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A CLASSIC EXAMPLE OF URBAN-RURAL LINKAGES THROUGH ANCIENT YODA ELA IN SRI LANKA - SYMBIOSIS OF TOTAL ENVIRONMENT ON EFFICIENT WATER MANAGEMENT

UN EXEMPLE CLASSIQUE DE LIENS URBAINS-RURAUX PAR L'ANCIENNE YODA ELA AU SRI LANKA - SYMBIOSE DE L'ENVIRONNEMENT TOTAL SUR LA GESTION EFFICACE DE L'EAU

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ABSTRACT

Among the ancient irrigation practices, the Sri Lankan dry zone water management systems sustained for over 2000 years have been well documented. With the influx of communities settling around the historical urban centers, efficient water management was necessary. The invention of the Tank Cascaded system (TCS) and a network of canal systems have emerged to supply water to these centers, which lasted even at present. This paper aims at unraveling some unique functions of the Yoda Ela (YE) canal located in the northern dry zone connecting Kala Wewa (reservoir) with Tissa Wewa. After examining the aerial photographs, Google Earth Pro, and Digital Elevation Models (DEM) followed by field investigations to assess the respective environmental changes, it was evident that the water supply from a transboundary canal took place with the utmost care and in a sustainable manner. Minimal hydrochemical variations and sediment migration coupled with well-maintained irrigation and domestic water supply sustain the community living around this 87 km long canal. The Yoda Ela is one of the excellent representations exemplifying the urban-rural linkages from the total environment and global water history perspectives.

Keywords: Total environment, Dry zone irrigation, Sustainability, Yoda Ela, Urban-rural.

RESUME

Parmi les anciennes pratiques d'irrigation, les systèmes sri-lankais de gestion de l'eau des zones sèches maintenus pendant plus de 2000 ans ont été bien documentés. Avec l'afflux de communautés s'installant autour des centres urbains historiques, une gestion efficace de l'eau était nécessaire. L'invention du système « Tank Cascaded » (TCS) et d'un réseau de systèmes de canaux ont vu le jour pour alimenter en eau ces centres, qui ont perduré encore aujourd'hui. Cet article vise à démêler certaines fonctions uniques du canal Yoda Ela (YE) situé dans la zone sèche du nord reliant Kala Wewa (réservoir) à Tissa Wewa. Après avoir examiné les photographies aériennes, Google Earth Pro et les modèles numériques d'élévation (DEM) suivis d'enquêtes sur le terrain pour évaluer les changements environnementaux respectifs, il était évident que l'approvisionnement en eau d'un canal transfrontalier s'est déroulé avec le plus grand soin et de manière durable. Des variations hydrochimiques minimales et une migration des sédiments, associées à une irrigation et à un approvisionnement en eau domestique bien entretenus, soutiennent la communauté vivant autour de ce canal de 87 km de long. Le Yoda Ela est l'une des excellentes représentations illustrant les liens urbains-ruraux du point de vue de l'environnement total et de l'histoire mondiale de l'eau.

Mots clés : Environnement total, Irrigation en zone sèche, Durabilité, Yoda Ela, Urbain-rural.

INTRODUCTION

Water supply to dry areas for irrigation and domestic requirement is a challenge not only at present but even in the ancient historical periods (Oweis, 2005; Toriman and Mokhtar, 2012; Al Obaidy, and Al-Khateeb, 2013). Many civilizations have adequately domesticated the available water resources and the majority was dependent upon a very well-organized system of water management (Mithen, 2010). The Indus valley, Egypt, and Mesopotamia excelled with cultural upbringing mainly supported by achievements in sophisticated hydraulic engineering and systematic water management skills (Crary, 1949; Helbaek, 1960). Implementation of such irrigation systems adjusted by application of different strategies for efficient interaction with the total environment was evident. Many of those strategies were depending on the elements of the environment viz:

geological, climatological, biological, and sociological conditions either to avoid negative impacts or to enhance the positive outcomes for the benefit of the people (Mertz et al., 2009; Scholz and Binder, 2011). Even community watershed management at the landscape has also been used as a growth engine for sustainable development in the dry regions through efficient rainwater management (Wani et al., 2003; Wani and Ramakrishna, 2005).

The Yoda Ela (YE) in the northern dry zone of Sri Lanka which supports sustainable living for over 1500 years has been selected for this study (fig. 1). As a tropical island in the Indian Ocean, Sri Lanka has three climatic zones viz; the dry, the wet, and the intermediate zones defined by the average annual rainfall (ARF) (Fig. 1). The rainfall is less during southwest monsoons compared with the northeast monsoon in the northern dry zone of Sri Lanka (Fig. 2).

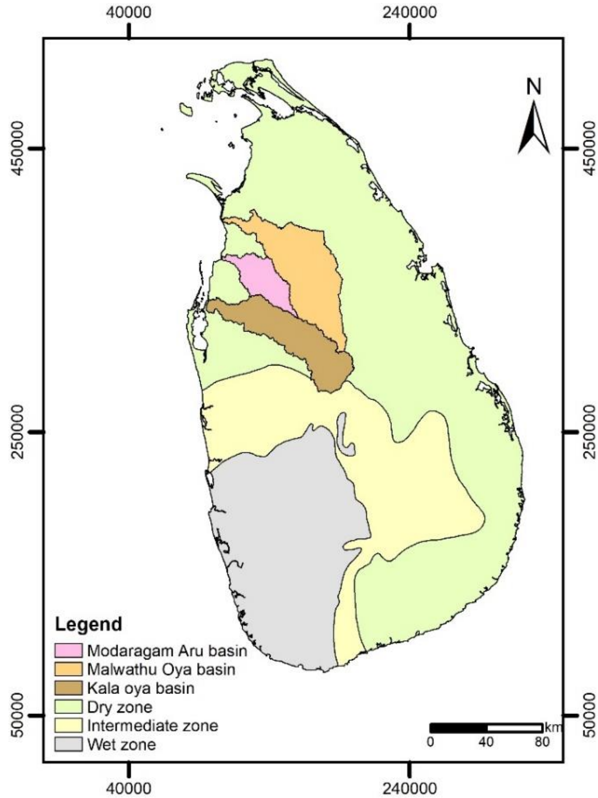

Figure 1: A map of Sri Lanka showing the climatic boundaries and major cities

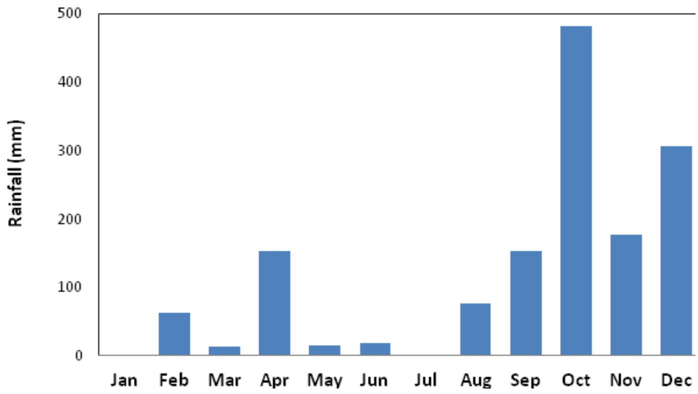

Figure 2: Average monthly rainfall over study area for the year 2019

The dry zone receives ARF < 1750 mm and is generally confined to a topographically flat area, where paddy and other crops bearing lands are being cultivated from the ancient period onward (Siriweera, 2002). Such cultivation could be implemented in the dry zone due to a large number of cascaded manmade water bodies (tanks) that store and harvest rainwater. A 'cascade' is defined as a connected series of village irrigation tanks organized within a micro-catchment of the dry zone landscape, storing, conveying, and utilizing water from an ephemeral rivulet (Madduma Bandara, 1985; Mahatantila et al., 2008) (Fig. 3). Artificial water channels are used for conveying and distributing water from such tanks while supporting the croplands in between. Those tanks and water conveying channels have been connected as a network for a sustainable water supply mainly to the flood irrigated paddy cultivations (Seneviratne, 1987). As a result, a flourishing civilization centered on urban Anuradhpura concurrent with supplemental agricultural products coming through the rural areas supported by efficient water management through Tank Cascade System (TCS) have emerged. The introduction of Yoda Ela seems after the originally established smaller TCS system but has been proved as a remarkable mega engineering feat since it contributed needy water to the then Dry Zone Capital of Anuradhapura.

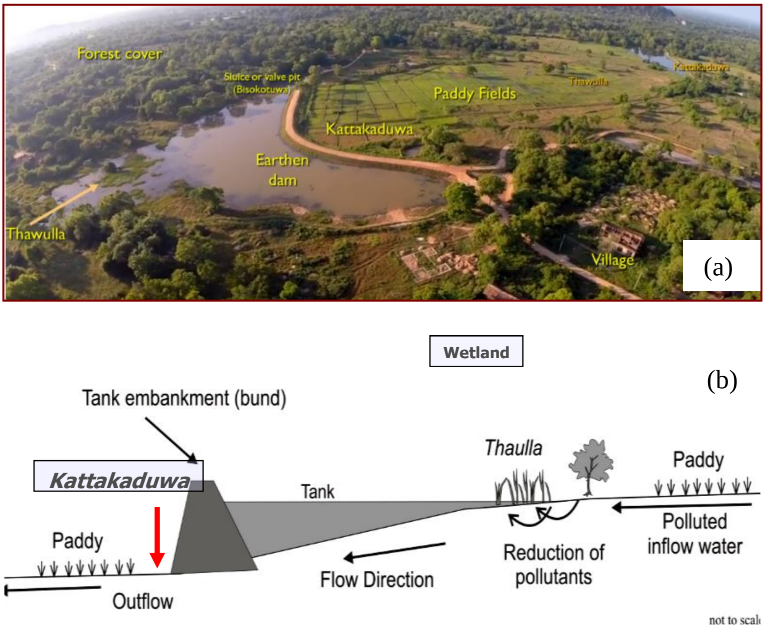

Figure 3: a) A drone photograph showing the Tank Cascade System (TCS) with elements associated, b) a section drawn through the tank bund aiding removal pollutants for sustainability (Mahtantila et al., 2008).

GENERAL BACKGROUND

Ancient Yoda Ela (YE)

Yoda Ela (YE) is a magnificent creation of the ancient irrigation engineers which was built during the reign of King Dhatusena (459-477 AD) to convey water from the Kala Wewa in the Kala Oya basin to Tissa Wewa in the Malwathu Oya basin (fig. 1). Though the evidence state that several political turmoils took place during this era opposing this movement, the king has taken an initiative that lasted for a longer period of sustainability in the dry zone of Sri Lanka (Geiger, 1908; Gunawardana, 1989). Since the trade route passes through Gokanna (Trincomalee Harbour) in the east to Mahatota (Mannar Harbour) in the west was busy and efficient, the capital Anuradhapura attracted many traders (Liyanagamage and Gunavardhana, 1965). Therefore, the amount of water required had been surpassed what was available in and around the citadel, so the king had to implement an efficient water resources development plan to cater to the expected demand. The diversion canal from the northcentral region to the northern dry zone was emerged as a result and continuously maintained covering both irrigation requirements to the peasants in the arid areas and to supply water to the city dwellers in the citadel

(Gilliland et al., 2013). As such several episodes of YE reconstructions in history were also recorded (Brohier, 1934) until the beginning of the "Mahaweli" development project in the year 1975 which abandoned a segment of the previous flow path of YE (Panapitiya, 2010). Literature and maps from the earlier periods indicate the presence of similar YE's in many parts of the country which may indicate that the system was an engineering concept implemented to convey water to the country's lowland (Brohier, 1934; Arumugam, 1969).

Flow path variation and its effects on YE

The entire length of the flow path of the YE is about 87 km (54 miles) and consists of a delicately worked meandering route. Although it has a low flow rate, water is radially accelerating along with meanders while being subjected to deflect and deformed along the whole stream giving steady but sluggish flow. YE has been built to follow outstanding gradients that vary from 10-20 centimetres per kilometre in most parts of its flow. It is also collecting water from 66 mini catchments whereas it fed water to about 120 small lakes along its length (Brohier, 1934). In many respects, it is akin to an elongated reservoir because of the single embankment. This single embankment supports the lateral push of waters towards the upslope while reducing the pressure on the bank so that free flooding on the opposite side of the embankment is maintained. The existence of a single embankment throughout the entire length is depending on the slope and headwater valleys.

The flow path of the YE was separated into 3 segments covering headwater regions of Kala Oya, Moderagam Aru, and Malwathu Oya basins (fig. 1). In the historical periods no need to implement any controlling mechanisms across the ancient YE because its water was conveying along the routes defined by nature. However, after the middle section was completely abandoned by the recent irrigation development, the original efficiently maintained YE functions were obliterated (Panapitiya, 2010). At present, the YE mainly provides water to paddy cultivations up to Mahailuppallama, but earlier it was a major source providing water for domestic consumption in many ancient dwellers in the capital Anuradhapura. The meanders among others were the key behind sustainability as reported previously and it has been demonstrated as a time-tested ancient hydraulic regime providing efficient water management (Rathnayake and Jayasena, 2020). It is a classic example of multiple usages by urban city dwellers and rural peasants with a balanced symbiosis of the total environment.

A comparison of YE functions with modern canals

A comparison of irrigation with the ancient YE and from a modern canal shows some pertinent issues cropped up at present. Deterioration of water quality parameters such as increasing salinity and hardness have been reported (Ranathunga et al., 2019). The groundwater flow has been obstructed by deepening the canal and concreting the embankments on either side (Chandrasena et al., 2016). Stream embankment and bed erosion have been augmented after the introduction of a straightened channel with increasing discharge. With this modern irrigation system, effects of backwaters on destabilization along the banks were evident causing erosion and excessive sediment accumulation in the bed. Moreover, when comparing with ancient and modern irrigation practices, the analysis demonstrates the importance of evaluating the efficiency of proper hydrological practices against politically driven “ad hoc” modern water management implementation strategies (Jayasena et al., 2019).

The present study based on the ancient YE, and its modern counterpart New Jaya Ganga (NJG) would provide a unique opportunity to carry out a comparison of technologies and hydraulic engineering practices. Urban-rural linkages on water history from the perspective of the total environment, and their respective impacts on environmental sustainability are also addressing since they also cover the most pertinent objects in this study. In addition, assessing the persistence of each category on future diversity by comparison of ancient and modern irrigation technologies is also addressed.

MATERIALS AND METHODS

The urban-rural linkages through the YE and its counterpart NJG would be compared using currently available literature and field surveys. The literature on ancient irrigation networks and water distributing technologies related to YE, its renovations and construction records, command areas between Kala Wewa and Tissa Wewa, and recent discoveries were initially compiled. The desktop and field study examines the geometry of the YE with its channel parameters, sinusoidal distribution, meander patterns, and drainage divides and compared them with NJG. Spatial water quality variations in terms of transmission through YE and subsequent addition of NJG were also assessed. The rainfall, physical parameters, and agricultural extent, along with these channels were also collected (Mahaweli Authority of Sri Lanka, 2017). The soft dataset of 1:10000 (sheet 36) and 1:50000 maps (sheet 31) were bought from the Department of Survey, Sri Lanka. An aerial view of the flow paths including remnant parts of YE, the surrounding topography, channel morphology, and the positioning of embankments, were extracted using Google Earth pro. The digital elevation model (DEM) covering the study area was downloaded (earthexplorer.usgs.gov, accessed 2021) and the watershed was delineated using spatial analyst and hydrology tools in ArcMap 10.4. Lengths of channel segments and elevation (extracted from the DEM) were initially calculated using ArcGIS and respective sinuosity and slopes were then determined.

Water quality was measured from samples collected along with the YE and NJG. Thirty-one (31) water samples were collected into High-Density Poly Ethelene bottles from 11 locations identified along with the YE (fig. 4). Samples for cation analyses were filtered through a 0.45 syringe and acidified with conc. HNO_3. Water and air temperatures, pH, electric conductivity (EC), and Total Dissolved Solids (TDS) of water were measured at sampling sites using portable meters. Eight (8) undisturbed sediment core samples at least 2 m in length were extracted from the bed and the embankments, viz: 3 samples from the

NJG and 5 samples from the ancient YE (fig. 4). Major cation and anion concentrations of water were measured using standard procedures (APHA, 1998). Granulometric parameters of the sediments were determined by dry sieving for the fraction >0.075mm followed by the hydrometer method for the fractions < 0.075mm.

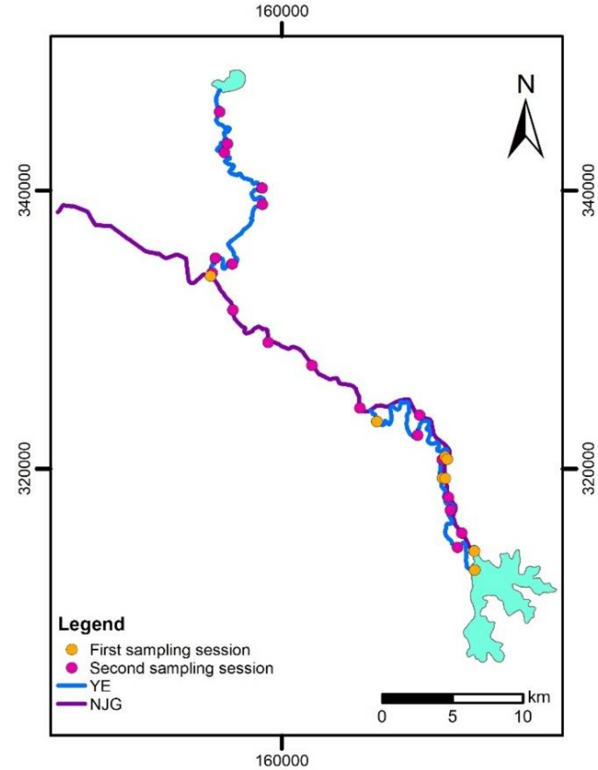

Figure 4: Map showing sampling locations from active and abandoned segments of YE and the NJG

RESULTS AND DISCUSSION

Water quality variations, geomorphology, trans basin canal traces, socio-economic conditions, technology involved with designing and conveying, and managing water supply through ancient YE will be addressed in this section. The YE represents an example of a major linkage of peasants and farmers in the northcentral landmass with chieftains and other government whips in the Anuradhapura Citadel. In the more modern situations, a major river or a lake is responsible for major city development, however, the ancient citadel in Anuradhapura was located in the middle of the dry zone. Similar examples of flourishing major cities can be drawn from the fertile crescent in

Mesopotamia, Egypt, the Indus valley, etc., which were heavily dependent on the scanty water resources available through sophisticated hydraulic engineering and systematic water management skills (Crary, 1949; Helbaek, 1960). Some of the skills they mastered are still not clear but descended from the generations, the basic principles, and tools they used are outstanding. Maybe some of those skills were systematically and chronologically shaped up by more modern tools and concepts. Some of these ancient works still portrayed very sophisticated techniques which are clearly surpassing our expectations as shown in the overall design of YE in northcentral Sri Lanka. The following discussion based on current observations and data gathered on YE and NJG expresses significant changes in thinking and maneuvering patterns over the two systems. Again, the discussion would not only compare physical systems as most current projects are concerned with but also the effects of total environmental systems covering various sector achievements in major ancient hydraulic systems.

Chemical Signatures

Hydrogeochemical variations are sensitive enough to surface and groundwater sources coupled with anthropogenic inputs from the study area. Therefore, interpretations were established by considering longitudinal variations of surface and groundwater quality at the selected sampling points with water samples collected from the ancient YE and NJG (Table 1).

Table 1: Maximum and minimum values of chemical parameters for YE and NJG water samples

		pH	EC	TDS	Alkalinity	Hardness	RSC	SAR	Mg Haz.	KR
			(μS/cm)	mg/l	mg/l	(mg/l)	(meq/L)			
Surface water	Max	8.11	882	432	324	493	8.2	2.41	67	1.3
	Min.	7.12	227	108	121	117.5	-6.1	0.53	36	0.4
Groundwater	Max	7.57	1909.5	971.5	752	950.5				
	Min.	6.9	645	313	226	239				

Parallel variations of pH for groundwater and surface water were recorded in the reach up to location 4 where the YE and NJG fed separately by Kala Wewa. However, beyond location 4 both the YE and NJG joining each other where an opposite relationship can be seen (fig. 5). The EC and TDS for groundwater were generally high compared with the surface water. EC/TDS of all surface water indicate very low values up to location 7. The alkalinity of the groundwater water exhibits more variation however it is low in the surface water. Groundwater is more alkaline in all locations. The hardness of groundwater is also higher than that of surface water.

Irrigation Water quality

The suitability criteria for agricultural water are different from drinking water. Therefore, to assess the suitability of water of YE for irrigation, RSC, EC, SAR, and KR hazard parameters were evaluated (Table 2). Classification of groundwater based on salinity hazard by Wilcox (1955) shows selected locations except for 2, 9 along the YE show good quality water for irrigation. Moreover, there was a significant increase in EC after location 7 downstream, which may be due to the inherent nature of the soil and the bedrock found in the region which supports salt accumulation (fig. 5 & 6).

Table 2: Chemical Parameters used for irrigation and groundwater

Parameter	Formulae	References
Residual Sodium Carbonate	RSC = $(HCO^{3-} + CO_2^{2-}) - (Ca^{2+} + Mg^{2+})$	Eaton, 1950
Sodium Adsorption Ratio	SAR = $Na+/(Ca^{2+}+Mg^{2+}/2)1/2$	Richards, 1954
Kelley's Ratio	KR = $Na+/(Ca^{2+}+Mg^{2+})$	Kelly, 1963
Electrical Conductivity	EC (µS/cm) = 6.2 × 104 × I (mol/L)	McCleskey et al., 2012

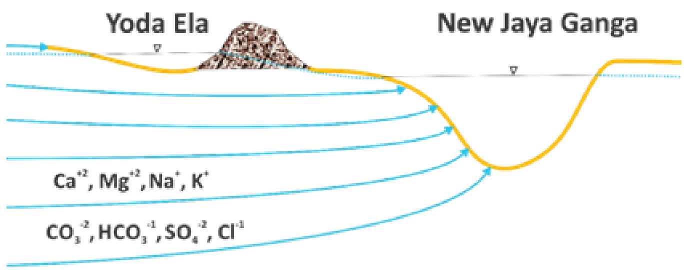

Figure 5: Water quality changes due to groundwater encroachment to NJG compared to surface water in YE

The classification of water quality for irrigation based on RSC (Eaton, 1950) shows downstream of YE, beyond location 8 falls under unsuitable quality, however, most upstream locations are in a marginally suitable range. Excess sodium in water gets adsorbed on soil particles which changes the soil properties and reduces the permeability of soil (Ayers and Bronson, 1975). Therefore, SAR is an important parameter for the determination of the suitability of irrigation water. All locations along the YE are in excellent condition based on SAR classification (Richards, 1954). However, according to the magnesium hazard, only less than 50% is suitable for irrigation. The upper segment of YE up to location 3 has unsuitable water for irrigation and most location of the middle and lower segments show excellent condition (fig. 6). According to Kelly's ratio, the water up to location 7 is suitable for the irrigation, however, beyond location 8 water quality was unsuitable (Kelly, 1963).

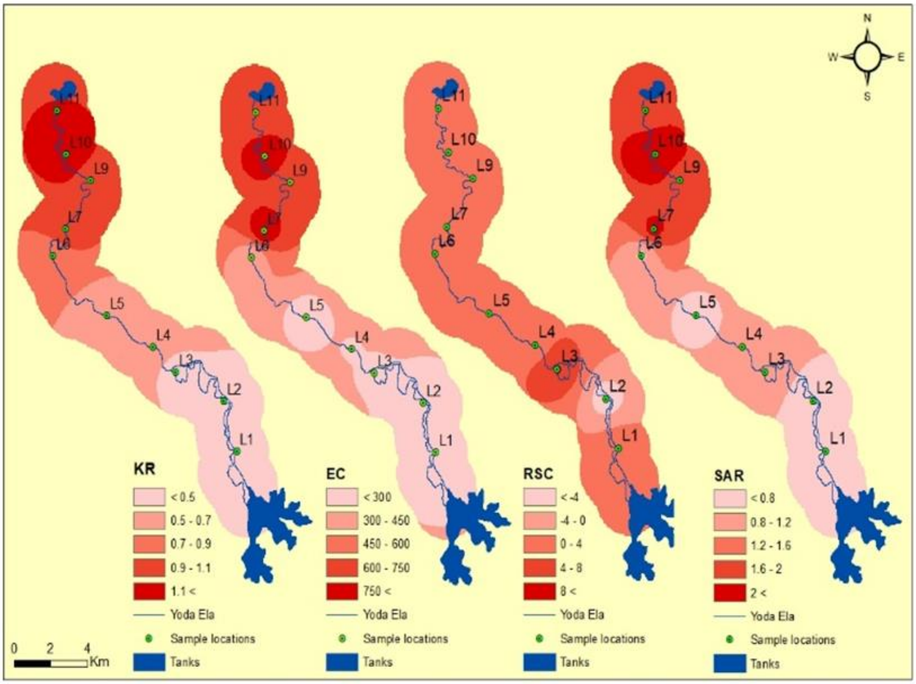

Figure 6: The variations of KR, EC, RSC, SAR along with the YE

Geomorphic control on the hydraulic regime

The elevation difference as shown by the DEM at the two ends of YE is 36 m. The exit at the sluice from Kala Wewa to the YE has an elevation of 131 m above mean sea level (MSL) while the entry point to Tissa Wewa is reaching 95 m MSL. The YE maintains an elegant meandering channel path with a single embankment following the contours (fig. 7) and running through the parched lowlands. The slopes of the canal segments for each basin are Kala Oya 0.266, Modaragam Aru 0.155, and Malwathu Oya 1.003 mkm^{-1} respectively. Even in Machu Picchu, Peru, representing one of those advanced hydraulic structures, maintained its irrigation canals with a slope of 1 to 4.8% (Wright et al., 1997), which is far higher than the slopes of YE which vary from 0.019-0.020%. However, many shorter qanats in the MENA countries show downward gradients vary from 1 -1.5mkm^{-1} but almost horizontal for longer qanats (Smith, 1953; Nasiri and Mafakheri, 2015). When considering the entire flow path, the slope of 0.420 mkm^{-1} was maintained by the YE. The biggest inquiry here is how the ancients maintained such precision in surveying in afforested areas. As pointed out in the DEM, the flow path follows the precision of modern contour patterns which unless by an aerial survey could be a difficult task in afforested catchments. A question has been raised by many Sri Lankan scholars, since it may have either designed by unknown technology from the west, for instance, similar to rudimentary surveying used by Muqannis in the qanats construction, or by methods alien to the current society (Laessøe, 1951; Wessels and Hogeeveen, 2002; Jayasena and Gangadhara, 2006; Yazdi and Khaneiki, 2012; Shiraazi, 2012; Yazdi and Khaneiki, 2016). Moreover, it is common knowledge that such precision with the qanat technology has routinely been obtained with a spirit level and string. Therefore, the answer behind the YE may lay either behind the technology transfer or a consortium of ancient hydraulic experts involved with the dry zone development project in Sri Lanka.

The meandering nature of the YE follows natural morphology as appeared in the contouring patterns and the DEM (fig. 7a). Some loops can be observed with exceeding sinuosity of five that they had a long-distance instead of passing high elevated spurs with a deep cut. At places, some of those cuts are extended approximately 18 m (~60 feet). The YE is a trans-basin canal that conveys water from the Kala Oya to the Malwathu Oya basins with a short distance running through the Modaragam Aru basin in between (fig. 7b). The tributaries of these basins are contributing headwater flow and overland flow to the meandering path of the YE so that only one embankment was constructed akin to represents its functions as an elongated reservoir (fig. 7b). The YE was supplied with overland flow including contributions of headwater tributaries through command areas of 95.1, 15.6, and 15.7 km^2 via Kala Oya, Modaragam Aru, and the Malwathu Oya, respectively (Rathnayake and Jayasena, 2020).

Especially, the side of the single embankment has been designed corresponding to the flow direction of natural tributaries. The tributaries of Kala Oya and Modaragam Aru flow towards west and NNW direction so that the YE embankment was constructed on the left-hand side [LHS] however the tributaries of Malwathu Oya flow towards the east so that the embankment was constructed on the right-hand side [RHS] (fig. 7d). It revealed that the interchange of the respective sides of the embankment is located near Pahalawewa when the YE passing the drainage divide between Modaragam Aru and Malwathu Oya. At the Pahalawewa area, the channel [bearing] perpendicularly crosses the drainage divide by passing approximately 3 km within a deep cut when compared with other areas. Paddy fields and homelands mostly were located downslope below the embankment of YE while the forest covers the upslope above it. A similar phenomenon has been used to augment water supply to Minneriya and Giritale tanks through Elahera (canal diversion) - Minneriya Yoda Ela, which bifurcates after 34 km at Diyabeduma (drainage divide) (Silva et al., 2014). Irrigation water is issued during the cultivating stages so that more water is issued during the ‘Yala’ season [May to end of August] than the ‘Maha’ season [September to March]. Moreover, 10 cusecs are daily discharged regularly to maintain the sustainability of the environment including drinking water to animals while preventing weed growth along the channel.

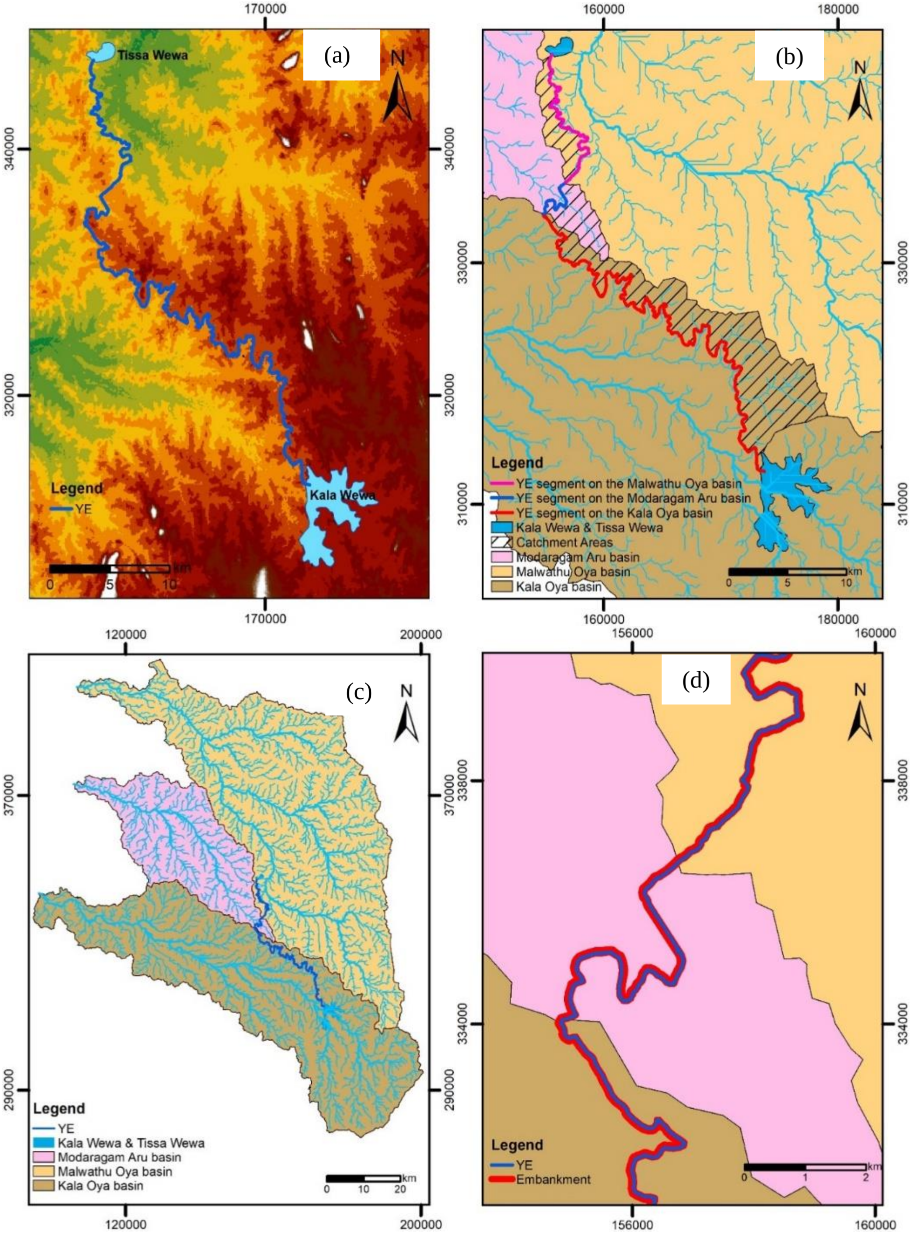

Figure 7: **a): Yoda Ela flow path extracted on to DEM; (b): Kala Oya, Modaragam Aru, and Malwathu Oya drainage basins; (c): YE fed by headward streams from the respective basins as indicated by arrows, and (d): the enlarged section of the area around headwater of Modaragam Aru indicating (by an arrow) how embankment on LHS change into RHS of the YE**

Figure 8: The single embankment associated with the flow of the YE canal left bank (left) and right bank (right). The paddy fields are usually away from the bank towards downslope while forests, shrubs, and herbal plants are away from the point bar upslope

Comparison of Turbidity variations along the channels

Suspended sediments are added to the channels from the Kala Wewa via sluice, in addition to contributions from the tributaries of the natural headwater drainage network and minimal through bank erosion. Among these factors, only the bank erosion is triggered by the discharge of the channels. Though the NJG gets sediments from the croplands as the wastewater, no water is passing to the ancient YE from the farmlands. Turbidity of the discharged water through sluices of Kala Wewa depends on the slope and the local inflow along the flow path. We examined its variations up to Mahailuppallama about 25 km relative to the entire flow path. The theoretical bases were verified by testing the turbidity of the water samples collected. Turbidity values have been plotted vs. the distance along the channels separately. In the first sampling season, sluice discharges were 90 and 800 cusecs from the YE and the NJG respectively and in the second period, they were 125 and 400 cusecs.

The figures illustrate that the turbidity near the sluice of the YE is relatively higher than the values near the sluice of the NJG (figs. 8 and 9). This is because the water discharges to the sluice of the YE are located at a deeper level of the Kala Wewa when compared to that of the NJG so that more suspended sediments tend to leave through the deeper conduit. It is a question of whether such a mechanism associated with the YE is representing a technical artifact of the ancient hydraulic engineers because it removes more sediments from the tank. The YE up to Mahailuppallama shows a gradual decrease of suspended sediments mainly due to the sluggish flow (figs. 8 and 9). There is a sudden drop in turbidity at 26 km (fig. 8) which could be due to sediment load abruptly settled at the nearby Kon Wewa. However, increasing turbidity may be partly supported by the algal growth due to the backwater effect from the Kiralogama Wewa. The segment of YE from Batuwatta up to Tissa Wewa shows an irregular pattern of turbidity variations which may be due to more modern construction implants causing backwater effects or algal growth. At some places, the YE acts as a natural stream with areas having local rapids due to roots of Kumbuk (Terminalia Arjuna) trees and boulders on the constructed channel bed. Besides, this segment is fed by spill water with unregulated discharge coming from the nearby tanks (e.g., Divul Wewa) and some return flow from the paddy fields, so that the turbidity varies from place to place.

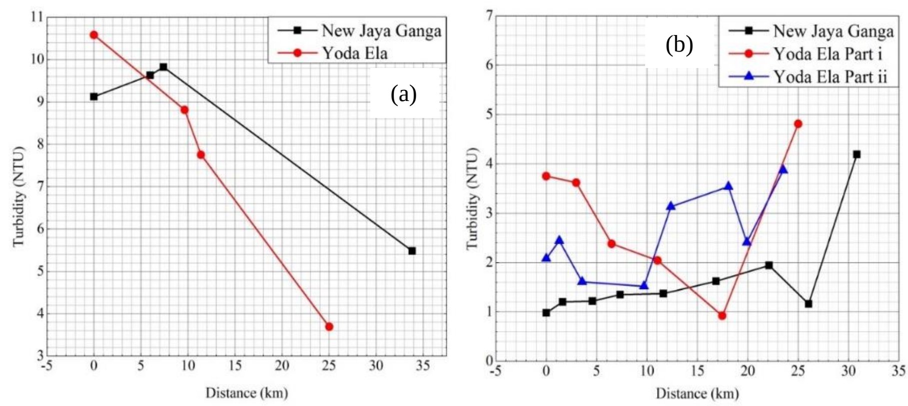

Figure 9: Turbidities of water samples collected a). first term b). second term

It is interesting to show that the ancient YE behave in a very delicate and controlled manner when discharging waters to the nearby tanks. Aerial photographs and satellite images provide the remnant traces of the abandoned YE segment where a different mechanism had been used to supply additional water to the nearby tanks. In the past the YE did not directly discharge water to the tanks; instead, hydraulically feed through the "Thaulla" area (fig. 10). Such technically adaptable sustainable water distributing system observed in the past has been obliterated by the new canal system which uses direct discharge of waters to the tanks causing an increase in the sediment load to the reservoirs in one hand and backwater effects along with the upstream aiding for excessive detachments of sediments along the banks.

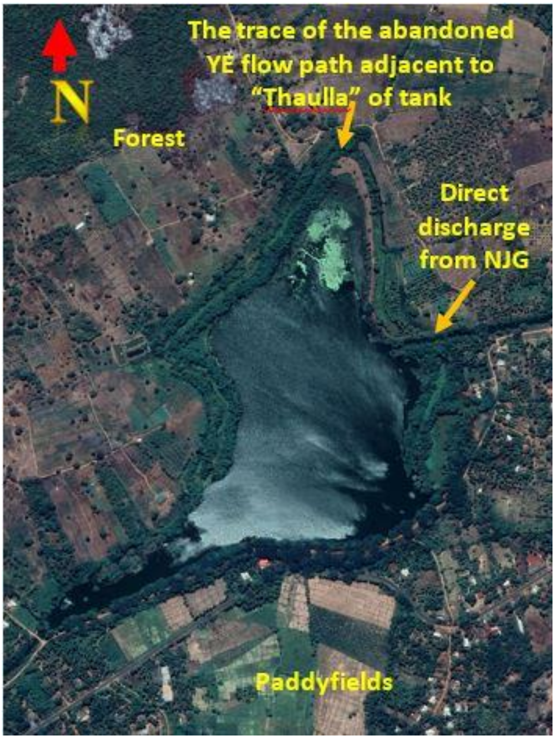

Figure 10: Satellite Image of the Kiralogama Wewa

Comparison of Sediment Deposition

ArcGIS was used to calculate the sinuosity indices on several segments along with the YE. The YE provides a meandering channel corresponding to the overall calculated sinuosity index of 2.20 (Rathnayake and Jayasena, 2020). Along the channel path of the YE with frequent meanders, sediments mostly deposited along the point bars as well as a part of the sediments slowly settled down in the flood-prone areas adjacent to the free boundary of the channel without the embankment (Fig. 11). The NJG with straight embankments, however, display excessive erosion and braided coarse sand bar development causing uncontrolled sedimentation. In general, the channel bed of the YE consists of poorly sorted medium sand while well-sorted fine sand is present in the flood areas indicating such controlled deposition (figs. 12 and 13). The sediments bringing by the sequence of natural tributaries in the headwater regions also tend to settle down in flood areas.

Figure 11: The ancient (left) and modern (right) canals showing contrasting differences in the meandering, sediment deposition, and flow properties

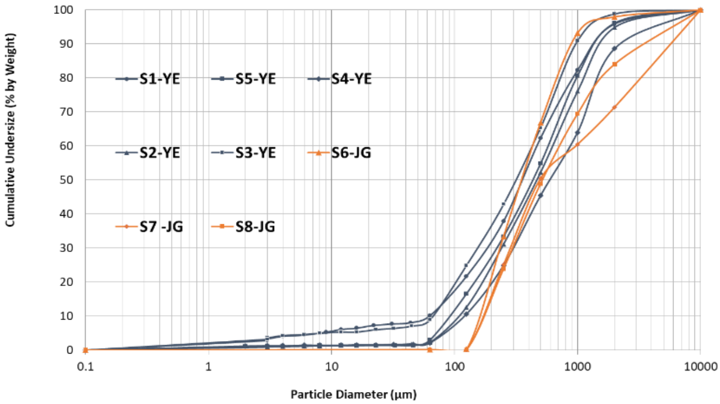

Figure 12: Particle size distribution (PSD) for bedload of ancient YE and NJG

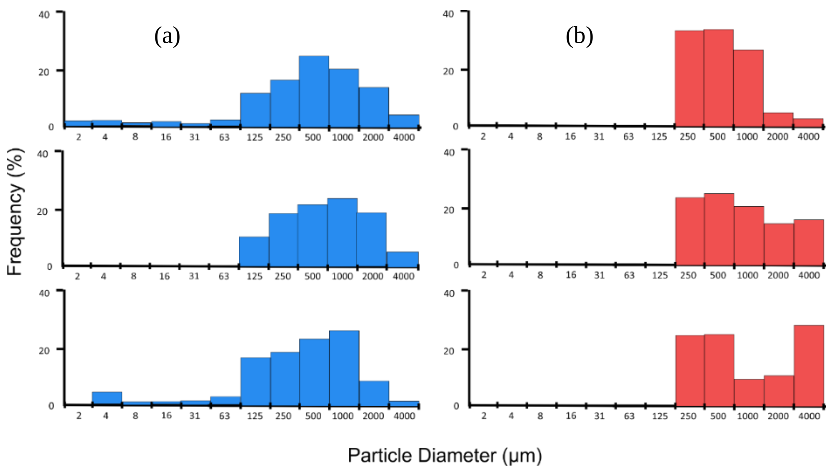

Figure 13: Histograms of sediments collected from a).YE (Blue) and b). NJG (Brown)

SUMMARY

Sustainability was not an issue in the ancient hydraulic regime as evident by the mutual interference covering technical environmental, financial, and societal intervenes delicately balance in the total environment as shown in figure 14. It is clear that the ancient YE had been constructed with in-depth technical evaluation covering natural slopes controlled by drainage divides, sedimentation patterns, flow properties, and environmental sustainability. The YE construction maintained an elegant meandering channel following the contours with a drop of 36 m for the entire length of 87 km. Besides, the longitudinal slopes of the canal segments for each basin are low with Kala Oya, 0.266, Modaragam Aru, 0.155, and Malwathu Oya, 1.003 mkm^{-1} respectively justifying a remarkable technical achievement during the 5th century AD. The YE when crossing through the headwaters of the above drainage basins (command areas of 95.1, 15.6, and 15.7 km^2 respectively) received overland flow contributions through forests that had maintained a good quality unless obliterated by the current system. The single embankment changes from right-hand to left-hand after the drainage divide between Malwathu Oya and Modaragam Aru near Pahalawewa was performed to accommodate only overland flow through headwater forests and shrubs maintaining relatively good quality water. The canal designing method was properly drafted with unknown technical maneuverability to achieve the total environmental objectives. The process of controlled sedimentation along with the point bars and flood-prone areas as observed in the YE is absent in the modern canals. The modern canals display excessive erosion and deposition causing uncontrolled sedimentation coupled with development of braided sand bars. However, the ancient canal represents with sluggish flow and the channel bed consists of poorly sorted medium to well-sorted fine sand, indicating more controlled deposition. The YE flow path does not correspond to the pure sine generated curve as of stable meanders in the mature stage rivers; however, artificially generated meanders crossing such headwater regions of the trans-basin canal sustained a controlled flow

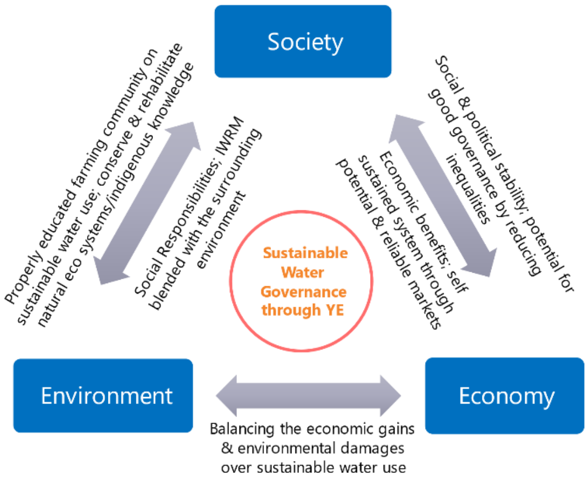

Figure 14: A ternary output showing interrelations of Society, Environment and Economy on sustainable water governance in the YE

The urban-rural linkage with sustainable water governance through YE has demonstrated success in the historical periods. It was achieved through a technically sound physical system, maneuvered by socially accepted norms through education while balancing economic gains on the one hand and sustainability of the total environment on the other. Therefore, we considered this ancient YE serves as a masterpiece of an urban-rural linkage to maintain sustainability in the historical periods. However, modern engineering practices completely obliterated such well-defined natural systems with forcefully maneuvered flow mechanisms by embanking the flow both on the surface and within the subsurface. Considering the dry zone areas consist of similar YE-type canal remnants, one could argue that such technical mechanisms had been serving the same purpose throughout the country during the historical periods.

CONCLUSIONS

YE operated for almost 1500 years, is a classic example demonstrating uninterrupted urban-rural linkage through sustainable water management in the dry zone of Sri Lanka. Advanced Hydraulic Engineering supported by aerial and ground surveys may have been used for the construction of ancient Yoda Ela. Its functions encompass blending with the total environment so that hydrogeochemical, geomorphological, hydrodynamic, economic, and social interactions were balancing to achieve sustainable water governance (fig. 14). The YE can be considered as a properly designed technical product satisfying geo-environmental conditions in dry flat areas. Though the majority believe water supply to the dry zone was increased by modernization, the overall system output has been deteriorating in terms of sustainability and longevity of the productive environment. We concluded that the time-tested sustainable water allocation practice from the indigenous irrigation systems has been obliterated by modernization efforts. It is recommended that existing indigenous irrigation practices need proper evaluations encompassing the total environmental concepts before taking modernization decisions on pure political drive.

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