective action. The core insight of collective action theory is that social groups are more likely to cooperate if they create their own rules, a finding that is partly based on field research of the cultural institutions underlying irrigation practices in India (e.g. Wade 1988). Reservoir management in India thus forms the basis of theories of collective action. Resource importance, predictability and scarcity, the number of people involved, their social and cultural diversity, the importance of the resource managed, the required contribution of each person, the temptation to free ride, collective benefit, rule-making autonomy, and leadership all constitute important variables in studies of collective action (Ostrom 1990, p 148).

Theories of collective action present a robust set of definable social variables and strong predictions about cooperation, and have been particularly useful to archaeologists exploring the emergence of certain forms of social and political complexity without simplistic recourse to the agency of a hierarchical ruling elite (e.g. Blanton and Fargher 2008, Carballo 2013, Demarrais 2016, Halperin 2017, Feinman and Carballo 2018, Green 2020). Theories of collective action thus offer an interdisciplinary link between past societies and present context. Indeed, in his foundational study of collective action in Indian irrigation, Bardhan (2000, p 849) found that the perceived age of a water management system was one of the strongest predictors of its sustainability. We thus frame past water management practices in terms of collective action, drawing on common factors and variables found within past and present water management strategies, which should highlight ways that past practices can guide policies in the present.

5. Deep histories of water management in northwest India and Telangana

The significance of archaeological and historical data for understanding South Asian agriculture in the present and future has not been recognized. This is partly because knowledge about the long-term trajectories of South Asian agriculture is incomplete, with some contexts offering data sets that can be used to create well-developed narratives and others offering only a basic outline. Two examples have particular potential to shape policy by generating agricultural heritage—the water management systems of the Indus Civilization in northwest India, which comprises the earliest large-scale agricultural system in India's semi-arid and temperate climate zone, and the massive system of reservoirs associated with the medieval Kakatiya Dynasty in south India. Both systems made use of a diverse range of crops, many of which are no longer cultivated. Indus water management systems were the earliest to appear in the semi-arid and temperate states of Punjab and Haryana, which are also the states that played a central role in India's Green Revolution. The Kakatiya tank system remains central to the modern dryland farming system of Telangana, and represents an explicit link between present water management strategies and the medieval past. Comparing these examples of agricultural heritage yields insights into sustainable differences in water management between semi-arid/temperate and equatorial regions, and the importance of local cooperation and collective action to the management of surface water in both regions.

In northwest India, early agriculture supported the emergence of South Asia's earliest cities—those of the Indus Civilization (*c.* 2600–1900 BC). The Indus Civilization drew many communities of farmers and pastoralists into one of the world's earliest urban economies (Wright 2010). Botanical data from archaeological excavations indicate that Indus communities relied on a range of crops, including wheat, barley, rice, millet and pulses (e.g. Weber 1999, Bates 2019). Indus villages were located in different environmental contexts within northwest India, and each settlement has a different cropping pattern (Petrie and Bates 2017, Petrie *et al* 2017). Thus, each community's agriculture and cropping strategies appears to have been adapted to its local setting (Petrie and Bates 2017, Petrie *et al* 2017), changing through time as settlement distributions suggests that Indus Civilization urbanized and de-urbanized (e.g. Green and Petrie 2018).

There is little direct evidence of surface water management for agriculture in Indus communities, though there is ample indirect evidence to suggest that a range of water management strategies would not have been beyond their capacities. Indus cities incorporated sophisticated water technologies, including wells and brick-lined tanks (e.g. Marshall 1931, Rao 1973, Jansen 1993, Bisht 2015). These features incorporated the labor of many different people toward a common goal, indicating collective action at the civic scale (Wright 2016, Green 2018) with a conspicuous absence of top-down labor management (Possehl 2002, Kenoyer 2008, Wright 2010, Vidale 2010, Petrie 2013, 2019, Green 2020). Miller (2015) has also argued that the unpredictability of inundation in the Indus River Basin may have required large-scale authorities to re-apportion land to farmers at relatively short notice. Thus, bottom-up decision making and coordination among many different groups likely played a significant role in the emergence of Indus cities. While these patterns largely pertain to urban contexts, it is not unreasonable to infer that rural communities developed their own rules to manage and use local sources of surface water. The location of many rural settlements in proximity to watercourses and the prevalence of wheat and barley suggest a preference for areas with some water capture potential (Miller 2006, 2015, Chakrabarti and Saini 2009, Chakrabarti 2014). However, as Indus urbanization occurred in northwest India, numerous rural communities were located in areas without obvious direct access to a watercourse (Singh *et al* 2010, 2011, 2018, 2019, Petrie *et al* 2017, Green *et al* 2019). It is thus likely that in northwest India, ancient settlement locations indicate the use of a range of different surface water sources, including seasonal watercourses (Petrie *et al* 2017: Petrie 2017, Petrie 2019). Moreover, evidence for many different past watercourses is evident in the microtopography of the region, which may have included perennial and ephemeral watercourses (Orengo and Petrie 2017). While agricultural activities based on winter rain gathered through the hydrological systems likely have a long history in northwest India, they were from the very beginning, augmented through the use of other surface water sources, likely managed according to local rules. The number of Indus settlements increased in northwest India as urbanism declined by 1900 BC, suggesting that rural communities maximized the use of different water sources (e.g. Petrie *et al* 2017, Green *et al* 2020).

Archaeological excavations suggest that the dryland farming systems of South India have their roots in the Neolithic Period, when millets, pulses, and a range of other crops appear in archaeobotanical assemblages (Fuller 2006, Kingwell-Banham and Fuller 2018). In Telangana, there is strong evidence that a large-scale dryland farming system was used in its Medieval Period, and historical records suggest millets, pulses and rice, all played important roles in the region's farming (e.g. Mangalam 1986). In the Vijayanagara Empire (AD 1336–1646), which was centered in neighboring Karnataka, rice became a centerpiece of elite cuisine that resulted in the progressive large-scale construction of the infrastructure necessary to produce it (Morrison 2014).

Figure 6. Historical 'tank' in Telangana. Photo taken by Adam S. Green.

Telangana's network of tanks includes dams that were constructed across slopes to collect and store water by taking advantage of non-anthropogenic topographic features and depressions. Many of these dams were established by the Kakatiya Dynasty (*c.* AD 956–1323), who arose as military chiefs that initially fought on behalf of either the Chalukya or Rashtrakuta Empires (Parabrahma Sastry 1978, Yazdani 2013). When the Kakatiyas formed their own polity, a succession of dynamic and energetic rulers integrated increasing parts of Telanagana and the Andhra coast into their territory. As in the later empires in neighboring Karnataka (e.g. Morrison 2009), Kakatiya ideology emphasized the construction and maintenance of tanks. Constructing and de-silting tanks were listed among the seven most virtuous deeds that could be undertaken by a ruler on earth (Parabrahma Sastry 1978), a tradition that persisted under later polities (e.g. Morrison 2009). Whenever a new Kakatiya leader took power, she or he would begin the construction of a new tank, making more land available for farming. One such tank was constructed at Bayyaram (figure 6), and has an epigraph (figure 7) stating that 'excavating the big-tank …uplifted the earth, in other words placed the kingdom on firm basis,' (Parabrahma Sastry 1978, p 25).

Surviving tanks are often located in the same watershed, and it is possible that in the past the tanks formed a network in which overflow from one tank was tapped to fill downstream tanks. An example can be seen in the arrangement of villages surrounding Katakshapur tank (figure 8). Sluice gates at different heights connected to networks of ditches in surrounding fields. Over the course of a growing season, the sluice gates could be opened in sequence—the higher sluice gate would provide water to a series of nearby fields, the next highest would water another series of fields, and so on. So long as the sluice gates were de-silted and opened in the proper order at the proper times, they provided an effective and efficient means of storing and distributing the water captured from monsoon rains. Historically, the tank system has been critical to the growth of agriculture in Telangana, contributing to soil and water conservation, flood control, drought mitigation, livestock and domestic uses, recharge of ground water, microclimates and environmental protection. The circumstances that have resulted in the tanks falling into disuse requires further investigation, but as in other parts of India (e.g. Bardhan 2000), increased agricultural production for the market and the imposition of state-level water management rules have likely played a role.

6. Using lessons from the past to enhance agricultural interventions

South Asia's agricultural heritage provides clear lessons for increasing sustainable surface water use. The trajectory of water management strategies in India's semi-arid/temperate and equatorial zones reveals a long-term homogenization of agricultural practices that contradicts the region's socio-environmental

Figure 7. Bayyaram inscription in Telangana. Photo taken by Adam S. Green in 2019.

diversity (see figure 4). The increasing production of water-intensive rice in the face of limited surface water availability in both parts of the country is the fundamental challenge that emerges from this contradiction. Though it has provided food and livelihoods for millions, the rise of pumped groundwater use has created serious environmental challenges, contributing to the depletion of aquifers, the excessive

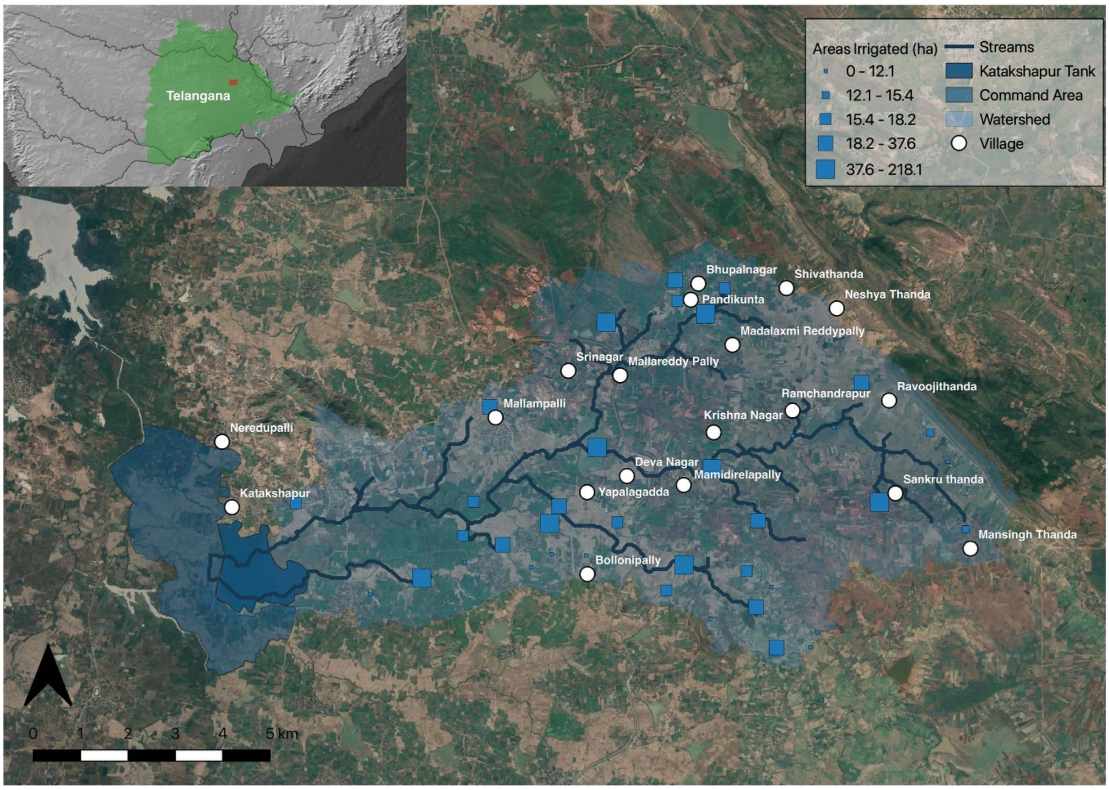

Figure 8. Watershed of Katakshapur tank in Telangana. Data from ICRISAT projected over Natural Earth (naturalearthdata.com), Map Data ©2020 Google, ©2020 CNES/Airbus, ©2020 Maxar Technologies.

use of water, increases in air pollution, and crop residue burning. While bore wells can empower the small-scale farmer, they do so at the cost of the commons, providing relatively unrestricted use of a collective water source in absence of coordination.

To increase the resilience and sustainability of Indian agriculture, a dramatic shift away from groundwater overuse is essential. Reducing the use of water and energy, both of which are under extreme stress, in Indian agriculture has been identified as a key policy objective (Vatta and Tanjea 2018). Local rules, developed through increases in local-level collective action, have the potential to lead to the more sustainable use of both. Large-scale public investments are potentially critical, but should only be used to increase the availability of surface water. Archaeological and historical examples and modern collective action theory both suggest that the local level participatory governance by users results in more sustainable and equitable outcomes. The construction of Kakatiya tanks is an ideal example of this kind of arrangement. It is also likely that Indus communities also made public investments in water management. Large-scale investments may also have been necessary to maintain these gains in surface water availability, as was seen in the ideological importance the Kakatiyas placed on tank management. These relatively costly investments may have yielded considerable increases in the capacity to produce a narrow range of staple crops.

Public investments can ensure surface water availability but, building on the lessons from the past, we argue that sustainable water management also requires the application of local knowledge through coordination at local levels. In the Indus Civilization, early water management likely involved the collective use of a variety of local water sources (Petrie *et al* 2017: Petrie 2017, 2019). In the Kakatiya polity, the timing of sluicegate opening and the maintenance of field canals appear to have relied on village-level authorities. Both water management strategies took advantage of natural gradients in the local landscape—in northwest India, water redirection and storage was probably minimal, while in Telangana, tanks were positioned to draw water from extensive rain-fed catchments. Comparing the deep histories of these systems suggests that the resilience and sustainability of both irrigated and dryland farming systems can be improved by building capacities for collective action at both state and village-level scales.

The final element of the framework involves translating these lessons into positive changes in Indian agricultural practices related to water management and use. There are clear ways that local knowledge can be used to maximize the use of surface water. Flexible capacities for small-scale collective action can maximize the use of local knowledge from dependent communities and maximize resilience. This shift would involve developing interventions that renovate and improve historic water reservoirs to increase surface water availability, empower farming communities to reduce groundwater use, and increase their collective control over surface water sources.

Reducing water stress is also crucial. To achieve the long-term sustainability of the water-energy-agriculture nexus in India, efficient water use through new technologies and practices, crop change and active participation of communities or user associations in the management of water bodies (aspects of which were prevalent in the past) are essential (Rao 2002). In Punjab, conservation agriculture practices (e.g. direct seeded rice, mulching) have been promoted as demand-reduction interventions (Mishra *et al* 2017). These interventions use existing water resources more efficiently by reducing non-productive evaporation, utilizing residue moisture effectively, and enhances resource use efficiency (Das *et al* 2020). Additional interventions such as digital soil moisture sensors, the promotion of short duration varieties, crop diversification through reducing market risk for alternative crops and community participation for effective water management and farm decision making are already underway, and are bridging the gap between demand and supply for irrigation water and achieve long-term sustainability of natural resources (Kamraju and Anuradha, 2017; Kakumanu *et al* 2019). In Telangana, climate smart crops such as millets, pigeon pea and chickpea were traditionally cultivated in uplands; and proper maintenance of surface water tanks through desilting and collective action of the community at downstream ecosystem has been learnt through historical backstopping, and has been targeted under the recent government policy and public welfare programs (e.g. Millets mission program; and Mission Kakatiya) (Devakumar and Chhonkar 2013, Dasgupta 2017, Anitha *et al* 2019). If the monsoon is weak, farmers often leave the land fallow for half the year. This practice wastes the residual moisture that remains in the soil after the kharif season, so encouraging farmers to grow drought hardy, post rice crops (e.g. chickpeas, sorghum) helps use the region's water more efficiently. In Telangana, agronomic interventions are underway and the state is aiming to meet their food and fodder needs through promoting climate smart crops through various government schemes and marketing mechanisms (Parasar and Bhavani 2018). If these interventions in water demand management are coupled with programs to empower farming communities to take collective control over surface water sources and stabilize surface and ground water supply, India has the potential to make transformations in the present that are deeply rooted in an awareness of sustainable past practices.

7. Conclusions

In this paper, we have presented an interdisciplinary framework that draws on patterns from the past to guide interventions aimed to improve the sustainability and resilience of India's agriculture. Our framework is derived from the deep history of agriculture in northwest India and Telangana, regions that have been home to a diverse range of sustainable water management strategies and cropping choices in the past. In recent years, these patterns from the past have been endangered by water-intensive rice and wheat monocropping, reservoir mismanagement, and the increased use of bore wells, all of which are increasing the depletion of groundwater. However, an examination of the archaeological and historical record reveals a range of lessons (e.g. bottom-up management strategies, top-down investments) that can be applied to strengthen different interventions (e.g. community participation programs, state-sponsored reservoir renovation). Undertaking these interventions stands to decrease the threat of groundwater depletion, and increase the resilience and sustainability of India's agriculture.

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Data availability statement

No new data were created or analysed in this study.

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