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WATER ENGINEERING HERITAGE OF THE KNUCKLES MOUNTAIN RANGE AN EXPLORATORY ANALYSIS OF PHILOSOPHICAL FOUNDATION

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ABSTRACT

Transferring indigenous knowledge into modern-day water management strategies is crucial in sustainable exploitation of water resources amidst climate change impacts. However, human-centred understanding on sustainable water infrastructure acquired from lived experiences over generations is limitedly disseminated. The present study articulates the philosophy of engineering design and governance of ancient irrigation systems in mountainous geographies, by an exploratory case study in the Knuckles Mountain Range in Sri Lanka. Mixed–method research design was adopted, by triangulating water walks, transect walks, in-depth interviews, field (ground) measurements, photogrammetry and archival research. Results reveal undocumented unique minor irrigation systems built in confined mountainous streams attributed with step pools, for gravity irrigation. Head-works comprise porous-weirs, stoney head-sluices, off-taking canals integrated with micro-tunnels and spillways. Water conveyance subsystems in the command area comprises shunts, entranceways and three types of outlets operated sequentially. Alternative water sources include retention ponds called '*Pathaha*', and subterranean watercourses originated from a micro-watershed called '*Rawana Wewa*'. Two types of porous-weirs identifiable are the cross-vane type rock weirs built on the downstream step of step pools and the wooden leaky weirs. Said mirror irrigation system is founded on the values of altruism and minimalism, and the principles of low-impact-development and participatory governance, in which religious ideologies dictating social norms. Implementing efficacious policy instruments to disseminate internalized knowledge promoting nature-based designs and community participation in water resources management are recommended. Further research is encouraged on potential reintroduction of ancient porous hydraulic control structures into flood management strategies.

Keywords: Water-landscape, Hydraulics, Porous-weir, Traditional-knowledge, Water-governance.

INTRODUCTION

Water serves in social, cultural and economic spheres where water diversion and retention for those purposes have been practiced by humans since ancient times (Aroua, 2018; 2022). Thereby, hydraulic civilization has accumulated a wealth of indigenous knowledge. Convincingly, conservation and transferring of principles, values and knowhow embedded in water engineering heritage into modern-day use is necessary in confronting with climate change impacts, specially on water resources (Assemian et al., 2021; Aroua, 2020; Remini, 2020a; Nakou et al., 2023).

Among the most remarkable achievements of ancient hydraulic engineering stands the foggara system, a millennia-old irrigation network that continues to testify to the ingenuity and resilience of early desert civilizations (Remini, 2013; Remini et al., 2014; Remini, 2018). The foggaras, also known as *qanats* or *khettaras* in other regions, represent a sophisticated underground water collection and conveyance technology, designed to harness groundwater from aquifers and gently transport it toward oases and cultivated zones by gravity alone. Emerging more than 2,500 years ago in the Saharan and pre-Saharan regions of North Africa, these structures are a masterpiece of sustainable engineering, reflecting a deep understanding of hydrology, geology, and community-based water governance (Remini, 2024a; 2024b).

What defines engineering heritage is discoursed from physical and nonphysical perspectives. Engineering heritage has tangible artefacts, internalized knowledge, dynamic processes and collective memory and identity, for forming and sustaining a group's identity (Pranskūnienė and Zabulionienė, 2023). Hence, heritage is part of the social learning process, requiring the retention of indigenous populations for heritage conservation through lived experiences.

Historical irrigation systems are attributed with mechanisms of sourcing water from direct precipitation, floods and aquifers (Rezzoug et al., 2016; Remini, 2019; Remini, 2020b). However, collapse of community-led water management, unsustainable exploitation of groundwater through deep-wells, climate change, and lack of expertise and government support have led these ancient irrigation systems to experience gradual degradation over the past decades (Weerahewa et al., 2023). Importantly, these ancient irrigation systems can be reintroduced by strategically incorporating into the sustainable development agendas such as the Horizon Europe programme (Branduini and Zaina, 2023). Nonetheless, spatiotemporal scaling issues of historical irrigation systems in managing irrigation water demand and associated sociocultural concerns should be accounted (Tianduowa et al., 2018). Therefore, it is convincing that, simply restoration of historical irrigation systems is insufficient to achieve water sustainability.

Weirs, in general, are historical hydraulic control structures built to regulate upstream water level (e.g. lifting and diversion of water, and flood management) of open waterbodies (i.e. rivers, channels, reservoirs, estuaries, etc.), permitting water to flow over or pass through it. Notably, in today's context, weirs also serve in measuring the flow in watercourses. Moreover, weirs have been a part of sociocultural recognition, for example, '*Irish Fishing-weirs*' in Ireland (Pickles, 2021). Nevertheless, large-scale weirs have been found causing disruptions in habitat transition in riparian ecosystems (Im et al., 2020). Porous-weirs (Kumar et al., 2025; Pirzad et al., 2022) are a type of weirs facilitating through-flow while lifting the water level upstream. Notably, porous-weirs are attributed with commonalities (e.g. constituent materials, construction methods such as interlocking, etc.) with '*Leaky-weirs*' (Norman et al., 2025), '*Leaky-barrier*'(Leakey et al., 2022), '*Porous-check-dam*'(Roberts and Roots, 2023), and '*Rubble-mound-weirs*' (Michioku, 2020), however, with varying purposes (e.g. slowing the flow, aquifer recharge, etc.). Moreover, '*Rubble-mound-weirs*' (e.g. in River Danube in Germany, Maruyama River in Japan, and Fuefuki River in Japan) offer ecohydrological benefits including habitat provisioning (Michioku, 2020). Arguably, porous-weirs perform as sediment traps (Kumar et al., 2025) as well as pervious structures for transporting sediments downstream (Peeters et al., 2020), depending on the built and status of weir, sediment dynamics, and geomorphological determinants and flow regime of the watercourse, and hydrological events such as floods. Therefore, critical evaluation of potential demerits of porous-weirs is crucial in permanent installations.

The failure mechanism of porous-weirs built in mountainous rivers during hydrological extremes is debated from multiple perspectives. The geomorphology of the watercourses and the engineering design related challenges are pivotal in developing nature-based sustainable water infrastructure in mountainous geographies. Particularly, understanding on hydrodynamics of hydraulic control structures installed in confined mountainous rivers having high sediment caliber attributed with step pools is crucial in establishing cause-effect relationship of damages, such as porous-weirs built on the steps in case of the present study. Despite the fact that theories on formation of step pool sequences are evolving; large boulders serving as keystones contribute to determining the location, height and wavelength of the steps, and energy dissipation, and stability (Chartrand and Whiting, 2000; Chin, 1999; Nickolotsky and Pavlowsky, 2007; Zimmermann and Church, 2001). Accordingly, the height of the upstream step and the configuration affect the pressure gradient and lift forces acting on sediments in respective downstream pool, signifying that relatively small pools are subjected to undergo intense turbulence, facilitating the transportation of sediments. Therefore, natural materials like cobbles used to construct porous weirs can be dislodged destabilizing the structure, depending on the flow regime and geometry of the step pools.

Contrastingly, empirical findings demonstrate that, ramps installed on the crest of the steps reduces scouring in the downstream pool (Nafchi et al., 2021). Given the downstream scouring, a main cause of weir failure in the typical scenario; rock weirs built on the steps can be expected to be relatively stable. However, form drag and surface drag acting on cobbles like nonhomogeneous objects having varying cross-sectional area and roughness used to construct porous hydraulic control structures can induce structural failure by decreased capacity of through-flow during peak flows. Hence, the present study aims at widening the understanding on philosophical grounds of water engineering heritage of civilizations in geographically challenging mountainous areas to inform policies to transfer of indigenous knowledge into modern-day water management strategies.

METHODOLOGY

Geography of study area - Knuckles Mountain Range

The Knuckles Mountain Range is situated in Kandy and Matale administrative districts in Sri Lanka. The main livelihood activities in this area comprise farming and tourism. This mountain range designated as an environmental protection area (Fig.1) hosts tropical sub-montane semi-evergreen forests, tropical montane evergreen forests and grasslands, riverine forests, pygmy forests and savannah. Relief features 300 – 900 m and average annual rainfall is > 2000 mm. Soils are mostly granular (alluvial and colluvial) and the bedrock (charnockite) is located close to land surface.

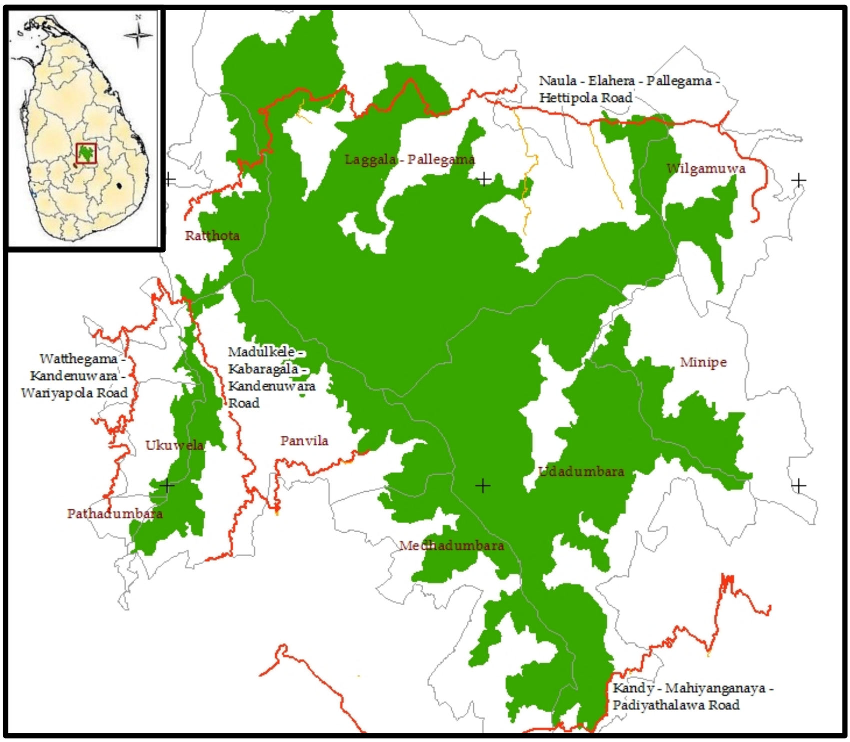

Figure 1: Knuckles Mountain Range (Source: Central Environment Authority of Sri Lanka, 2017)

Research design and analysis

The present exploratory case study adopted mixed-method research design (McBride et al., 2019). Methodological triangulation, data triangulation and theory triangulation were employed. Data collection instruments devised were the field (ground) measurements, photogrammetry, in-depth interviews and water walks (Holstead et al., 2024) and transect walks through three field visits in February and March 2025. Stakeholders were identified (i.e. inhabitants, government officials, and academics). Purposive sampling and snowball sampling were employed. A total of 30 respondents participated in in-depth interviews, conducted face-to-face or over-the-phone depending on the participant's availability and preference. Sampling adequacy was based on redundancy. Potential bias introduced by the researcher's judgement was eliminated by reflecting the researcher's beliefs systems and method choices. Archival research was conducted on archaeological and historical facets and linguistics (e.g. literature including '*Neethi Nighanduwa*'). The examined channel sections were characterized according to the Montgomery and Buffington Classification (Buffington and Montgomery, 2022). Field photos for the image analysis were obtained from a smartphone camera (1/5-inch CMOS sensor; 2.51 mm focal length; 4:3 aspect ratio; 3264x2448 pixel resolution). The dimensions of hydraulic structures in field photos were measured by image analysis (Jasmari, 2022) by using *Digimizer* software (version 6.4.5) (Rau et al., 2021), calibrated and validated by physical measurements using a standard measuring tape. The criteria (e.g. crest-depth to crest-length ratio) established in the literature (Chen et al., 2018) were used to classify the observed hydraulic control structures. Secondary data (e.g. map extracts) were gathered from public domain. QGIS (version: 3.36.2) with OpenStreetMap was used for georeferencing of the study area. Construction materials of observed hydraulic structures and retention ponds called *Pathahas* were assessed by observations and by consulting senior inhabitants. Preliminary damage cause analysis was performed for hydraulic control structures.

RESULTS AND DISCUSSION

Historical account of the study area

Despite the origin of indigenous knowhow on water management in the country is debatable (e.g. previous authors attempt to establish the roots to the era of legendary Queen *Kuweni* and Indian migrants); historical facets convince that dominant monarchical leaderships have been influential to the evolvement of the irrigation systems in the mountainous regions in Sri Lanka. Furthermore, the influence of the mainstream construction methods adopted in the well-known tank-cascade systems established in the dry zone of the country is reflected by the civilizations in the central highlands using similar technical terminology (e.g. '*Pitawana*' for spillway) in their water systems, with exceptions. However, linguistically and technologically, terms such as '*Heede(n)duwa*' (i.e. shunt) unique to the study area of the present study emphasizes conceptual differences in the water systems in addition to the adaptation to mountainous geographic contexts. Notably, geographically isolated remote villages including *Meemure*, *Ranamure* and *Laggala* in the Knuckles Mountain Range have shown close relationships (deplomatic and military) with legendary King *Ravana*–I, King *Gajabahu*–II (1132–1153), King *Parakramabahu*–I (1153–1186), King *Wimaladharmasooriya*–I (1592–1604), King *Sri Weeraparakrama Narendrasinghe* (1707–1739), King *Keerthi Sri Rajasinghe* (1747–1780), King *Raajadhi Rajasinghe* (1780–1798), and King *Sri Wikrama Rajasinghe* (1798–1815). For example, inhabitants of *Meemure* ancestral to the *Yakka* tribe ('*Yaksha Gothra*') mastered in metallurgy are believed to have been descended from legendary King *Ravana*–I famed for engineering marvels including the flying machine called '*Da(n)dumonaraya*' strategically chosing *Laggala* village as the capital and King *Parakramabahu*–I (1153–1186) reigned in the *Polonnaruwa* kingdom demonstrating advancements in construction of complex tank ('*Wewa*') cascade systems are remarkable. Morever, King *Sri Weeraparakrama Narendrasinghe* (1707–1739) providing state support for construction of weirs (e.g. weir in *Rawan Oya*), reservoirs (e.g. *Kotta Wewa*) and canals (e.g. *Bandara Ela*), and King *Wimaladharmasooriya*–I promoting the development of '*Pathahas*' as communal sources of water are noteworthy. Spring dams on the River Tiout (Naama Algeria) are also some ancient hydraulic structures used in storing and diversion of water for irrigation. These dams intended to store spring water discharged and the surplus water is transported to irrigate palm groves located on both the banks of the river (Remini, 2022; Remini, 2025). Moreover, '*Pathahas*' as integral part of minor irrigation schemes in villages recognized as a developmental priority by the *Kandyan* Peasantry Commission Report (1951) highlighting the necessity of immediate restoration constrained by inadequate technical expertise showcases how indispensable these historical water systems are.

Ancient irrigation system of the study area

The unique ancient water infrastructure of the Knuckles Mountain Range (Fig. 2) has been built in the confined mountainous streams attributed with moderate-to-high stream gradient, high sediment caliber, low sinuosity, low width-to-depth ratio and step pools, geomorphologically characterized according to the Montgomery and Buffington Classification. These step pool sequences have varying step height and wavelength, for example, '*Dimbigolle Oya*' or '*Meemure Oya*'. The engineering design of said minor irrigation system is featured with combined operation of subsystems of water divergence, conveyance and governance. The headworks further comprise porous-weirs, stoney head-sluices (Image 1), off-taking canals with micro-tunnels and spillways. The water conveyance subsystem in the command area attributed with terraced subfields further comprises shunts called '*Heede(n)duwa*' or '*Pitalaya*', entranceways called '*Nawatha*' and three types of outlets operated sequentially called '*Ela-wakkada*', '*Isnan-wakkada*', and '*Pa-wakkada*'. The alternative water sources include the geometrically leaf-shaped retention ponds called '*Pathaha*' and subterranean watercourses originated from a historic micro-watershed called '*Rawana Wewa*' at *Uyangomuwa* low-relief nearby *Lakegala* inselberg.

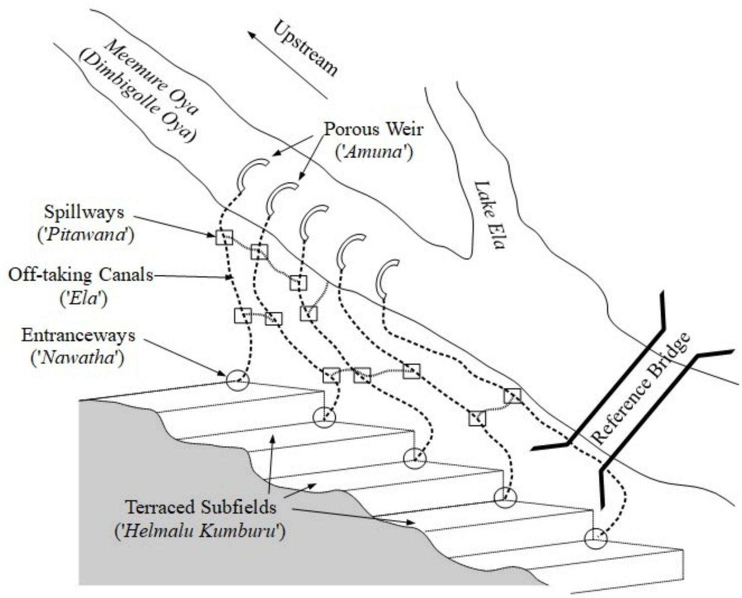

Figure 2: The conceptual layout of minor irrigation system

Image 1: Stoney head-sluice

There are two types of porous-weirs identifiable, built using locally sourced materials; (1) arch-shaped cross-vane type short-crested (crest-length 0.15-0.30 m, crest-height 0.15-0.60 m and crest-width 0.45-2.0 m) rock weirs (Image 2) constituting interlocking rocks (e.g. cobbles) built on the downstream step supported on large rock abutments (available in *Meemure* village), and (2) wooden leaky weirs fixedly supported on the river bed (available in *Rathninda* village). Considerable leaking through porous-weirs is observable. A mixture of rice straw and mud have been placed in between the layers of interlocking rocks in constructing these weirs, for added stability and minimization of excessive seepage. Despite the apparent simplicity, said porous-weirs are found to have ecohydrological benefits for river hydrology (e.g. sediment dynamics) and riparian habitats (e.g. fish breeding and migration). These weirs are temporary structures, environmentally friendly, cheap, used only to lift the water level to a satisfactory level to obtain the head required for diversion and gravity irrigation. Admirably, weirs built on the steps located at large boulders prevent destabilization from downstream scouring, which is low-cost nature-based design. These weirs may act as ramps by changing the hydrodynamics, as empirically demonstrated by Nafchi et al. (2021). Nevertheless, given the use of nonhomogeneous stones and inconsistent quality of construction leading to varying crest shapes (e.g. round versus flat) as reported in the present study, further empirical investigations are required for theory development to transfer this knowledge into other domains such as natural flood management.

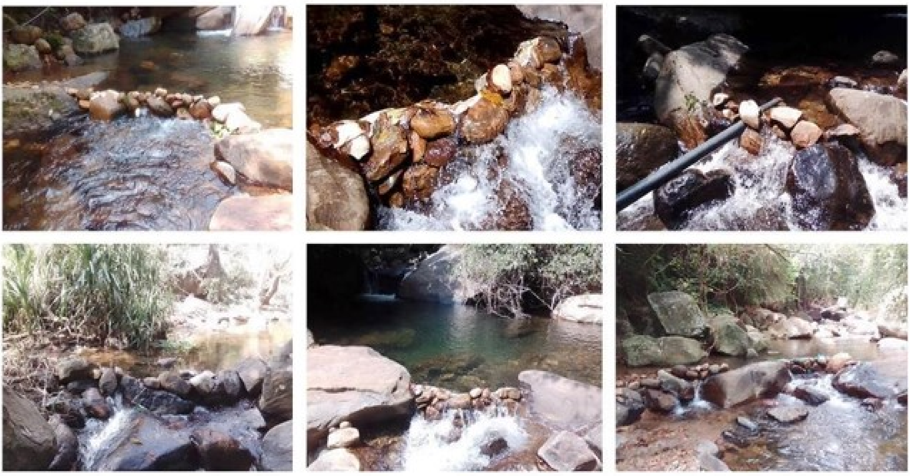

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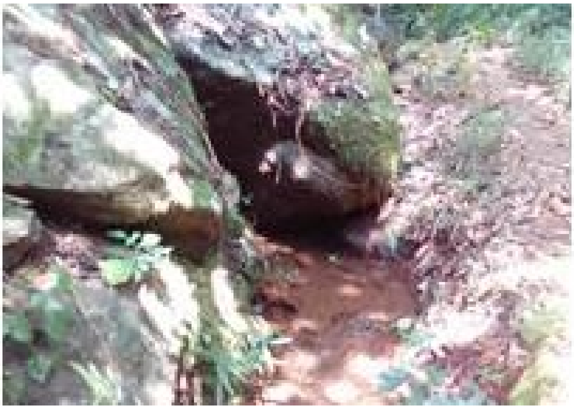
Image 2: Porous-weir (Type: rock weirs)

However, a preliminary damage cause analysis shows that inconsistencies in construction and maintenance processes govern the dislodging of constituent rocks leading to full or partial destruction of weirs during '*South-and-South-East-Asian'* monsoons, depending on the step height and wavelength. Given the significantly varying step-height leading to developing intense turbulence in small pools, constituent cobbles of said weirs can be mobilized due to the increased lift forces, as theorized by Zimmermann and Church (2001). Notably, preventive maintenance is not within practice. Nonetheless, the maintenance protocol is definable as the realignment of dislocated cobbles, repairing broken sections with missing cobbles by inserting new or reusable stones, completely rebuilt if substantially destroyed during the irrigation period, reapply of mud-straw mixture in between the interlocking cobbles, removal of excess debris affecting the stability of the weir and in the respective upstream sections, ensuring proper functioning of canal head regulator, and material collection, logistics, and preparation for repairs, and participatory decision making, while ensuring personal safety measures in all works, ensuring security from threats leading to physical damages by non-hydrological causes including wildlife. Notably, male labour is dominant in construction and repaire works of said weirs. However, skilled labour shortage for maintenance of weirs is evident.

Currently, five off-taking canals are in operation (Image 3), upstream of the reference bridge at 7° 26' 36.52" N, 80° 50' 33.99" E. The average dimensions of an off-taking canal are width 0.15-0.6 m, depth 0.15-0.2 m. These canals which have been engraved into the fractured bedrock near the land surface, aligning with contours of the natural landscape, which showcase low-impact developmental approach. Moreover, stone-liner in off-taking canals (including monolithic sections) extends the design life. However, earthen embankments (Image 4) reinforced with stones are available in some cases for required contouring on undulating land surface. Micro-tunnels (Image 3) built through rock-soil masses along the way of the off-taking canal system are prominent. The head-sluice is made of stones with little preparation or meticulously selected natural stones, and by situating horizontal slabs of stone on two vertical stoney walls. The spillways with breakable weirs (Image 5) integrated into each off-taking canal divert unused excess water into the neighboring off-taking canals, equitably sharing water resources. There are no river-training-works such as guide banks or marginal bunds.

(a)

(b)



(c)

Image 3: (a) and (b) represent off-taking canals with micro-tunnels; (c) Micro-tunnels of the off-taking canal

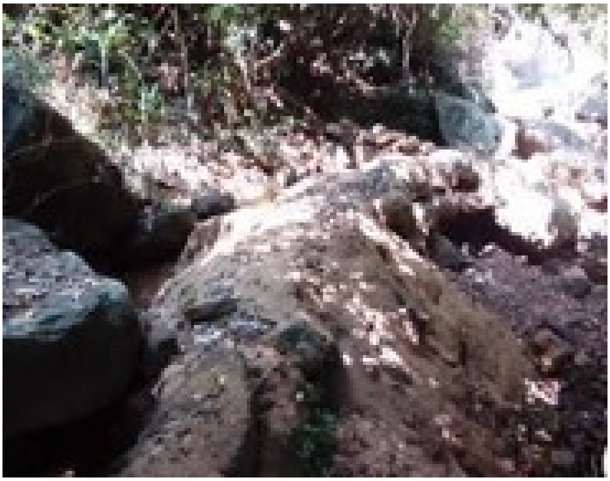


Image 4: Earthen embankments of off-taking canals for contouring

Image 5: Spillways with breakable weirs

The command area is attributed with terraced subfields (Image 6). The subfields situated far from an off-taking canals receive unused irrigation water directly through shunts (Image 7) and used waters from the outlets (Image 8) of adjoining upper-elevated subfields. The irrigation scheduling is remarked by completely draining from subfields before sowing, by opening the outlet-1 ('*Ela-wakkada*'). After two to three days of sowing, outlet-2 ('*Isnan-wakkada*') is closed to partially inundate the fields. Thereafter, waters in the subfields are allowed to permeate into the soil and evaporate for about 2–to-3 days and the process is repeated three times. Subsequently, subfields are fully inundated by operating the outlet-3 ('*Pa-wakkada*'). However, by convention, shunts are not permitted to carry used water from the subfields to prevent pollution, as some of the shunts converge with the mainstream eventually, which reflects environmental consciousness.

Image 6: Terraced subfields

(a)

(b)

Image 7: Shunts


(a)


(b)


(c)

Image 8: (a) represents Entranceways; (b) and (c) represent outlets

A *Pathaha* (Image 9) is a natural, semi-natural or man-made pit-type retention ponds vividly appeared as leaf-shaped or the like waterbody sunken in the ground, which may or may not have embankments, from which water is withdrawn for multiple uses. These retention ponds receive inflows from streamlets, springs and direct rains. Typically, a Pathaha is geometrically featured with long diameter 1.5-3.0 m, short diameter ~1.5 m and depth 0.30-0.6 m. There are two *Pathahas* currently in operation located at the paddy field called '*Weekade*' in *Meemure* village (7° 26' 51.28" N, 80° 50' 37.28" E and 7° 26' 58.95" N, 80° 50' 38.15" E). However, *Pathahas* are no longer serving as communal water sources in today's context due to private ownership of lands. The said '*Rawana Wewa*' micro-watershed (Image 10) is believed to be a tank in ancient times, however, currently partially covered with large boulders detached from *Lakegala* inselberg undergoing mass wasting. The subterranean water courses originated from this area nourish irrigation fields at *Narangamuwa* (e.g. '*Gawara Vila*' serving as an intermediary waterbody), *Ranamure* and *Laggala* villages situated in the northern part of the Knuckles Mountain Range, which requires further hydrogeological studies.

Image 9: Pathaha


(a)


(b)

Image 10: (a) and (b) represents '*Rawana Wewa*' micro-watershed

The system of governance of said minor irrigation system is more tied up to the local culture, in which customs (i.e. rituals) play a significant role in influencing the principles and belief system on governance, for example, altruism and minimalism. Moreover, religious ideologies dictate social norms. The philosophy of engineering design and water governance of said mirror irrigation system is founded on altruism, minimalism, low-impact-development, and community-participation.

Nevertheless, in scaling-up for meeting the requirements of the modern-day socioeconomically complex water infrastructure considerably vulnerable to climate change impacts; the knowhow derived from these historic irrigation systems should be critically evaluated for potential contextual limitations. As Tianduowa et al. (2018) demonstrated, advanced hydraulic modelling tools can be effectively used in assessing spatiotemporal scaling issues associated with ancient irrigation systems. However, in line with Weerahewa et al. (2023) and Branduini and Zaina (2023); it is questionable whether the heritage and cultural identities of the study area of the present study are being preserved, given the over-tourism and rural-urban migration. Moreover, the cultivation system is being transformed from self-sustaining subsistence model to commercial farming system demanding more natural resources.

CONCLUSION

The present study investigated the water engineering heritage of ancient civilizations in the Knuckles Mountain Range, by conducting an exploratory case study, by identifying elements of matrix defining natural setting, socio-economic-cultural context, and traditional-knowhow. The philosophy of engineering design of said minor irrigation system is articulated by the appreciation of minimalism, altruism and low-impact development. The system of governance is grounded on the principles of participatory governance tied to cultural practices and religious ideologies. The undocumented *Pathahas* in the study area rediscovered is defined as a natural or manmade pit-type perennial body of water sunken in the ground vividly appeared as leaf-shaped or the like, which may or may not have embankments, from which water can be withdrawn to irrigate some known acreage in addition to multiple uses. Devising new policy instruments and evaluation of current policies to reintroduce indigenous knowhow by promoting nature-based designs and participatory governance are recommended. Future works of this research include digital preservation of said minor irrigation by employing heritage informatics and advanced remote sensing and photogrammetry technologies validated by ground observations. Further research is encouraged on potentials of reintroduction of ancient porous hydraulic control structures into natural flood management strategies.

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