Sustainable irrigation – a new challenge?

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Abstract

Irrigation has been practiced for some six or seven thousand years in various parts of the world. When sedentary farming emerged in areas along major rivers in the Fertile Crescent, the Indus Valley and China, irrigation soon followed to sustain food production through dry periods. Many of the areas suitable for irrigation were prone to flooding and therefore canals and other structures were not only needed to supply water for irrigation, but also to drain excess water from the fields, and for flood protection. Such structures were well beyond individual farmers and more complex societies emerged. The term 'sustainability' was not known to the first irrigators; they experimented, observed, learned, changed and adapted to their physical environment and changing climate. In some instances, the physical conditions were not suitable for intensive irrigation. Hence, for a number of reasons such as deforestation, soil erosion, salinization and siltation, some hydraulic societies ceased to exist, while in other instances continued for millennia until irrigation intensified due to increased population pressure resulting in changing technologies and practices. In some places irrigation has continued in the same location until today. This paper explores these experiences from around the world and tries to draw lessons for today's irrigation communities. We find that: decentralizing is better than centralizing; diversity is better than uniformity; and local self-ingenuity and self-reliance yield superior results. If exogenous technologies or knowledge are applied, it should be in conjunction with, and adapted to, local conditions, knowledge and cultures. We also find that many of the mistakes irrigators made thousands of years ago are being repeated today and, consequently, we are suffering the same effects – there seems to be a breakdown in our historical memory.

Keywords: sustainable irrigation, Mesopotamia, Egypt, Oman, India.

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1 Introduction

The concept of sustainable development gained prominence in 1987 with the Bruntland report *Our Common Future* [1], which refers to sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their needs. However, the problem of meeting the current generation's need for food and fresh water has been a challenge for mankind since the beginning.

Sedentary farming developed along the world's major rivers in Mesopotamia, Egypt, the Indus Valley, China, and in Mesoamerica. The new farmers soon learned that production could be increased if water was made available when natural precipitation was inadequate [3]. Under these circumstances, farmers could produce more food than they needed for subsistence. This made it possible to release human resources from food production and enabled the emergence of full time trades people and managers who could spend their time securing food production through the construction of more complex, large-scale irrigation structures. This required more complex and organized societies that developed division of labour, laws, and political hierarchies. The development of larger scale irrigation therefore coincided with the first urban societies, termed hydraulic societies [4]. Among them are the Sumerian in Mesopotamia, the Egyptian, and the Harappan Civilization in the Indus Valley. The first written law, the law of Hammurabi from 1,784 BC, includes 300 sections concerning irrigation [5].

Since the first hydraulic societies, history has seen the emergence of many civilizations based on irrigation which initially prospered. However, irrigation has problems which can cause the downfall of societies that rely on it. The construction of irrigation infrastructure and the introduction of intensive irrigation have caused sedimentation of canals, water-logging, and salinization and created havoc in places such as Mesopotamia. In some instances, salinity and water logging resulted in declining yields in the short term, while in others it took centuries and even millennia. In most cases, population pressures and/or confrontation with exogenous technologies resulted in the adoption of irrigation practices which were unsuitable for the local conditions.

Historical records make it clear that the destructive impact of man was already apparent five thousand years ago in China and the Middle East, when the first period of accelerated, man-made erosion began [6]. Cutting or forests, cultivation of sloping lands, overgrazing and salt accumulation were responsible for most of the land degradation in the uplands of China and around the Fertile Crescent. Already 1,600 BC, the Chinese Emperor You acknowledged this when he said *to protect your rivers, protect your mountains*.

2 Examples of early irrigation systems/societies

2.1 Mesopotamia

Irrigated agriculture in Mesopotamia has been practiced along the banks of the Euphrates and Tigris Rivers as far back as the 4th or 5th millennium BC [7].

Some 10,000 years ago, sedentary farming started in areas with sufficient rainfall. However, around 4000 BC local people had moved to the dryer plains of Lower Mesopotamia. They found that crops would not grow with the natural precipitation alone. Initially, their response was to sow seeds following the spring floods to benefit from the moisture in the ground. However, in some years dryness caused the crops to die before harvest.

In response to this problem they built diversion canals to convey water from the Euphrates and Tigris to their fields, allowing them to apply water when needed and also to expand production onto areas not covered by the spring floods. They practiced irrigated basin agriculture which included alternate-year weed-fallowing during which the land is temporarily abandoned, with the result that wild plants take over and dry out the subsoil to a depth of 2 meters, thus lowering the water table and preventing the salt from coming to the surface [8]. These irrigation networks consisted of short canals, keeping the irrigation in close proximity to the main watercourse. One of the benefits of the short canals was that siltation was not a big problem and could easily be cleaned up. The small and simple systems meant that canals could be constructed, maintained, operated, and replaced by the local group of farmers without the need for a powerful centralized government. The ability to control the two worst problems associated with irrigation, siltation and salinization, meant that this system was in operation over a very long period of time [6].

To satisfy the need for water and food for an increasing population and the expanding urban societies such as Ur, there was a massive and unprecedented increase in building irrigation works in the Euphrates Valley sometime during the 3rd millennium BC. Vast canals and complex systems of branch canals were constructed to supply water to unused desert land and depression areas.

A particularly devastating impact was experienced following the building of the 300 km long Nahrwan Canal around 2400 BC in Southern Iraq. The system consisted of a complex network of canals skilfully planned and regulated. The methods employed appear to mainly involve gravity flow from the Euphrates to irrigate land previously supplied from the Tigris. The canal was so large that it was referred to as 'the Tigris' [9]. These massive systems included thousands of brick sluice gates along its branches. In short, it was a system that could only be built and maintained by the resources of a specialized, centralized and powerful government. The result was a total shift in the concept of irrigation away from the previously small and locally controlled systems toward a wholesale reshaping of the physical environment [6]. This resulted in seepage, flooding and over-irrigation. Combined with the abandonment of fallowing and insufficient drainage, the groundwater level started to rise, eventually causing extensive problems with soil salinity as is evidenced in temple records of the time [6]. The long canals also resulted in widespread siltation of canals and the deposit of infertile silt on the land, further reducing the fertility of the soil.

As a consequence, there was a gradual but marked reduction in the production of salt-sensitive wheat, the preferred food crop, and an increased production of the more salt-tolerant, but less attractive barley. Around 3500 BC, archaeological evidence suggests that an equal amount of wheat and barley was grown in

Southern Iraq. By 2500 BC wheat accounted for only one sixth of production, by about 2100 BC for no more than two percent, and by 1700 BC no wheat was grown at all. Not only did they suffer a shift from wheat to barley, but soil fertility also declined dramatically. Around 2400 BC, yields were about 2,537 kg per hectare; by 2100 BC it had declined to 1,460 kg, and by 1700 BC to 897 kg per hectare. Inevitably, the large-scale, centralized irrigation systems broke down under the strain of social upheaval [6] and a civilization disappeared.

The Babylonian King Hammurabi in 1784 BC introduced the first written law setting out the rights and obligations of all men, known as the 'Code of Hammurabi'. Reflecting the importance of irrigation the Code contained about 300 sections dealing with various aspects of irrigation. One of the laws said: "if a man is negligent in strengthening the banks of his field and has not maintained his banks and then a breach has occurred in his bank and so he has let the waters carry away (the soil on) the water-land, the man in whose bank the breach has occurred shall replace the corn which he has (caused to be) lost" [5].

The destruction of irrigated farmland in what today is known as Iraq is not isolated to ancient times. After the collapse of the ancient societies, irrigation continued on a smaller scale with many areas being abandoned as the old system deteriorated and was not maintained. Under The British Mandate (1914–1932) a slow revival and restoration of ancient works took place. Canals were dredged, regulators and weirs were constructed and the system was steadily extended and improved. At the same time, the *shaduf,* or the old fashioned waterwheels, was replaced with hundreds of diesel-pumps, and the land under perennial irrigation along both the Euphrates and Tigris were expanded. After The Second World War, an Irrigation Development Commission was formed to usher in a new era during which rapidly increasing oil revenues were used to invest in development of new irrigation schemes, dams and hydro-power, and reservoirs and flood control measures [10].

In more recent times, the upstream states of Syria and Turkey have dammed the Euphrates and Tigris to develop irrigation in their own countries. This has significantly reduced the volume of water flowing into Iraq and thereby also reduced water quality, especially resulting in increased salinity levels [11]. These new initiatives are causing further water logging and salinity affecting 8.5 million ha or 64% of the total arable land in Iraq, while 20-30% of irrigated land has been abandoned due to salinization [12]

Goldsmith concludes that "when (large-scale irrigation) regions are left in the uncontrolled possession of a landlord class, which is either of foreign origin or a partner in a precarious alliance with a foreign conqueror, rural investments are in danger of being neglected, because the landlords inevitably go for quick profits and liquid assets. In extreme cases the result is starvation and depopulation" [7].

It has often been argued that the collapse of the ancient civilization in Mesopotamia with their well-organized and productive farms was associated with a changing climate and drying of the land. However, while there is ample geological and archaeological evidence that this area was wetter and likely more fertile in the distant past, there is no conclusive evidence that these changes took place in historic time and certainly not over the last 10,000 years. Hence, the decay of a civilization and the disappearance of what was likely the oldest and possibly the most advanced hydraulic society must be found in other factors. It is most likely that it was associated with the actions that people took over a long period of time and in their inability to adopt the way they farmed as they experienced the negative consequences of their actions. There is no reason to believe that the farmers of the time did not understand cause and effect in their landscape, that when they extended the canals and abandoned fallowing they caused the problems which eventually resulted in their demise [13].

2.2 Egypt – the Nile

About the same time as in Mesopotamia, farmers started irrigating along the Nile, utilizing the flash spring floods to inundate their fields in the narrow and low-lying Nile Valley. It was mainly a natural phenomenon but farmers dug flat-bottomed basins along the river and a system of canals to flood the fields from the upstream ends of the basin and drain the water back into the river at the downstream end. The canals were also used to convey the water to fields further away from the river. However, this was limited to the low lying areas of fertile soil which could be reached without lifting devices. Irrigation was also limited to once a year to coincide with the natural flood when water came down from the mountains in Ethiopia and Uganda. Water was in abundance and there was no opportunity to irrigate outside this period, thus preventing continuous cropping.

Inundation irrigation worked sustainably for 5,000 years because of its simplicity, efficiency, and cost-effectiveness. The Nile performed three important functions; i) it provided irrigation water, ii) it disposed of drainage water; and iii) it rejuvenated the soil by depositing fertile silt from the upstream mountains. Further, large volumes of water were used only once a year which leached potential salt deposits out of the soil [14].

This system supplied Egypt with ample food up until the 18th century. The population and irrigated area in Egypt prior to 1800 peaked in about 100 AD when Egypt supplied the Roman Empire with vast quantities of grain [14]. In the 19th century Egypt experienced a population explosion, and an increase in the use of agricultural land for cotton production for export to England [15]. As a consequence, food production started to fall short of needs. To expand irrigation for food and cotton production a series of dams were built across the Nile north of Cairo, followed by a number of other dams. Dam building culminated when British engineers built the first Aswan Dam in 1904, which was subsequently expanded twice by 1934 and completed when the high Aswan Dam was constructed from 1964 to 1970.

These developments fundamentally changed irrigation and the flow of the River Nile. Annual inundation and cropping was replaced by continued irrigation with two or three crops a year. The Nile was controlled and did not flood anymore; instead, the fields were continuously wet and were never thoroughly leached to flush out the salt from the soil. In addition, the water no longer deposited the nutritional silt, as this was now trapped behind the dam wall. This resulted in decreasing fertility, a buildup of soil salinity and water logging [16]. Already in 1928 scholars warned about the threat of land salinization and that the big dams would hold back the silt that had replenished the fertility of the floodplain for millennia and the cotton harvest started to decline [17]. A crude estimate of the amount of crop yield reduction attributed to salinization and waterlogging in the Nile Valley indicates it to be at least 17 percent on 80 to 90 percent of the old irrigated land. In the newly irrigated land, the figure is likely to be a minimum of 25 percent [18]. As in Mesopotamia, it can be observed that human interactions altering the natural flow of the river caused soil degradation, most importantly in this instance water logging and salinization. Whereas increased siltation in Mesopotamia was part of the problem as the silt was unfertile, in Egypt the fact that the large dams prevented the fertile silt from reaching the fields was part of the problem. As in Mesopotamia, these actions were taken in response to increased population pressures but also as a result of a political decision made by a colonial power to increase export of cotton and unwillingness to adapt when the impacts started to appear.

2.3 The qanat system

For at least the last 2500 years underground water mobilization systems, known as qanat systems have been constructed and used throughout the Arab World.

Qanat technology originated in the highlands of western Iran, northern Iraq, and Eastern Turkey, possibly in connection with early mining ventures in that region. These are areas where water scarcity is extreme, but maybe more importantly, where the availability of fertile land was even scarcer and located in areas at some distance from the water source. Hence, water needed to be conveyed to where the fertile land was, thereby allowing people to inhabit areas with little rainfall. Although it originated in Iran, the system spread throughout the Middle East, the Arabic Peninsula, North Africa, and along the old Silk Route [19].

This discussion is based on qanat systems in Oman, where they are locally know as falaj systems. There are three types depending on the source of water: i) Daudi systems supplied by groundwater and conveyed by underground tunnels; ii) Ghaili systems supplied by open channels fed by surface water in oases; and iii) Aini systems supplied by springs in the foothills [20]. Common among the three systems is that they are based on gravity and water cannot be extracted faster than it is naturally replenished. Therefore, the systems are sustainable.

This paper concentrates on the Daudi system. The system extracts water from the top of aquifers high in the mountains and brings the water in underground tunnels down to the lower areas, and from there in open channels into villages and onto the small fields, mainly for irrigation of date palms, but also for other cash or subsistence crops [20, 21]. This system has several unique features for sustainable irrigation from environmental, social and economic perspectives.

The Daudi system cannot mine the aquifer as the off-take is located high in the aquifer profile: consequently, the system only harvests the overflow or the renewable yield from the aquifer. The system requires skill to establish and maintain, but it is entirely gravity fed so there is no pumping cost and potential disruption caused by shortage of power or spare parts. This reduces the monetary expense associated with running the system and provides a secure water supply.

In most systems only a small proportion of the water rights are privately owned. In one system, visited by one of the authors, only 15% of the water rights are privately owned, 10% are owned by the village community and the rest by semi-public charity organizations. The water owned by the village community is sold to the farmers at auction every week and the proceeds are used to finance the maintenance and administration of the system. The majority of the water owned by semi-public institutions is sold to the farmers at annual auctions and the proceeds are used to pay for schools, police, priests and the poor.

In a sense, this system acknowledges the fact that all wealth is derived from the availability of water and, hence, the water is sold to farmers to fund the maintenance of the system and the running of the community. This system resolves many of the problems facing irrigation systems in developing countries, such as: i) fee collection and therefore adequate funding of operation and maintenance resulting in inefficient systems with reduced productivity; ii) equitable distribution of the wealth generated by the water. In this system equity is ensured as most farmers have to buy the water each year and the revenue is used to pay communal expenses; iii) risk sharing associated with reduced supply during periods of scarcity. This is also an integral part of the system as farmers have the right to the flow from the system during a specified period of time; during periods of scarcity the flow simply yields less water. During periods of severe drought, the watering cycle is extended from, for example, every seventh day to every tenth day. Hence, the cost and pain of scarcity is shared. The weekly auctions can then be used to redistribute who gets access to the limited flow; and iv) water for domestic use. This is also supplied by the system; as the canals enter the village, there are access points where villagers can take water for drinking and household purposes; further downstream are places where households are allowed to wash their clothes, after which point the water is diverted into the fields.

This system has operated for thousands of years [20, 21]. In Oman more than three thousand such systems were once in operation. Today many have run dry while others are currently under threat. So, why is this sustainable system under threat? In most instances this is due to the introduction of modern technologies that are enabling users to mine the aquifers. Private farmers are sinking tube wells into the same aquifers from which the qanat systems are supplied. Once the water level in the aquifer drops below the off-take for the qanat system, the flow of water ceases and the system runs dry, stopping the supply of water for both domestic and farming purposes as well as the flow of revenue supporting the communities.

2.4 India – a diversity of systems

Archaeological evidence suggests that irrigation systems have existed on the Indian subcontinent for at least 5,000 years. Reflecting the wide variability of rainfall, temperature, altitude, topography and soil types; the subcontinent has seen a wide variety of early settlements devising their own unique systems of water harvesting adapted to local conditions [22].

For example, in southern parts of India tens of thousands of village tanks (dams) were constructed. This suited local conditions in the region which were dominated by scanty rainfall, steep slopes with fast run-off, and soils with low water retention. There was, therefore, a need to be able to retain and store the water when it was available and apply it when the soil needed it at a rate at which it could be absorbed by the soil [22]. In other parts of the country, communities have devised various other means of water harvesting from rivers, aquifers and rainwater runoff to provide water for drinking and agriculture.

Evidence suggests that these traditional systems were very efficient and productive. A British survey of 2,000 villages in the province of Tamil Nadu found that between 1762 and 1766 some villages produced up to 12 tons of rice per hectare, a level of productivity which today has only been achieved in the most successful areas, during the most productive era of the Green Revolution [23]. The same document also reported that the availability of food per household was five tons compared to today's three-quarter tons. Emphasizing the productivity and efficiency of farming and irrigation in India is a report in the Ecologist Magazine by a British agricultural expert. He wrote the report based on a tour of India that he conducted in the 19th century to see how he could best advise Indian farmers how to improve their agricultural practices. He concluded that he could learn more from the Indian farmers than they could learn from him, as they knew so much about soil composition and health, pest control and water management, crop breeding, and all other aspects of agriculture [24].

The traditional irrigation systems suffered during three periods. When the East India Company ruled India, their primary interest was to extract resources from existing infrastructure and, therefore, they failed to invest in improvements and neglected to maintain infrastructure such as irrigation systems. To make matters worse, transport infrastructure such as roads and railways were often constructed on embankments which interrupted the traditional contour-based irrigation canals and tanks. It also cut off large areas from supply of loam-bearing water from rivers, leaving the land unproductive and sterile [25].

During the early days of the British colonial rule there was some investment in irrigation such as weirs, dams and barrages mainly in the Punjab region to produce export crops such as cotton, opium, sugar cane and wheat which generated most revenue to the state [26]. On the other hand, the British showed no interest in the traditional small scale peasant irrigation systems of wells, dams, small canals and tanks which had fed the Indian population for thousands of years. Various actions of the British Colonial system were detrimental to the continued use of traditional irrigation systems: i) British tax policies heavily penalized peasants who sank their own wells at their own expense; ii) the generally high land tax level during the early colonial period left local communities with no financial ability to maintain their irrigation systems; iii) the taxation system destroyed the social fabric and system which had enabled local communities to construct and maintain irrigation system themselves. Indeed, British rule relieved local political chiefs from their obligations to invest in community resources and public institutions such as tank systems; iv) modern irrigation systems when constructed were in many instances deliberately situated in ways that supplanted other prevailing irrigation structures; and v) in some instances local farmers were actually forbidden to use their traditional system so as to ensure their payment to the new systems [27]. The refusal of the state to support local irrigation became a smouldering grievance everywhere in interior India. This disruption of the community structures was detrimental as traditionally irrigation systems in India have always been treated as communally managed common resources [28].

Since Independence the Central Indian Government has shown relatively little interest in traditional small village irrigation systems. The Government has been far more interested in promoting the construction of large dams and in enhancing control over the resources by taking over the village tanks. This has led to a further breakdown of the community control and management practices that were so vital for the sustainability of the system. A substantial number of tanks acquired by the state have fallen into disrepair because village communities have stopped contributing the voluntary labour for desilting and upkeep of the tanks and the state is not able to perform or pay for the functions earlier undertaken by the people. By doing this, the state has also shown that it believes it is better to construct new large dams rather than revive the efficient network of the village tanks across India [29–33].

The impact of the government's program was amplified by its commitment to the new infrastructure and the fact that it promoted its use through a set of subsidies which made it more viable for the farmers to use the new systems than maintain the old systems. This has happened in a number of ways: i) subsidies for electricity supplies made it cheap to pump water from dams via canals or from tube wells deep in the ground; ii) subsidies for fertilizer which made farmers less dependent on the use of the tank silt which was used in the past as production enhancing material; iii) subsidies for water from the major dams reduced the dependence on tanks for irrigation; and iv) subsidies for diesel pumps also reduced the dependence on water from tanks [34].

The introduction of the Green Revolution in the late 1960s following severe drought and hunger further intensified irrigation, especially from groundwater in Punjab. Not only was the area under irrigation expanded but new high responsive varieties were introduced requiring the application of more water per hectare of crop. Finally, rice, a very water demanding crop, was introduced in Punjab. Most of this irrigation was supplied by tube wells which soon lowered the aquifers to levels not accessible by the traditionally dug wells and, hence, forced these smaller farmers to abandon irrigation, invest in tube wells or sell to neighbouring larger farmers who could afford such investments. As a consequence of these changes, aquifer levels are dropping at high rates, challenging future food production. Water tables are rising in many areas with associated salinity and other soil degradation problems. Since the introduction of the Green Revolution in India, severe land degradation is reported to have affected 58 million hectares in 1990 (20% of land). Punjab and Hyryana are experiencing declining wheat yields, with soils becoming unsuitable for wheat cultivation [35].

3 Discussion and conclusions

Irrigation has been practiced for more than 6,000 years in various parts of the world to feed and clothe a growing population. In many places irrigation was initially sustainable for many years while farming practices were used which allowed the land to recover between crops and irrigation applications were scheduled so that salinity build up was prevented. Once irrigation intensified and continuous irrigation and cropping was introduced, the land did not have time to recover and salinity and water logging problems started to reduce productivity and in some instances resulted in the collapse of societies. In Mesopotamia this started relatively early, while in Egypt it did not start until last century.

In Oman the qanat system worked both economically, socially and environmentally sustainably up until recent times, when the introduction of modern technology in the form of tube wells has caused the closure of many systems as aquifer levels are drawn down below the off-take of the qanat system.

In India, British Colonial rule destroyed in a variety of ways many traditional irrigation systems which had successfully fed the local populations for many generations. Not only did they destroy or disrupt the physical structures, they also destroyed the social and community structures that had kept these systems in operation. The change in priority from feeding the local population to maximizing export production and revenue from land taxes were the major reasons for this development. Since Independence, the Indian Government has continued the destruction of the local systems through its emphasis on very large systems and associated subsidy systems favouring the new mega systems at the expense of the local system.

What we can learn from all of this is that we have to respect existing physical and social structures and not replace them with modern technology until we are sure that we fully understand how they operate and how the modern technology is going to interrupt the existing systems and structures. Pursuit of short-term economic gains does not justify causing environmental damage as such harm imposes social and economic costs in terms of higher health bills or diminishing agricultural returns on future generations [36]. The most successful systems rely on local knowledge and organization. We conclude that

- decentralizing is better than centralizing;
- that diversity is better than uniformity; and that
- self-ingenuity and self-reliance yield superior results.

If exogenous technologies or knowledge are applied it should be in conjunction with, and adapted to, local conditions, knowledge and cultures, drawing on generations of knowledge of the local conditions.

Maybe most importantly, we should appreciate that the problems discussed in this paper have been caused by human interference with natural systems and by an inability or unwillingness to take appropriate measures when negative impacts of this interference emerged. This problem is not isolated to early civilizations and developing countries. Irrigation experiences from the last couple of hundred years in California, Australia and elsewhere have repeated the same type of manipulation with natural systems as discussed here and have been experiencing the same consequences of water logging and salinization, causing millions of hectares to be taken out of production. These developments today, as they did then, represent the most serious challenge to future food security and the future of our societies as we know them.

Since these problems are caused by human actions and behaviour, only by changing this behaviour can we rectify the problems. The issue will ultimately be whether we have the political will and foresight to do it.

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