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Water resource development planning around village cascades: piloting of a scientific methodology in Yan Oya river basin of Sri Lanka

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ABSTRACT

In the dry zone of Sri Lanka experiencing hydrological and weather extremes, non-availability of validated scientific data on stream-flows and groundwater stocks for sufficient time periods, and the presence of large numbers of small and large tanks that divert the water from the streams, make water resource planning a very complex challenge. An integrated modelling exercise was carried out: first using a hydrological simulation model to assess the annual and seasonal water flows of Yan Oya basin of Anuradhapura district and its seven sub-watersheds for 30 years and their dependability; then using a water balance model to analyze the extent to which the current water demands of five selected cascades are being met from the supplies available; and assessing the scope for augmenting the existing storage capacity of the tanks to reduce the irrigation deficits. This article presents the results of the study with regard to: the basin flows and their variability; and water balance scenarios for five selected cascades, with and without modifications in tank storage capacity. The article also discusses how the results from such integrated modelling studies should be used by irrigation planners for taking water management decisions for the basin with decentralized storages like tanks.

Key words: Basin hydrology, Basin water balance, Integrated modelling, Rainfall-runoff modelling, Small storage systems, Tank cascade system

HIGHLIGHTS

- Water resources planning around small systems is complex.
- Non-availability of scientific data on stream-flows, and the presence of large number of small water systems are major challenges.
- SWAT modelling was done to assess the yield of Yan Oya basin.
- The rainfall-runoff model estimated for the basin showed linear relationship.
- Analysis of five cascades with 30 tanks showed that in 16 cases, supply deficit existed.

INTRODUCTION

The island of Sri Lanka mainly consists of plains between 30 and 200 m above mean sea level. In the southwest, ridges and valleys rise gradually to merge with the central highlands. The mountains and the south-western part of the country receive an average annual rainfall of 2,500 mm and is known as the 'wet zone'. The western slopes in the highland receive as high as 4,500 mm (Yoshino & Suppiah, 1984). The 'dry zone', comprised of most of the southeast, east, and northern parts of the country, receives between 1,200 and 1,700 mm of rainfall annually, much of the rain falling from October to January (Burt & Weerasinghe, 2014). The arid northwest and southeast coasts receive the lowest amount of rainfall ranging from 600 to 1,200 mm per year. The wet zone is surrounded by a transitional zone on all sides except on the western side.

The climate of Sri Lanka is classified into two distinguished monsoons – South-West monsoon from mid-May to September (*Yala*) and North-East monsoon (*Maha*) from November to February (Dharmasena, 2010). From mid-May to October, heavy rains occur on the mountain slopes and the south-western parts of the island. From November to February, the north-eastern slopes of the mountains receive up to 1,250 mm of rain. During the inter-monsoonal months from October to November, the southwest, northeast, and eastern parts of the island receive rains from tropical cyclones. During the second inter-monsoonal period (March to mid-May), light thundershowers may occur.

The island country has 16 principal rivers rising in the central highlands and flowing in a radial pattern toward the sea with hydroelectric, transportation and irrigation projects built on some of them. Ancient Sri Lanka had an irrigation civilisation that revolved around small irrigation tanks managed by village communities, established as a 'cascade' along a watershed, in the dry zone. They served the purpose of both drought and flood proofing, given the high inter-annual variability in the rainfall of the region. These small tank cascade systems could be considered as well-designed irrigation systems with a distinctive assembly of land uses. The land and water management practices that were refined and perfected over several centuries in order to match the unpredictable nature of rainfall, along with the special attributes of the landscape, led to this unique system of irrigation development (Panabokke *et al*., 2002). As noted by Panabokke (1999), the builders of these small tanks must have had a profound understanding of landscapes and hydrology of the region.

These tank cascades suffered serious setbacks with the British rule. Though many of the tanks are still used, they are not as efficient as in pre-British times due to non-availability of water owing to the construction of many dams upstream and also unscientific revival of tanks without due regard to the interconnectedness of the tanks that lie in a cascade.

Irrigation systems in Sri Lanka are classified into major irrigation, medium irrigation, minor irrigation and rain fed systems. Major irrigation systems are managed by the central Irrigation Department and Mahaweli Authority of Sri Lanka. Medium and minor irrigation systems come under the Provincial Irrigation Department and the Department of Agrarian Development, respectively. A major irrigation system is defined as one that has a command area of more than 1,000 ha and medium schemes between 80 and 1,000 ha. Small tanks or minor irrigation systems are those having an irrigated command area of 80 ha or less (Sivayoganathan & Mowjood, 2003).

Water resources development planning around small storage systems involve complex considerations in river basins of arid zones due to the high variability in hydrological regime and climatic conditions that change not only the water flows, but also the effective water demands and water diversions on a seasonal and annual basis (Imbulana & Seenithamby, 2020). Therefore, planning of development and management of tanks is a very challenging task. In the dry zone of Sri Lanka, experiencing such hydrological and weather extremes, these challenges are compounded by the non-availability of validated scientific data on stream-flows and groundwater stocks for sufficient time periods, and the presence of large numbers of small and large water systems that divert the water from the lower order streams, such as cascade tanks, and individual village tanks and for which information on storages and diversions are hard to obtain.

As noted by Tennakoon (2015), renovation of individual tanks in isolation has been the practice over the past several decades, but it should not be attempted as it creates more human, physical and environmental problems (Tennakoon, 2015). A study of the cascading tanks of Anuradhapura tank cascade system showed that whatever development effort is undertaken in the dry zone area, it is largely centred on a single tank of the cascading system and that the single tank rehabilitation will not be adequate in this region, and instead the project should involve the whole cascade system. The rehabilitation programmes for the cascading tank systems need improvement in survey, planning and coordination components (Sengupta *et al.*, 2013).

Yan Oya is the fifth longest river in Sri Lanka with a length of 142 km. An integrated modelling exercise was carried out for Yan Oya basin in Anuradhapura province and its sub-watersheds for several years: first using a hydrological simulation model (the Soil Water Assessment Tool) to assess the annual and seasonal water flows (runoff); then using a water balance model to analyze the extent to which the current water demands in the basin are being met from the supplies available from the cascade tanks, especially in the dry years (the years in which the rainfall of an area is much less than the mean annual rainfall of that area is referred to as dry years); and assessing the scope for augmenting the existing storage capacity of the tanks to increase the supplies and to reduce the irrigation deficits that exist, or reducing the demand for water in agriculture, using various 'water balance scenarios'.

In this paper, we will present the results of the study with regard to: the basin flows and their variability and dependability; water balance scenarios for the basin with different water management interventions on the demand and supply side; and the most preferred options for improving water management in the basin to deal with droughts and floods. The study will also deal with the most crucial and yet the least-appreciated aspect of how the results from such integrated modelling studies should be used by irrigation planners for taking water management decisions for the basin with decentralized storages such as tanks.

AGRICULTURE AND TANK IRRIGATION IN THE DRY ZONE OF SRI LANKA

The dry zone forms about 70% of Sri Lanka's geographical area. It is estimated that there are about 18,000 ponds and tanks in the area, some of them as old as 1,500 years. About half of them are classified as 'abandoned' or badly in need of repair. There is increasing use of ground water in the area with private investment in wells and pumps increasing. The reason for this is that they allow multiple-cropping of high-value upland crops, give farmers more discretion over water use, promote diversification of crops and livestock, and increase farmers' incomes. However, many of these wells are running dry or producing poor quality water (IWMI, 2010). The capacity to apply water in specific quantities, at specific times of the year, is possible with agro-wells but not with surface irrigation in a smallholder context.

The livelihood of a large population in the dry zone depends on small tank-based irrigated farming. Before the advent of modern irrigation systems, the dry zones had an intricate environmentally-friendly irrigation system based on a series of tanks known as an *ellengava*. According to Tennakoon (2015) 'An *ellangava* is a very low gradient sluggishly moving water path from a head-end of summit of a micro- or a meso-valley to its lower-end at a large reservoir or a large secondary stream (*Oya),* filling a chain of tanks one after another on its way down, gently spilling over the tanks' excess water into long flat plains in between the tanks and in that whole process, the tanks accumulating, preserving, releasing and guiding water to downstream fields for irrigation'. However, this system of irrigation was ignored during the British rule.

Participation of farmers in the construction, operation and maintenance of irrigation systems was an obligatory requirement during the time of ancient kings and was called 'Rajakariya', which means work performed by the people for the king. This system was abolished during British rule and there was no farmer participation in irrigation management, even after independence in 1948, which led to the farmers expecting all maintenance of the irrigation system to be carried out by the government machinery. Since 1978 there have been many experiments in participatory irrigation management (PIM) in Sri Lanka and PIM was approved as a policy in 1992. Legal backing for Farmer Organizations was granted by the Agrarian Services Act of 1991 and PIM for major irrigation was approved legally in 1994.

As early as the second century BC, the village tank was a well-established feature of the dry zone of Sri Lanka where any form of naturally occurring shallow water was absent in the hard rock region. These were followed by the construction of larger tanks with greater storage capacity and the chain of cascading tanks that stored water as it moved from the summit to the valley. While tanks were the prominent feature of the dry zone, in the mountainous regions, the anicut or amuna system enabled the farmers to increase their cropping intensity (Panabokke, 2001).

Geekiyanage & Pushpakumara (2013) describe how the Tank Cascade System (TCS) has retarded negative consequences of chronic and recurrent droughts, seasonal flooding, land degradation and enhanced food security while helping to attain self-sufficiency in rice. The main components of the TCS are: the interceptor or Kattakaduwa whose main function is to absorb the salts and heavy metals from seepage water across the embankment and act as a downstream wind barrier, a large sized tree belt known as Gasgommana located in the upper inundation area along the tank which acts as a wind barrier and reduces the occurrence of waves in the tank and hence reduces evapotranspiration, the community owned catchment forest or Mukalana, check dams and soil ridges that retain sediments in the upper catchment, and silt-trapping small tanks (Kuluwew) and waterholes in the catchment forests. The dedicated area for foraging birds, a strip of cultivated paddy land adjacent to a tank bund or at the downstream end of the paddy fields abutting the next tank, minimised damage to crop from birds. While the TCS has been successful for over two millennia in sustaining a variety of ecosystems in the dry zone of Sri Lanka and there are lessons that can be adopted from TCSs to ensure the present tank system is sustainable, increase of population and activities like ad hoc raising of dams and spillways has seriously disrupted the hydrological balance in TCSs (Geekiyanage & Pushpakumara, 2013). According to the authors, the indirect benefits from TCS include numerous environmental services from these naturalized habitats. Four distinctive zones identified in a TCS are: (i) tank bund and tank bed, (ii) associated irrigation channels and paddy fields, (iii) protected forest in the catchment and rain-fed uplands, and (iv) gangoda (hamlet or high elevation household area).

Goldsmith & Hildyard (1984) noted that the present irrigation system of most dry zone villages in Sri Lanka is crude in comparison to that which existed under the ancient civilisations and that it is rare to find a village which still has its full complement of operational tanks. Goldsmith & Hildyard (1984) stated: 'To the Irrigation Department, the smaller tanks are arcane relics of the past: their use cannot possibly be justified on the basis of conventional cost-benefit analysis and, therefore, in the eyes of the Irrigation Department, they are simply redundant.'

Bebermeier *et al.* (2017), based on sedimentological data from two connected minor tanks belonging to a tank cascade system that they investigated, concluded that the TCS has buffering capacity against past socio-economic developments and climate changes. They found that the tanks were not affected by severe erosion after the abandonment of the ancient capital Anuradhapura in the 11th century CE, a period that was characterized by socioeconomic instability and increased climatic fluctuations. The authors point to the potential of these tanks as a cornerstone in coping with future climate change in the dry zone of Sri Lanka (Bebermeier *et al.*, 2017).

According to Panabokke *et al.* (2001), minor irrigation systems thrive on unique customary water laws and traditions that have sustained a certain level of rural livelihood, continuous changes to which is the main constraint to development of minor irrigation in the dry zone. Small size of lands, seasonal cultivation and uncertain income has contributed to low levels of investment on minor irrigation. It is also observed that there is significant variation in yield between land irrigated by major and minor irrigation systems. The authors feel that in spite of the questionability of the scope of the tank cascade system in bringing about a great agricultural transformation, being an integral part of the rural landscape and ecosystem, sustainability of the TCS is to be ensured for economic, social and environmental reasons.

Aheeyar *et al*. (2012) noted that the dry zone of Sri Lanka is unproductive without irrigation. Hence irrigation has always been at the forefront of agricultural policy in Sri Lanka. While construction of new irrigation systems and restoration of ancient tank systems was the focus initially, with more and more areas coming under agriculture, the challenge was to provide irrigation to terrain that was more difficult and costly to service. The Tank Irrigation Modernization Project (TIMP) and the Village Irrigation Rehabilitation Project (VIRP) undertaken in the dry zone provided valuable lessons in planning and implementation of rehabilitation projects and in farmer participation in irrigation management. The study called for a coordinated effort in the areas of agro economic research, water management research and effective extension, plus participatory land and water use practices to increase the cropping intensity through more efficient water management together with improvements in cropping systems.

While the inflows into the cascade tanks must have only reduced with increasing cultivation of crops (like coconut) in the catchment, the demand for water from the tanks has increased over the years. Panabokke (1999) developed quantitative criteria for assessing the performance of small cascade tanks based on their hydrological characteristics, viz., ratio of total catchment area of all tanks in a cascade to the total water spread area (CAA/WA), and ratio of the command area and the water spread area (COA/WA). The performance was assessed by assessing the cumulative cropping intensity during the wet season over a five-year period. A study in Anuradhapura district covering 230 tanks showed that 197 of them have an adequate catchment area where the CAA/WA ratio is higher than 8.0. On the other hand, the command area of a very high proportion of these cascades (190 out of 230) was very much in excess of the tank water spread area (COA/WA >1) indicating a higher water demand in relation to the amount of water available in the tanks, and these impose severe stress on the overall hydrological balance of the cascade (Panabokke, 1999).

Panabokke (1999) noted that because of the unrestricted expansion of the 'akkarawela' (the local name for command area) that have taken place over the last century, water supply from the tanks is not able to meet the normal irrigation requirements of the present command area. In the search for a reliable and easily measurable index for characterizing the hydrological endowment of a cascade, it was found that the cropping intensity (CI) of the small tanks located within the cascade, averaged over five consecutive *maha* seasons, provides a reliable and easily measurable integrated value of its hydrological endowment.

In recognition of the dwindling potential of the local catchments to supply water to meet the irrigation needs of the command area, owing to catchment degradation and increasing water demands, which gets compounded by the occurrence of droughts, the Asian Development Bank (ADB) is supporting a major water resources project in Sri Lanka to divert untapped water from the Mahaweli River, the country's largest river basin with headwaters in the southern wet zone, to feed tanks and reservoirs in the northern dry zone, keeping them full throughout the year, thus enabling farmers to plant two crops instead of the usual single crop. The excess water available in the Mahaweli basin will be distributed through new canals that link existing tanks with the new tanks and reservoirs being constructed. This would deliver the runoff into existing tanks that up till now have been isolated from the Mahaweli System. The project is expected to optimize the use of storage infrastructure and minimize the number of new dams that need to be built. The project, when completed, will transfer up to one billion cubic meters of water annually to irrigation systems in the northern dry zone (ADB, 2014).

HISTORICAL DEVELOPMENT OF TANK CASCADES IN THE DRY ZONE OF SRI LANKA

Agriculture in the dry zone of Sri Lanka, the region where most of the country's agricultural activities take place, is facing key challenges related to water security resulting from climate change and variability. The dry zone is where most of the country's agricultural activities are carried out. A substantial number of agriculture-based livelihoods in the dry zone is supported by minor irrigation systems dependent on local rainfall for water replenishment. Dry zones in tropical countries are perceived as highly vulnerable to climate change (Kurukulasuriya & Rosenthal, 2003; Mbow *et al*. 2019). In recent times, the dry zone experienced cycles of alternating droughts and floods, which severely affected the economy of smallholder farmers supported by these irrigation systems.

The village tanks irrigate about 145,000 ha of agricultural land as opposed to 305,000 ha of irrigation by major irrigation facilities (Department of Census and Statistics, 2018). Therefore, village irrigation supports a significant number of farmer families in the dry zone. Services provided by village tanks are more in number and more diverse compared to major irrigation; the former provides water for agriculture, livestock, and domestic purposes. Efficient planning and utilization of water resources in village tanks will, therefore, benefit a significant number of the dry zone population (Imbulana & Seenithamby, 2020).

Dry zone agricultural systems are characterized by smallholder farming. Smallholder agriculture contributes to 80% of the total annual food production of the country and provides a livelihood to nearly 20% of the labour force (FAO, 2018). Recent studies have recognized smallholder farming as highly vulnerable to climate change with a high degree of confidence (Mbow *et al*., 2019). This is supported by tank systems that are largely fed mostly by rains during the Maha season and to a smaller extent by rains during the Yala season. Given the characteristic nature of inter- and intra-seasonal variability in rainfall, high evaporation rates, and paucity of shallow groundwater, the water storage in minor tanks are crucial to sustaining the livelihoods based on crop-livestock farming in the region. During the Major Cropping Season (Maha/wet season), these tanks usually spill. However, paddy cultivation during the minor cropping season (minor cropping/dry season) is often hindered due to insufficient storage in the tanks. Therefore, unless water transfers from external sources are possible, it is prudent to plan and practice adaptation strategies based on water management to ensure the sustainability of agricultural production (Imbulana & Seenithamby, 2020).

Tank cascades in Yan Oya river basin of Anuradhapura

Yan Oya is a major river basin located in Anuradhapura district. The Yan Oya is the fifth longest river in the country. It is approximately 142 km long. The catchment area of the basin receives approximately 2,371 million cubic metres of precipitation in a year, and approximately 17% of the water reaches the sea. It has a catchment area of 1,520 square kilometres. The basin is estimated to have a total of 1,500 small and large tanks, mostly in several cascades. Itakura (1995) carried out a water balance and water flow study for four small tanks in the Thirappane tank cascade in Anuradhapura District. He reported the average runoff to be 30 and 12% of the rainfall for two Maha seasons and for two Yala seasons it was 10 and 4.5% respectively. Itakura also measured the drainage return flow from upstream to downstream tanks. For the Maha seasons, drainage return flows averaged approximately 29% for the tank located at the lowest end of the main valley, and 12% for the tanks located at the lower end of the side valley. The return flows from irrigated paddy fields for Yala seasons were zero. Further, Matsuno *et al*. (2003) attempted to study the water circulation in a cascade, including ground water movement along the cascade.

A study carried out on the *Parana Halmillawewa* cascade in Anuradhapura district by Paranavithana (2010) revealed that there is a lateral formation of tanks at the same elevation adjacent to each other. These tank systems can be considered as lateral cascade systems. The basic reason behind these lateral cascade relations is to store water as much as possible among the population of the village without allowing the overflow to benefit the downstream tanks. These lateral relations were established by single embankment type contour canal connections. These canals were behaving as elongated reservoirs connecting lateral tanks.

Madduma Bandara *et al*. (2010) pointed out that if the water in a cascade is limited in relation to total demand, development (increase in storage capacity) of upstream tanks may be serious implications in terms of water availability for downstream users. The increased use of agro-chemicals for agriculture in recent years, and aquaculture development, has further complicated this situation. This means that the hydrology of the entire cascade needs to be understood and assessed in order to make the best use of the available water resources within the cascade.

A study of shallow groundwater behaviour under tank cascades by Perera *et al.* (2016) showed that the shallow ground water flow was occurring along the cascade but not across the cascades, even within a cluster of cascades. The regional water table contour maps suggested that groundwater movement occurred along the tank cascade within a climatic year, following the geomorphologic landscape and natural gradient.

While irrigation is a major user of water for economic production functions in the dry zone, several studies have highlighted the ecological values of the tanks. According to several studies, including Dharmasena (2010), Madduma Bandara *et al.* (2010), Perera (2010, 2011) and Marambe *et al.* (2012), the tank ecosystems play a vital role such as maintaining the biodiversity, wild fruit trees, protecting medicinal plants and supplying fibre used for making mats, in addition to maintaining the habitat of a number of species of fauna. Further, tank reservations around the tanks, especially '*Gasgommana*', '*Perahana*', and '*Kattakaduwa*', play a significant role for the sustainability of the tank as well as maintaining the biological diversity spots in the dry zone.

NEED FOR BASIN-WIDE HYDROLOGICAL PLANNING OF CASCADES

Most village tanks are in cascades. The spillover from the upstream tanks and excess runoff from the irrigated paddy fields contribute to the inflows of the downstream tanks in a cascade, apart from the runoff generated in the intermediate catchment. The excess water from these cascades flows into streams that form the tributaries of a major river, whose drainage area is a river basin. Hence, assessing effective water availability for future planning would require considering the river basin as the unit of analysis instead of the tank or cascade catchments.

At present, there is no methodology available for the planning of water management at the sub-watershed level or river basin level. However, the tank network is hydrologically connected such that the tanks in the downstream cascades in a basin receive drainage water and spill water from upstream cascades. If the cropping season is planned at the basin level, cropping intensity and farmer's income can be increased while minimizing crop losses.

A similar situation is encountered in the neighbouring peninsular region of south India, which has hundreds of thousands of such tanks, including individual tanks, cascade tanks (Kumar & Vedantam, 2016). The Indian states of Tamil Nadu, Telangana, Karnataka and Andhra Pradesh had taken up large-scale tank rehabilitation programmes in the recent past, but they were not based on any scientific assessment of the catchment hydrology, often leading to over-designed tank storage capacities with no improvement in their performance after rehabilitation (Kumar & Vedantam, 2016; Kumar *et al.*, 2017; Kumar, 2018).

In recent times the interest in seasonal planning at cascade level rather than for individual tanks has increased, and several projects are being implemented using the cascade as the spatial unit for water resources planning (Imbulana & Seenithamby, 2020). However, for more balanced development of water resources across the river basin, basin-wide planning is essential. Such an approach becomes essential when there is large spatial variation in resource endowment between cascades and between sub-watersheds within the same basin due to variations in climate, soils, landuse and rainfall.

However, well-informed water resources development planning is quite challenging in these systems, due to the paucity of data. Streamflow measurements, groundwater monitoring, tank water balance and physical data are very scarce in village irrigation systems as opposed to major irrigation systems. However, considering the vulnerability associated with village irrigation systems and their socio-economic significance, it is vital to develop a framework to facilitate seasonal cultivation and water resources development planning at the river basin level.

First and foremost, hydrological planning of the catchment is essential to decide on the optimum level of utilization of the limited water resource to maximize agricultural outputs, without compromising other water use sectors. Water resources planning should follow an integrated approach, looking at the basin as a whole, considering plausible future pathways shaped by climate, demands, water availability, technology etc.

APPROACH, METHODS AND ANALYTICAL PROCEDURES

The approach and methodology involved that for assessing the surface water availability in the basin and its sub-watersheds and preparing the water supply and demand balance for some of the cascades. Though it was originally planned to have the water balance for the entire basin, due to the presence of nearly a thousand small and large tanks, it was technically not possible to do the basin configuration. Hence, the water balance modelling was done for five selected cascades, after ascertaining the availability of excess water for harnessing at the aggregate level, by comparing the total dependable yield (75%) with the total existing storage capacity of tanks, as a way of rapid assessment. The main criterion for choosing these five cascades for detailed analysis was that they fall in the project area (also known as the hotspot area) of the Climate Smart Irrigated Agriculture project (implemented by the government of Sri Lanka through the Ministry of Agriculture and Ministry of Irrigation, and funded by the World Bank), which involved rehabilitation of cascade tanks as a major component. Yan Oya basin does not have historical stream flow data. Hence, in order to estimate the runoff, the SWAT model was used, and the runoff for different rainfall events was estimated for different hydrological response units (HRUs).

The approach, methodology and analytical tools used for the study consisted of: (1) collecting rainfall, weather (relative humidity, sunshine, temperature and wind velocity) and stream flow data from concerned agencies; (2) obtaining the DEMs of high resolution for river basins and delineate the basin and sub-watershed, cascade and micro-watershed boundaries using ARC-GIS Map 10; (3) extracting the topographical characteristics (basin area, catchment slopes, stream length, stream slope, etc.) by processing the DEM using ARC-GIS; (4) procuring remote sensing-based soil, land use and land cover maps to a scale of minimum 1:2,500 on raster format, compatible with ARC-GIS model or equivalent; (5) estimating the flow series for ungauged watersheds – required for simulating the inflows into the tanks – using the SWAT model that uses the rainfall data, land use and land cover data and processed DEMs; (6) estimating the demand of water in the command area of the tanks in different seasons using FAO CROPWAT model; and (7) running the WEAP model for a selected cascade that considers the inflows into each tank, the storage space in the tanks and the releases to the command areas to meet the various demands and evaporation, and the resultant outflows downstream.

Basins were divided into seven sub-watersheds mainly considering stream networks, and the boundaries of sub-watersheds were delineated following boundaries of the tank cascade catchments for estimating the runoff at the level of each of the hydrological units. The DEM was processed for estimating the storage-area-elevation curve of different tanks.

Types of data and sources

The types of data used for the analysis included: daily rainfall data for different gauging stations for 30 years (from 1991 to 2020), daily weather data; spatial data on land cover and soils, digital elevation model of the basin area to delineate the micro-catchments, cascades and sub-watersheds; area under different crops in different seasons; the data on crop sowing and harvesting in different seasons, soil infiltration properties; storage-area-elevation curves for the tanks in the selected cascades; daily evaporation rates; carrying capacity of the tanks; daily flow series for runoff of selected cascades.

PHYSICAL AND SOCIOECONOMIC CHARACTERISTICS OF YAN OYA BASIN

Topography and drainage

Yan Oya (river) originates in the hilly areas of Dambulla and Sigiriya, flows towards the northeastern region of Sri Lanka and escapes to the sea at Pulmoddai in Trincomalee district as a fourth order stream (Gunarathna *et al.* 2016). The Yan Oya river basin has a drainage area of 1,551.3 km^2. The river has a length of 142 km. The basin has seven sub-watersheds. The stream network of the basin is shown in Figure 1(a). Figure 1(b) shows the micro catchment of the basin, as demarcated by the DEM.

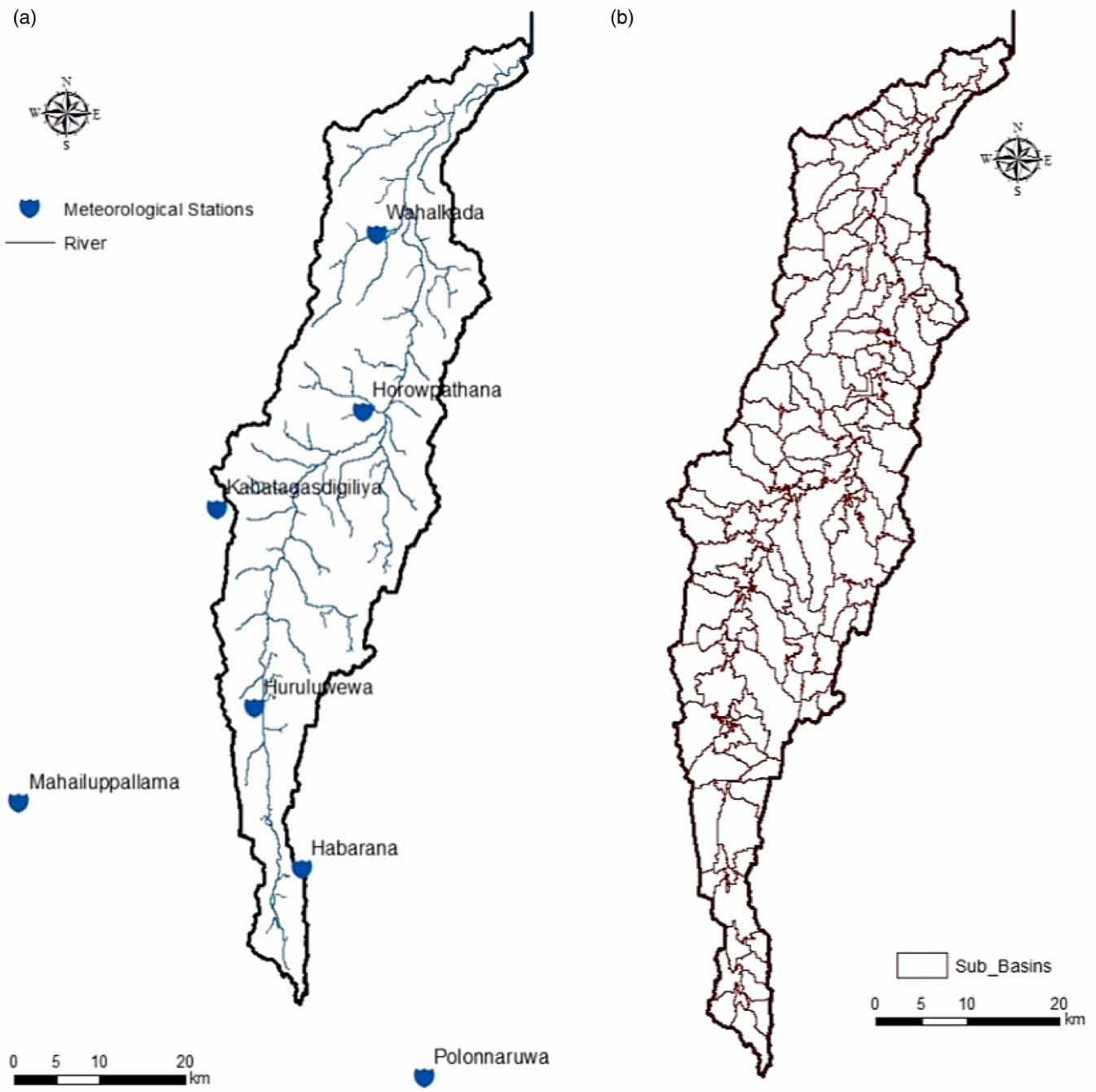

Fig. 1. | (a) Stream networks, (b) sub-watersheds.

Rainfall, climate and variability

The annual average rainfall in Anuradhapura area is 1,405 mm. The basic climate data for Anuradhapura is shown in Table 1. A distinct bimodal rainfall distribution is shown, dividing the year into two main cultivation seasons. 'Yala' (the minor) season receives highly variable rainfall from the first inter-monsoon. 'Maha' (the main) season receives the largest part of annual rainfall from both the second inter-monsoon and the northeast monsoon. This seasonal rainfall not only contributes to rainfed agricultural production but also to replenish the reservoirs in the dry zone. There is little seasonal variation of temperature, but diurnal variation is wide for the island. The diurnal range increases from the coastal areas towards the interior. In general, the diurnal range of temperature is about 8 °C in the coastal areas and increases towards the inner portion of the country, recording 14 °C in the central highlands. The decrease in temperature with altitude is greater on the western than eastern slopes of the highlands. Relative humidity varies from 70% during the day to 90% at night.

Besides the quantum of annual rainfall, one important factor that affects the water supplies available from existing storage systems and the irrigation water demand is the pattern of occurrence of rainfall. Even distribution of the rainfall not only increases the effective storage of the tanks, but also reduces the irrigation water demand of crops. The data pertaining to rainfall distribution show that though there is some rainfall in every month, 45% of the total annual rainfall occurs during the Maha season (November–February) and only 18.5% occurs during the Yala season (May–September). A good amount of rainfall also occurs during the two inter-monsoonal periods.

The (spatial) average annual rainfall of Yan Oya river basin for the period from 1991 to 2019 is presented in Figure 2. The average annual rainfall of the basin varied from the lowest at 844 mm in 2016 to the highest at 2,406 mm in 2016. The year 2011 can be considered as a very wet year (a wet year is one in which the annual

Table 1. | Rainfall and temperature at Anuradhapura (8.33°N 80.40°E, at 89 msl).

Attribute	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total/average
Rainfall	102	47	79	175	91	22	32	41	74	258	253	231	1,405
Temp (max)	30	32	35	33	32	32	32	33	33	32	31	30	32.08
Temp (min)	21	22	23	24	25	25	25	24	24	23	22	22	23.33
Temp (average)	25	26	28	27	28	27	27	27	27	27	26	25	

Source: Dharmasena (2010).

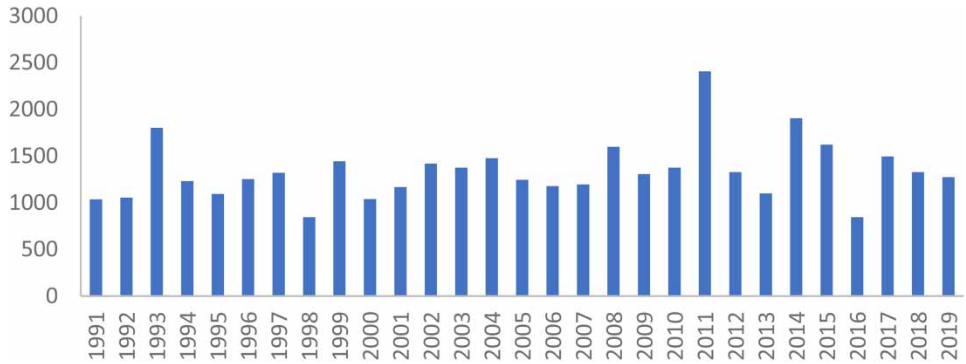

Fig. 2. | Average annual rainfall of Yan Oya river basin: 1991–2019.

rainfall of an area is much higher than the mean annual rainfall), and 2016 as a very dry year. Thus, the highest rainfall recorded (in 2011) is nearly 185% higher than the rainfall of the driest year (i.e. 2016). However, the rainfall is not uniform across the basin. The point rainfall data corresponding to the five rain-gauging stations show that the variation is significant. The graphical representation of the rainfall of five gauging stations of the basin for the period 1990–2019 is presented in Figure 3. It shows that in most years (barring a few instances), the rainfall varied widely between gauging stations. The rainfall difference in 2011 between the third station (Kahatagadsigilia) and the fifth (Wahalkada) was 1,571 mm.

The coefficient of variation in rainfall was estimated to be 24% for Habarana, 29% for Huruluwewa, 27% for Kahatagadsigilia, 26% for Horowpothana and 36% for Wahalkada. Hence the highest inter-annual variability in rainfall was observed in the last gauging station – from 431 to 2,852 mm. The mean monthly rainfall (for 30-year period) of the five gauging stations are presented in Table 2. The Maha season rainfall is around 878 mm in

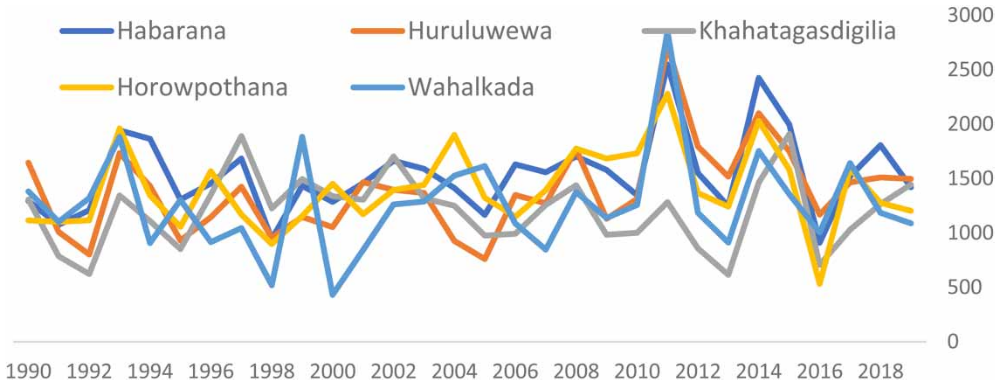

Fig. 3. | Historical annual rainfall of five gauging stations of Yan Oya basin: 1990–2019.

Table 2. | Mean monthly rainfall of the five gauging stations in Yan Oya basin.

	Monthly rainfall (mm)				
Month	**Habarana**	**Huruluwewa**	**Kahatagadsigilia**	**Horowpothana**	**Wahalkada**
Jan	160	124	97	140	138
Feb	92	77	62	69	71
Mar	61	55	49	51	50
Apr	116	112	101	97	49
May	88	84	66	77	59
Jun	5	5	9	11	10
Jul	28	23	26	34	25
Aug	50	53	43	60	49
Sep	86	75	82	114	86
Oct	221	229	214	187	175
Nov	301	262	228	264	295
Dec	325	285	226	295	256

Habarana, 748 mm for Huruluwewa, 613 mm for Kahatagadsigilia, 768 mm for Horowpothana and 760 mm for Wahalkada. The percentage rainfall during the Maha season therefore ranges from the lowest at 51% for Kahatagadsigilia to 60% for Wahalkada. Therefore, as compared to Anuradhapura district, the rainfall is more skewed in Yan Oya basin area, with the proportion of the annual rainfall occurring during the Maha season (51–60%) greater than that of the district (45%).

Groundwater in Yan Oya basin

The knowledge and understanding about groundwater resources in Sri Lanka is very poor, particularly when it comes to individual river basins that are small in size. As discussed earlier, a lion's share of the drainage area of Yan Oya is in Anuradhapura. The district of Anuradhapura, and for that matter the entire north central province, is underlain by hard rock crystalline formations belonging to Regolith aquifers as characterized by Herbert *et al.* (1988), and a 'fracture zone' aquifer which occurs at depths below 30 m. The nature of occurrence of this Regolith aquifer, its behaviour and its distribution in the landscape, has been described by Panabokke (2002).

This shallow Regolith aquifer is mainly confined to the narrow inland valley systems of the undulating mantled plain landscape situated within the agroecological region of DLL. The thickness of this Regolith is variable and is not greater than 10 m in this region. Both agro-wells and the domestic wells exploit this shallow phreatic aquifer which is present within this Regolith substratum up to depths of between 6 and 8 m. The water holding and transmissivity capabilities of the Regolith aquifer are comparatively limited (Panabokke, 2003).

During the early years of agro-well development in the north central region it was observed that most of these agro-wells were distributed around the small tanks and in close proximity to the village tank settlements. The indigenous knowledge of the villagers was used in siting these agro wells. It is now well recognized that the shallow Regolith aquifer is located around the valley floors of the cascades of small tanks. Field measurements carried out in Sri Lanka indicate a very good correlation between tank water levels and groundwater levels in the command area under these tanks. As a result, occurrence of water in the shallow Regolith aquifer is mainly confined to the main valleys which make up the cascade of small tanks (Panabokke, 2003).

The use of shallow groundwater from the Regolith aquifer zone in the hard metamorphic rock areas of the north central region has progressed very rapidly during the last 15 years. The erstwhile Agricultural Development Authority (ADA) had been promoting agro-well development in Anuradhapura district from the mid-1980s, in order to help the small-farmers cultivate high value crops under lift irrigation during the dry 'Yala' season. It is estimated that in the Anuradhapura district alone nearly 15,000 open dug wells (agro wells) were constructed, usually 5–10 m depth and 5–7 m in diameter, in order to abstract limited quantities of water for irrigating small plots 0.5–1.0 acre size to cultivate chilli, onion and other vegetables. Because of the shallow nature of these Regolith aquifers and their low specific yield, excessive pumping could easily lead to a rapid lowering of water levels to hit the bedrock (Panabokke, 2003).

Land use and land cover

The landuse details of Yan Oya basin are given in Table 3. A large proportion of the basin area (nearly 64%) is under forests and grassland. A little more than one sixth of the basin area is under paddy cultivation. One tenth of the basin area is under homesteads. Nearly 8% of the area is under water bodies, especially the small and large tanks. Thus, the existing landuse of the basin supresses the runoff from the rainfall as forests and grass, which occupy a large proportion of the basin drainage area, increases infiltration. The paddy wetlands also impound rainwater and reduce the runoff. The soil in the basin is reddish brown earth, with occasional rocky patches.

A pictorial representation of the land use map of Yan Oya basin is presented in Figure 4(a). The soil cover map is presented in Figure 4(b).

Table 3. | Land use in Yan Oya river basin.

Land use	Area (km^2)	Percentage area of the basin
Coconut	0.2	0.01
Forest	486.8	31.37
Grass	502.7	32.39
Homesteads	156.7	10.1
Marsh	6.6	0.43
Open forest	5.3	0.34
Paddy	265.3	17.1
Rock	8.6	0.55
Water	119.8	7.72

Population, and socioeconomic dynamic

Though the Yan Oya river basin falls in four districts of the north central province of Sri Lanka, a large share of the basin is in Anuradhapura district. A map showing the location of the basin vis-à-vis the four districts, viz., Anuradhapura, Trincomalee, Matale and Polonnaruwa, is given in Figure 5. The region is largely agrarian. The only major urban area falling in the area is Anuradhapura, and it is located outside the basin. In 2012, the total population of the basin was estimated to be 170,447. Since basin-wise population data are not officially available, this has to be estimated for arriving at the population of the basin area, the average rural population density of Anuradhapura district (110.68 persons/km^2) in the year 2012 and the drainage area of the basin were considered, as there are no cities or major towns inside the basin.

The basin has a total of 14,281 ha under paddy cultivation and 9,567 ha under upland cultivation. With the presence of around a thousand tanks, irrigation is quite extensive in the basin. The basin also has one of the oldest reservoirs, namely Huruluwewa, located in the Upper Yan Oya catchment, and has a gross storage capacity of around 60 MCM.

There is an ongoing project to build a reservoir across Yan Oya river at Pangurugaswewa in Trincomalee district, upstream of the existing Yan Oya anicut. The project envisages constructing an earthen dam and a saddle dam and 34 km-long canals to irrigate 5,696 ha of land in Anuradhapura and Trincomalee Districts. This includes 2,200 ha of existing commands under Padaviya scheme (a tank-based irrigation scheme built around a tank named Padavi Kulam), where severe water deficit is felt, especially during the Yala season. The scheme will also provide water to 140 ha land under the Wahalkada scheme and 100 ha of new land along the Left Bank canal and existing command areas under Yan Oya anicut (750 ha) and minor schemes located in Mee Oya basin (1,735 ha) in Trincomalee District (source: http://irrigationmin.gov.lk/yan-oya-project/index.html).

HYDROLOGICAL ASSESSMENT OF THE YAN OYA BASIN

The SWAT model was run to generate the runoff for each rainfall event and the total runoff for different seasons (Yala, Maha and the two inter-monsoonal seasons) was estimated along with the annual runoff. Figure 4 shows the rainfall-runoff relationship for the spatial average annual rainfall of the basin. The relationship between rainfall and runoff is linear. The R^2 value is 0.80. Hence the model is robust. The flows were also estimated for all seven sub-watersheds. They are presented in Table 4. The average annual runoff for the whole basin is 634.20

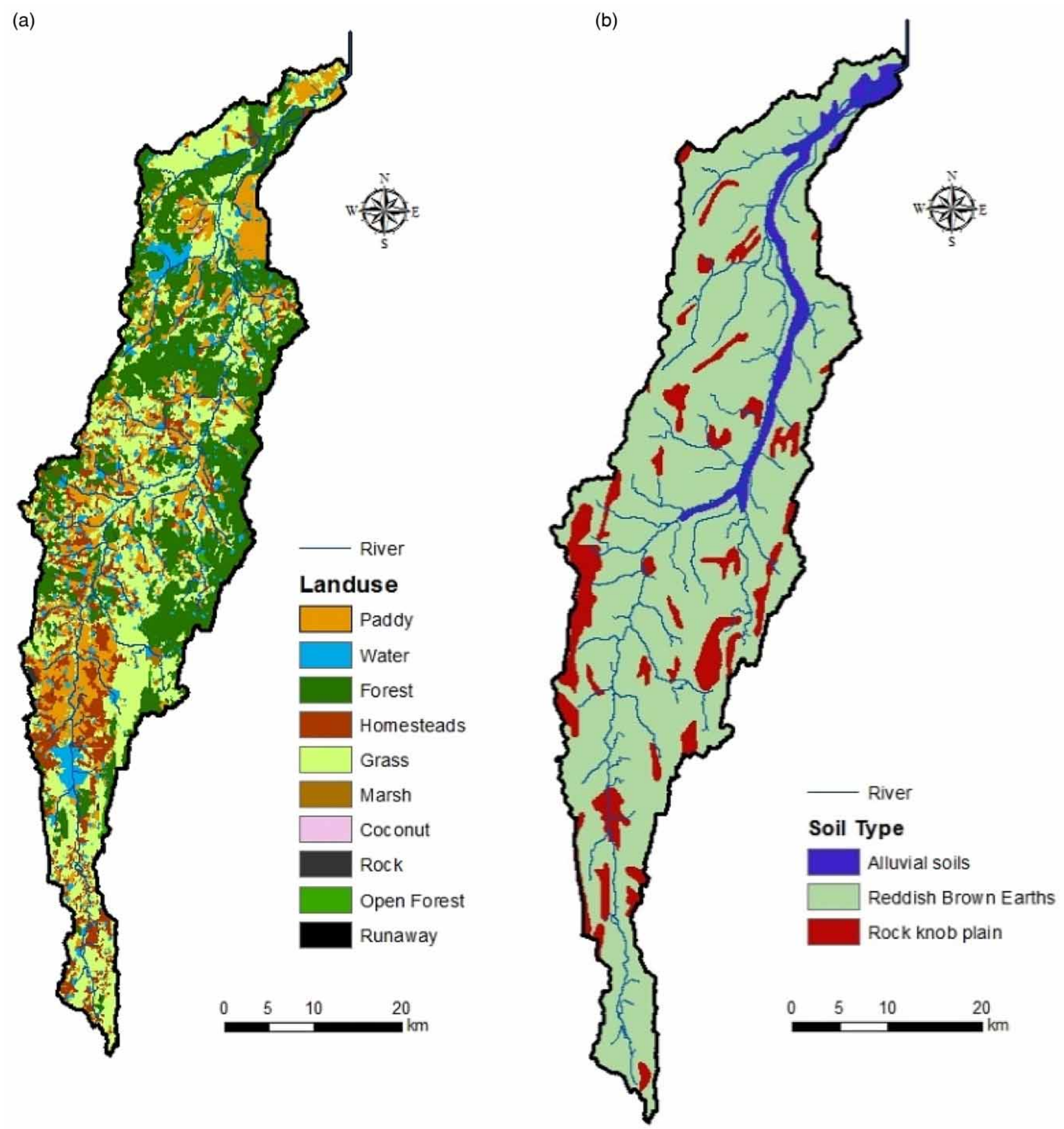

Fig. 4. | (a) Land use map of Yan Oya basin; (b) Soil map of Yan Oya basin.

MCM, against an average rainfall of 1,450 mm. Spatially, the mean annual rainfall varies from 1,472 mm in the uppermost sub-watershed to the lowest at 1,259 mm in the lowermost sub-watershed. The mean value of the runoff ranges from 0.33 for sub-watershed #3 to a maximum of 0.51 for sub-watershed #5. Hence, the average runoff generation potential is highest in sub-watershed 5.

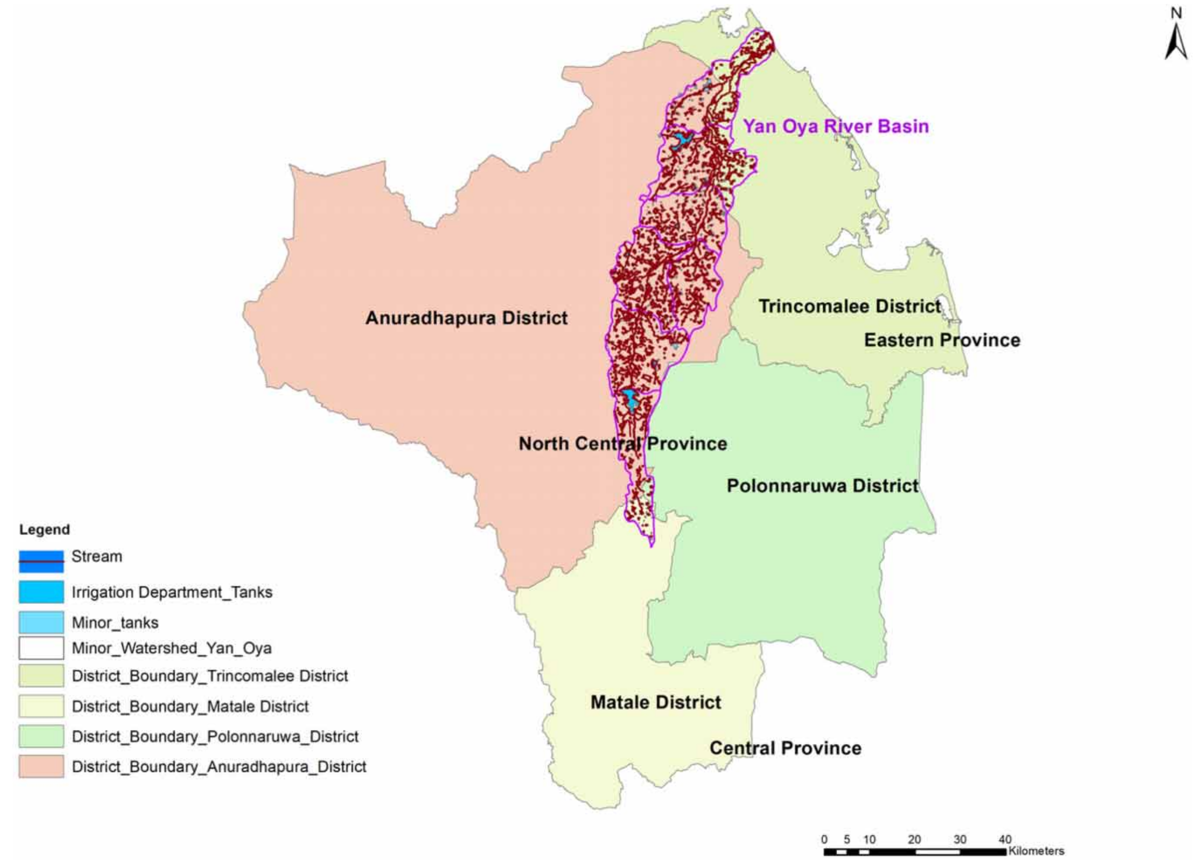

Fig. 5. | The location map of Yan Oya river basin.

Table 4. | The average rainfall, average annual yield and yield variations of different sub-watersheds of Yan Oya basin.

Basin hydrological attributes	1	2	3	4	5	6	7
Catchment area (km^2)	195.64	258.09	239.85	172.05	192.42	264.95	228.63
Average annual rainfall (mm)	1,472	1,332	1,270	1,400	1,406	1,274	1,259
Average annual discharge (MCM)	71.5	93.2	79.9	70.6	97.6	128.2	93.2
Highest annual discharge (MCM)	244.9	257.6	148.7	156.9	218.5	433.9	324
Lowest annual discharge (MCM)	16.5	29.5	32.7	23.7	32.2	19.7	13.8
CV in annual discharge (%)	65	52	40	44	45	64	66
Average annual run-off per unit area (MCM/km^2)	0.36	0.36	0.33	0.41	0.51	0.48	0.41

The coefficient of variation in annual flows ranges from the lowest at 40% for sub-watershed #3 to the highest at 66% for sub-watershed #7. The high coefficient of variation indicates high inter-annual variability in annual flows. From the table, it is evident that not only is there spatial variation in the rainfall and the surface water potential between sub-watersheds, but there is significant year to year variation in the runoff potential between years. These two factors pose significant challenges for basin-wide water management.

As per our estimates, for the basin as a whole, the runoff can be anywhere in the range of 285 to 1,773 MCM, with a remarkable variation in the annual rainfall – from 844 to 2,403 mm (see Figure 6). The runoff coefficient ranged from the lowest at 0.15 when the rainfall was 1,252 mm (1996) to the highest at 0.47 when the rainfall was 2,406 mm. The rainfall-runoff relationship is Y = –480.78–0.8335 X. As per the rainfall-runoff model, there would be no runoff until the annual rainfall exceeds 480 mm. This means the traditional approach of using a single runoff coefficient for estimating the runoff, irrespective of the quantum of rainfall, would lead to incorrect results.

That said, the traditional approach in Sri Lanka to estimate runoff for water resources planning has been to fix the coefficient on the basis of landuse, slope and soils. As per this method, the runoff coefficient estimated for the basin is 0.346. The annual runoff estimated using the traditional method and SWAT are compared and presented in Figure 7. The estimates show that in normal (normal rainfall years are those during which the annual rainfall of the area is very close to the mean annual rainfall) and low rainfall (dry) years, the traditional method tends to over-estimate the runoff, while in wet years, it underestimates the same. This is mainly because the traditional approach does not consider the effect of antecedent soil moisture on the runoff generating potential of the land surface.

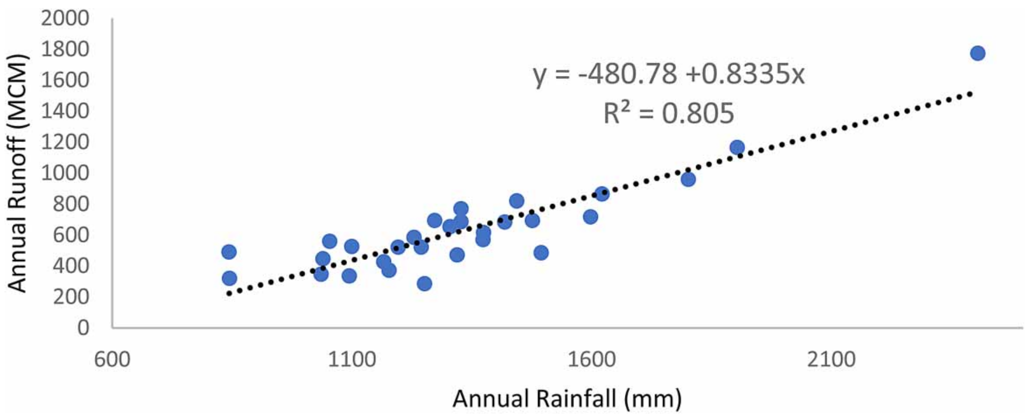

Fig. 6. | Rainfall-runoff relationship for Yan Oya basin.

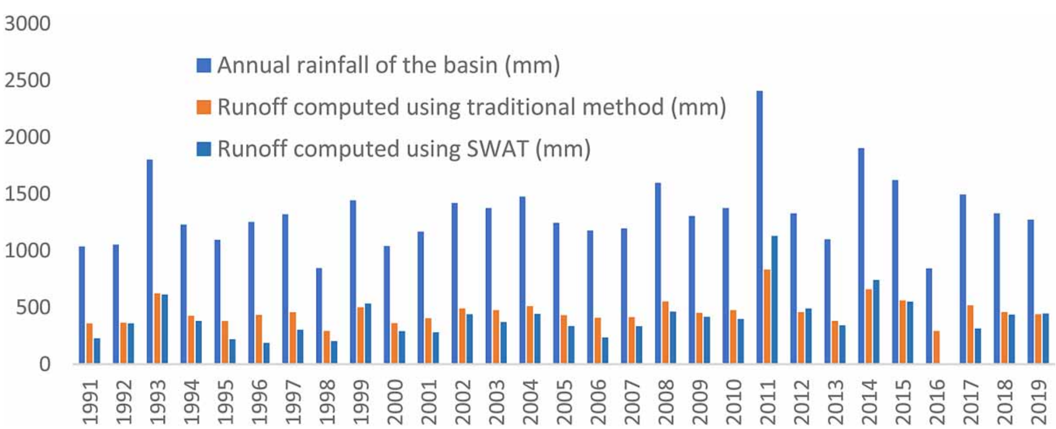

Fig. 7. | Comparison of runoff estimates from traditional methods and SWAT.

The rainfall-runoff relationship established on the basis of the estimated annual yield for the seven sub-watersheds of the basin is presented in Table 5. The variable X represents the rainfall in mm and the variable Y represents the total runoff from the sub-watershed. Power function was found to be the best fit model in all the cases. With very high R^2 values (with a minimum of 0.65 and a maximum of 0.90 in two cases), all the rainfall-runoff models are quite robust. The rainfall-runoff model for the third sub-watershed has the lowest R^2 value.

For regions like the dry zone of Sri Lanka, due to such high variations in annual yield of catchments, generally 75% dependable yield is considered for the purpose of planning irrigation schemes. The 75% dependable yield of the basin is estimated to be 407.30 MCM, and that of the sub-watersheds ranged from the lowest at 45.6 MCM for sub-watershed #1 to the highest at 77.2 MCM for sub-watershed #6.

WATER BALANCE SCENARIOS OF YAN OYA BASIN

As discussed in the Methodology section, there are 980 tanks and 107 tank cascade systems in the Yan Oya basin. It is not practical to develop the water supply-demand balance for the whole basin, considering the demand for water in the individual tank commands and supplies from each tank. Out of the 107 cascades, a total of five cascades were chosen for modelling. The tank cascades are namely, Ibbigewewa, Medawechchiya TCS, Dikwewa TCS and TCS 1 and 2 of Trincomalee. The first TCS has five tanks, the second one has 13 tanks, the third has six tanks and the fourth also has six tanks.

The WEAP configuration for each tank cascade takes into account the inflows from the catchment of individual tanks, the excess flows from the tank/s located upstream, the rainfall falling directly into the tank, the demand for water in the command areas and the return flows of water from the demand sites into the river downstream. The storage-area-elevation curve of the tank and the pan evaporation data of the nearest weather station are used to estimate the evaporation from the tanks for different stages of storage, which is determined by the change in inflows and outflows (releases and overflow downstream). The WEAP configurations for the five cascades are presented in Figure 8(a)–8(d). The fourth diagram covers two cascades, i.e. cascade 4 and cascade 5, of Trincomalee.

The names of tanks, the names of cascades in which they fall, their storage capacities and average estimated inflows are presented in Table 4. The water releases from the tank cascade systems to meet the seasonal irrigation water demands in the command areas and the seasonal water demands of the commands were simulated for a 29-year period, and the 'dependability' of the system was estimated on the basis of the percentage number of years for which the entire irrigation demand of the command area during the Maha and Yala seasons was met from the supplies (the dependability of irrigation water supply from a tank is estimated by taking the ratio of number of years during which the design command area is fully irrigated against the total number of years

Table 5. | The rainfall-runoff regression estimates for the seven sub-watersheds.

Sub-basin no.	Regression equation	Coefficient of determination (R^2)
1	$Y = 0.0000064\ X^{2.211}$	0.819
2	$Y = 0.0003280\ X^{1.738}$	0.778
3	$Y = 0.0008710\ X^{1.594}$	0.653
4	$Y = 0.000845\ X^{1.5600}$	0.723
5	$Y = 0.001617\ X^{1.5145}$	0.696
6	$Y = 0.000978\ X^{1.6398}$	0.900
7	$Y = 0.000866\ X^{1.6144}$	0.900

Source: Authors' own estimates.

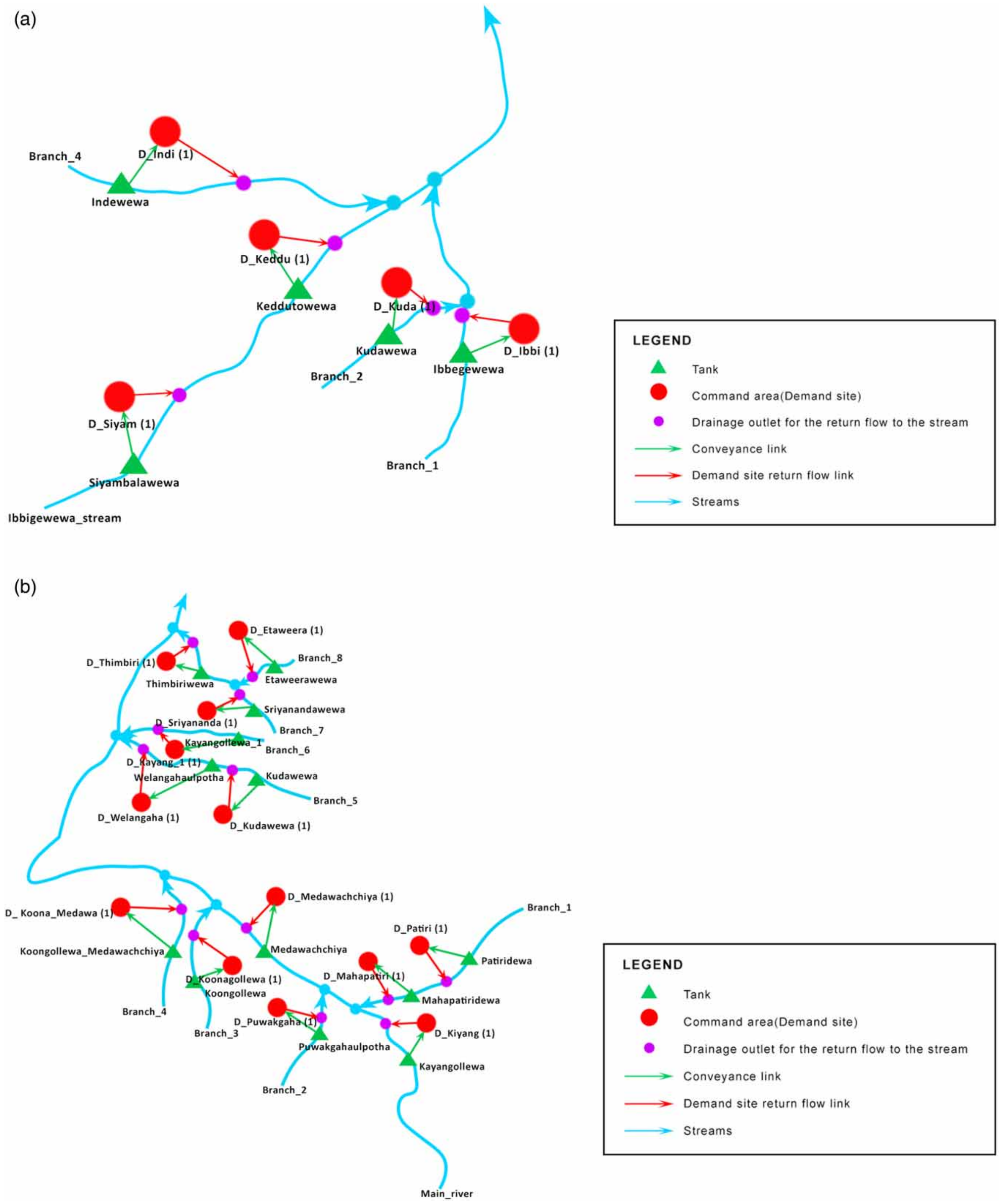

Fig. 8. | (a) WEAP configuration for Ibbigewewa tank cascade system; (b) WEAP configuration for Medawechchiya tank cascade system; (c) WEAP configuration for Dikwewa tank cascade system; (d) Tank cascade system 1 and 2 of Trincomalee. (*Continued*.)

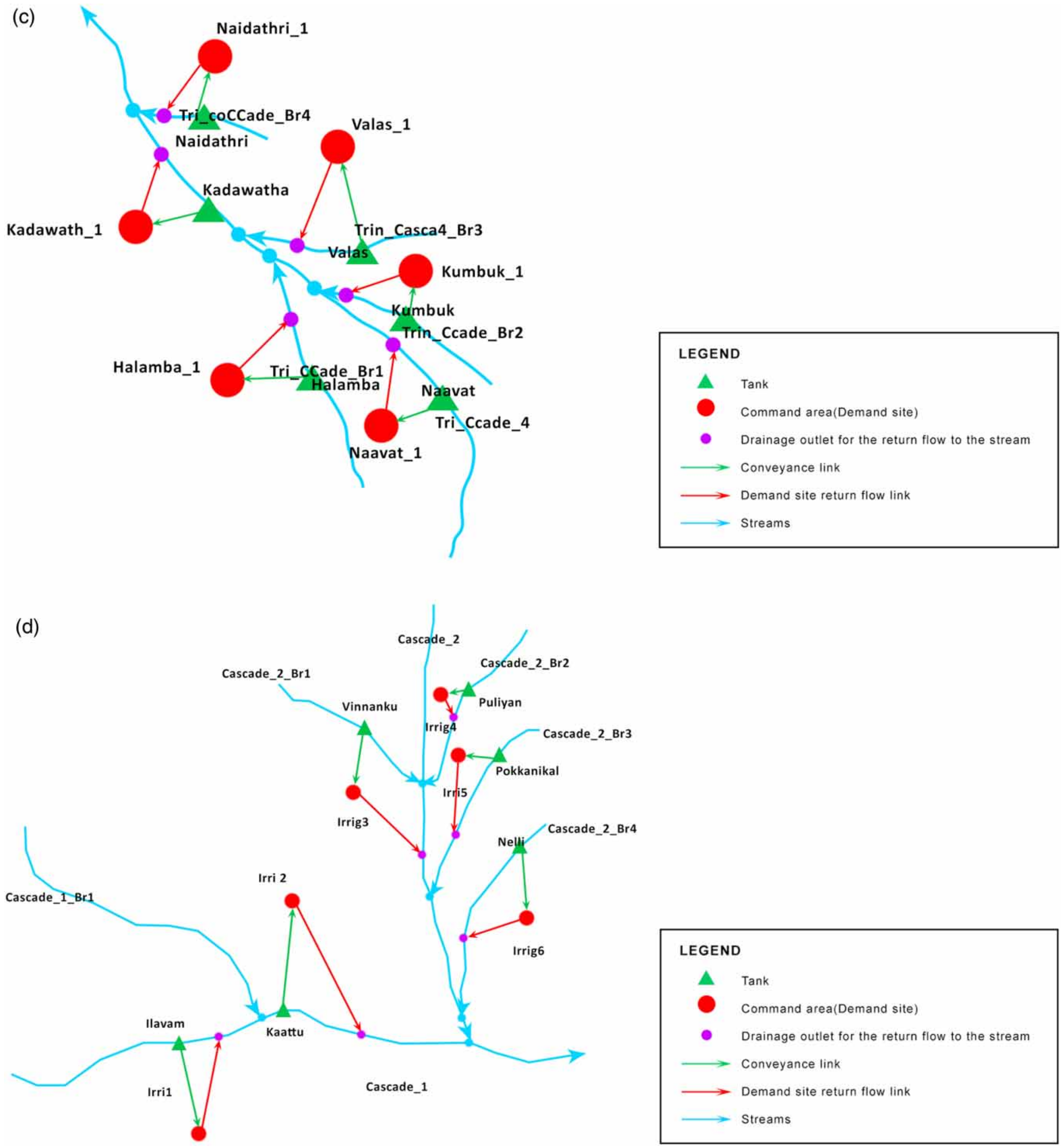

Fig. 8. | Continued.

considered, as a percentage). The irrigation demands of the cropping system were estimated using a modified Penman method, with the help of the FAO CROPWAT model. The seasonal inflows were estimated on the basis of the rainfall of the catchment and the rainfall-runoff relationship established for the sub-watershed in which the cascade falls.

The estimated monthly inflows into one of the tanks in Medachchiyawewa TCS, namely Kayangolewa, for the period January 1991 to December 2019, is given in Figure 9. The sharp variation in inflows across seasons and years is visible from Figure 9. Such sharp variation in inflows would seriously affect the water supply potential of the tank.

Table 6 presents the tank storage capacity, the irrigation water demand, and the dependability of the supplies from the commands against the average inflows from the catchments of the cascades. As can be seen, in many of the cases, the dependability of the tanks is low. Table 6 shows that in 14 out of the 30 cases (highlighted in dark grey), the average annual inflow is more than the annual irrigation demand, and the storage capacity of tanks (which determines the supply potential) is also more than the demand (like Ibbigewewa tank and Indiwewa tank in the first TCS; 1st, 5th, 6th, 11th and 13th tanks in Medawachchiya TCS; all the tanks in Dikwewa TCS). No intervention is required in these tanks in the current situation as in more than 75% of the years, the demands are fully met.

However, there are many tanks (13 in number) where the average inflow is less than the annual irrigation demand (like the 2nd, 3rd 4th, 7th, 10th, and 12th tanks in Medawachchiya TCS; Siyambalawewa and Keddutuwewa tanks in Ibbigewewa TCS; and the first four and the 6th tank in Trincomalee TCS). They are highlighted in light grey. In those cases, the dependability of supplies is poor. Increasing the storage capacity of the tanks does not help in those situations.

However, there are cases where the average inflow is higher than the average annual irrigation demand, yet the dependability of supplies is poor (Puwakgahaulpotha and Kudawewa in Medachchiyawewa TCS, and Kaattuthennamurippu Kulam in Trincomalee 1 and 2). As is evident from the table, in the case of Kaattuthennamurippu Kulam, this was due to the low storage capacity of the tank. The dependability can be increased by increasing the storage space. However, in the case of the other two tanks, the reason is the sharp variation in the inflows and demands in some low rainfall years. While the inflow drastically reduces, the irrigation demand of the crops increases due to low effective rainfall, with the result that the demand is higher than the inflow during those years.

The next level of analysis using a new scenario modelled in WEAP looked at the impact of storage capacity enhancement of some of the tanks in each cascade on the water supply potential. The storage capacity of some randomly chosen tanks (which offered low dependability) in each cascade was increased by 20%, and the models were rerun. The tanks chosen were: Ibbigewewa and Keddutuwewa in Ibbigewewa TCS;

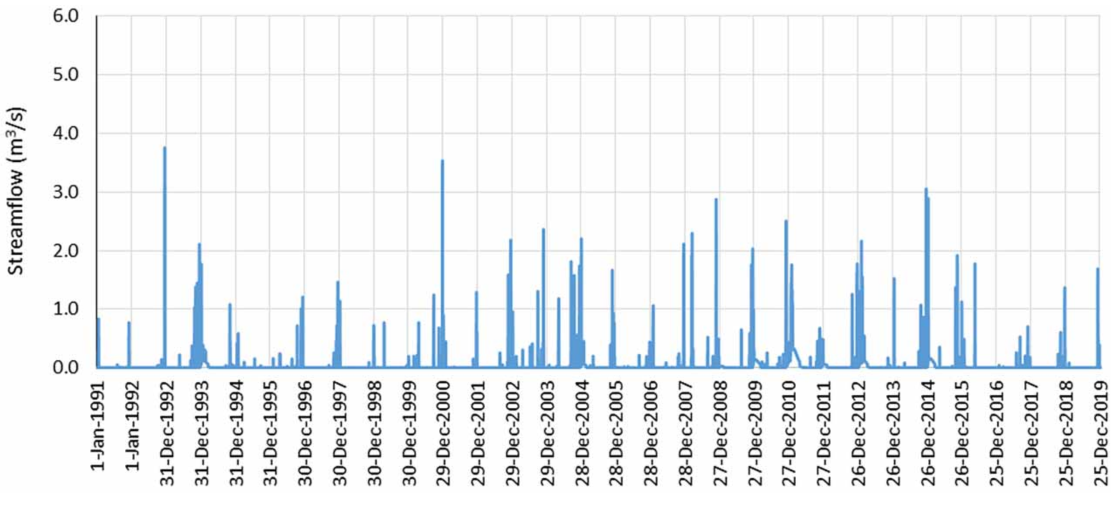

Fig. 9. | Inflows into Kayangolewa tank of Medachchiyawewa TCS.

Table 6. | Storage capacity, average inflows, irrigation water demands and the dependability of the tanks in the five selected cascades.

Cascade name	Total no. of tanks	Tank name	Average inflows into tanks (MCM/year)	Storage capacity (m^3)	Total annual average irrigation demand (MCM)	Dependability of the supplies from the tanks	Dependability of the supplies from the tanks[a]
Ibbigewewa TCS	05	Ibbigewewa	0.633	256948	0.102	**98.6**	**98.6**
		Siyambalawewa	0.069	91421	0.139	50.6	50.6
		Keddutuwewa	0.188	214123	0.269	**58.9**	**59.8**
		Indiwewa	0.214	192711	0.032	100.0	100.0
		Kudawewa	0.060	86850	0.056	73.3	73.3
Medawechchiya TCS	13	Kayangolewa	0.983	423796	0.315	80	80
		Patiridewa	0.484	429654	0.214	65	65
		Mahapitireddawa	0.498	556640	0.728	65	65
		Puwakgahaulpotha	0.453	226296	0.214	72	72
		Medawachchiya	1.649	2391757	0.788	95	95
		Koongollewa	0.094	222712	0.037	98	98
		Koongollewa-Medawachchiya	0.093	286300	0.166	**59**	**60**
		Kudawewa	0.206	163520	0.032	60	60
		Welangahaulpotha	0.052	38430	0.283	**60**	**61**
		Kayangollewa1	0.122	43812	0.385	45	45
		Siriyanandawewa	0.106	202969	0.093	82	82
		Etaweerawewa	0.169	104098	0.245	56	56
		Thimbiriwewa	0.146	294498	0.037	100	100
Dikwewa TCS	06	Halambawewa	0.188	38186	0.069	**85.1**	**85.6**
		Kadawathwewa	0.296	37265	0.573	85.0	85.3
		Kumbukwewa	0.096	104115	0.254	**79.6**	**81.1**
		Navaatkulam	0.349	76459	0.229	85.1	85.3
		Naidathriwewa	0.103	168716	0.183	95.1	95.1
		Valaswewa	0.073	79861	0.115	85.1	85.6
Trincomalee 1 and 2	06	Puliyan Kulam	0.135	36000	0.458	38.0	38.0
		Vinnanku Kulam	0.359	5000	0.390	45.0	45.0
		Pokkanikal Kulam	0.044	1100	0.080	42.0	42.0
		Nelli Kulam	0.057	12000	0.390	32.0	32.0
		Kaattuthennamurippu Kulam	0.959	50000	0.928	51.0	51.0
		Ilavam Kulam	0.349	5000	0.000		

[a]With 20% storage enhancement for selected tanks in the cascades.

Koongollewa-Medawachchiya and Welangahaulpotha in Medawachchiya TCS; and Welangahaulpotha and Kumbukwewa in Dikwewa TCS). The analysis found only negligible improvement in the dependability of the irrigation systems in meeting the command area water demands (see last column of Table 6).

HOW CAN THE WATER ECONOMY OF YAN OYA BASIN BE BETTER MANAGED?

The tanks in the dry zone of Sri Lanka are relics of an ancient hydraulic civilization that existed in the island. Many of these tanks are now lying abandoned. While some are still performing well as multiple use water systems, some require rehabilitation. As Goldsmith & Hildyard (1984) noted, the present irrigation system of most dry zone villages is crude in comparison to that which existed under the ancient civilisations. The authors noted: 'To the Irrigation Department, the smaller tanks are arcane relics of the past: their use cannot possibly be justified on the basis of conventional cost-benefit analysis and, therefore, in the eyes of the Irrigation Department, they are simply redundant'. Anuradhapura, which houses the capital of the ancient Kingdom, is known for many historical tank cascades.

The Yan Oya river basin, though small in size (with a drainage area of 1,541 km^2), has 980 small and large tanks that dot the region's landscape and their cascades, which are 107 in number. While the basin receives an average annual rainfall of around 1,452 mm, the inter-annual variability in rainfall is very high. The rainfall also varies spatially. The monsoon rains are also seasonal in nature. Around 40% of the rains occur during the Maha season in Anuradhapura district in which the basin is located. These tanks are important sources of irrigation for the paddy wetlands that support the region's rural economy. Apart from providing resilience against droughts, they help mitigate floods. Many of them are hundreds of years old. Streamflow data are not available for Yan Oya river basin, either for the main river or its small tributaries. Data on the physical characteristics of these tanks, such as storage-area-elevation curves, were also not available. These factors, when combined, pose significant challenges for hydrological planning for water resources development around the tank systems.

In this study, we began with an assessment of the hydrology of the basin, using the SWAT model, with the data on landcover, hydrological soil types, daily rainfall, and a digital elevation model of the basin. The runoff was estimated for each rainfall event using time series data of daily rainfall for 30 years (from 1990 to 2019) and the rainfall-runoff relationship for both annual and seasonal rainfalls were established for the seven sub-watersheds of the basin, along with the basin as a whole. Though the rainfall-runoff relationship was found to be linear, the estimates showed very high variability in the runoff, with changes witnessed in annual rainfall. Accordingly, the basin's dependable (runoff potential) yield at 75% probability of exceedance was estimated along with that of the seven sub-watersheds at 407.30 MCM.

The rainfall-runoff models estimated by the study were used to compute the inflow series for five cascades identified for intensive study, with a total of 30 tanks. The storage-area-elevation curves were established on the basis of high-resolution digital elevation models for the tanks, which were used for flow routing, on the basis of inflows, releases, evaporation and the storage space available in the tanks. The data on cropping in the command areas of the tank cascades during the Maha and Yala seasons, the weather data for the region and the growing season were used to estimate the irrigation demand for the crops grown during the season. It was assumed that 50% of the cultivable area shall be irrigated during the Yala season.

The WEAP model was used to simulate the water demand-supply scenarios of each of the five cascades and the tanks inside for the changing inflow conditions due to the varying rainfall for a 29-year period, and accordingly, the dependability of the tanks as irrigation water supply sources was estimated. The analysis of the aggregate yield of the basin and its sub-watersheds against the storage capacity of the tanks that already exist for supplying water for irrigation in the respective drainage areas, and the subsequent estimates of the dependability of the tanks, based on comparison of the average supplies with the average irrigation demands in the command areas, showed that though for 15 tanks there is supply deficit (reflected in low dependability), the scope for enhancing the storage capacity to enhance the supply does not exist as the average inflows are much less than the demand. Only in the case of one tank (viz., Kaattuthennamurippu Kulam), there is both need for and scope for enhancing the storage capacity as the current storage capacity is poor and there is sufficient inflow from the catchment.

The next level of analysis using scenarios modelled in WEAP looked at the impact of storage capacity enhancement of some of the tanks in each cascade on the water supply potential. The analysis found only negligible improvement in the dependability of the selected irrigation tanks in meeting the command area water demands. This basically meant that the inflows from the catchments of those tanks is fully appropriated through the available storage space in the tanks.

Future analysis of water balance should integrate the shallow aquifer system of the basin for the analysis in lieu of the hydraulic interaction between tanks and shallow groundwater (Herbert *et al.*, 1988). The analysis should focus on the impact of water use efficiency improvement for crops in the command area through adoption of efficient irrigation technologies and cropping pattern shift on water demands and groundwater resources, especially in the Yala season when the inflows are much less and the irrigation demands are high.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Aheeyar, M. M. M., Padmajani, M. T. & Bandara, M. A. C. S. (2012). *Farmer Participation in Irrigation System Management: Achievements and Drawbacks*. Research Report No. 151. Hector Kobbekaduwa Agrarian Research and Training Institute, Colombo.

Asian Development Bank (2014). *Sri Lanka: Water Resources Development Investment Program*. Technical Assistance Consultant's Report, prepared for the Ministry of Irrigation and Water Resources Management, Colombo, Sri Lanka, December 2014.

Bebermeier, W., Meister, J., Withanachchi, C. R., Millelhaufe, I. & Schütt, B. (2017). Tank cascade systems as a sustainable measure of watershed management in South Asia. *Water* 9, 231. doi:10.3390/w9030231., www.mdpi.com/journal/water

Burt, T. P. & Weerasinghe, K. D. N. (2014). Rainfall distributions in Sri Lanka in time and space: an analysis based on daily rainfall data. *Climate* 2, 242–263.

Department of Census and Statistics (2018). *Statistical Abstract.* Retrieved from Department of Census and Statistics, Sri Lanka. Available online: http://www.statistics.gov.lk/Abstract2018/index.asp?page=chap5/

Dharmasena, P. B. (2010). Evolution of hydraulic societies in the ancient Anuradhapura Kingdom of Sri Lanka. In *Landscapes and Societies*. Martini, I. P. & Chesworth, W. (eds.). Springer Science and Business Media BV, The Netherlands.

FAO (2018). *Country Gender Assessment of Agriculture and the Rural Sector in Sri Lanka.* Food and Agriculture Organization of the United Nations, Bangkok, Thailand.

Geekiyanage, N. & Pushpakumara, D. K. N. G. (2013). Ecology of ancient tank cascade systems in island Sri Lanka. *Journal of Marine and Island Cultures* 2, 93–101.

Goldsmith, E. & Hildyard, N. (1984). *Traditional Irrigation in the dry Zone of Sri Lanka*. Available at: http://www.edwardgoldsmith.org/1034/traditional-irrigation-in-the-dry-zone-of-sri-lanka/

Gunarathna, M. H. J. P., Kumari, M. K. N., Nirmanee, K. G. S. & Jayasinghe, G. Y. (2016). Spatial and seasonal water quality variation of Yan Oya in tropical Sri Lanka. *International Journal of Applied and Natural Sciences V*, 45–56.

Herbert, R., Ball, D. F., Rodriqo, I. D. P. & Wriqht, E. P. (1988). The regolith aquifer of hard rock areas and its exploitation with particular reference to Sri Lanka. *Journal of the Geological Society of Sri Lanka 1*, 64–72.

Imbulana, N. & Seenithamby, M. (2020). Hydrological and water balance studies to evaluate options for climate resilience in smallholder irrigation systems in Sri Lanka. *Water Policy 22*(6), 1024–1046.

International Water Management Institute (2010). *Water Issue Brief, ISSUE 7 2010.* IWMI, Colombo.

Itakura, J. (1995). *Water Balance Model for Planning Rehabilitation of A Tank Cascade Irrigation Systems in Sri Lanka (Working Paper No. 37)*. International Irrigation Management Institute, Colombo, p. 5.

Kumar, M. D. (2018). *Water Policy, Science and Politics: An Indian Perspective*. Elsevier Science, Amsterdam.

Kumar, M. D. & Vedantam, N. (2016). Groundwater use and decline in tank irrigation? Analysis from erstwhile Andhra Pradesh. In: *Rural Water Systems for Multiple Uses and Livelihood Security*. Kumar, M. D., James, A. J. & Kabir, Y. (eds.). Elsevier Science, Amsterdam, pp. 145–182.

Kumar, M. D., Bassi, N., Kishan, K. S., Chattopadhyay, S. & Ganguly, A. (2017). Rejuvenating tanks in Telangana. *Economic and Political Weekly 51*(34), 30–34.

Kurukulasuriya, P. & Rosenthal, S. (2003). Climate Change and Agriculture: A Review of Impacts and Adaptations. *Environment Department Papers; no. 91. Climate Change Series*. World Bank, Washington DC.

Madduma Bandara, C. M., Yatigammana, S. & Paranavithana, G. (2010). *Scientific validation of some traditional land and water management practices under Village Tank Cascade Systems*, in Economic Review (Vol. 36) People's Bank, Colombo.

Marambe, B., Pushpakumara, G. & Silva, P. (2012). Biodiversity and agrobiodiversity in Sri Lanka: village tank systems. In *Biodiversity Observation Network in the Asia-Pacific Region*. Nakano, S. I., Yahara, T., Nakashizuka, T. & Yamamoto, S. (eds.). Springer, Japan.

Matsuno, Y., Tasumi, M., van der Hoek, W., Sakthivadivel, R. & Otsuki, K. (2003). Analysis of return flows in a tank cascade system in Sri Lanka. *Paddy and Water Environment 1* (4), 173–181.

Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N. & Xu, Y. (2019). Food security. In: Shukla, P. R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V, Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. & Malley, J., eds. *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. In press.

Panabokke, C. R. (1999). *The Small Tank Cascade Systems of the Rajarata, Their Setting, Distribution Patterns and Hydrography*. IIMI-MASL, Colombo, Sri Lanka, p. 39.

Panabokke, C. R. (2001). The nature and properties of small tank systems of the dry zone and their sustainable production thresholds. In *Food Security and Small Tank Systems in Sri Lanka: Proceedings of the Workshop Organized by Working Committee on Agricultural Science and Forestry* (Gunasena, H. P. M., ed.)., 9 September 2000. National Science Foundation (NSF), Colombo, Sri Lanka, pp. 33–47.

Panabokke, C. R. (2002). *Nature of Occurrence of Regolith Aquifer in the Hard Rock Reqion of North Central dry Zone and its Rational Exploitation for Aqrowell Development Symposium. On use of Groundwater in Sri Lanka*. AESL/PGI A, Peradeniya.

Panabokke, C. R. (2003). Nature of occurrence and sustainable use of groundwater resources for agriculture in the north central, north western and north eastern regions of Sri Lanka. *Tropical Agricultural Research and Extension 6*, 8–13.

Panabokke, C. R., Tennakoon, M. U. A. & Ariyabandu, R. d. S. (2001). Small tank systems in Sri Lanka: issues and considerations. In *Food Security and Small Tank Systems in Sri Lanka: Proceedings of the Workshop Organized by the Working Committee on Agricultural Science and Forestry, 9 September 2000*. Gunasena, H. P. M. (ed.). National Science Foundation (NSF), Colombo, Sri Lanka, pp. 1–6.

Panabokke, C. R., Sakthivadivel, R. & Weerasinghe, A. D. (2002). *Small Tanks in Sri Lanka: Evolution, Present Status and Issues*. International Water Management Institute, Colombo, Sri Lanka, p. 73.

Paranavithana, G. N. (2010). Some civil engineering aspects of village tanks. In: *Proceedings of the National Conference on Cascade Irrigation Systems for Rural Sustainability*. Central Environmental Authority and Plan Sri Lanka, Colombo, p. 16.

Perera, M. P. (2010). *Irrigation Heritage of Sri Lanka (Sinhala Version)*. Center for Environmental Justice, Colombo.

Perera, M. P. (2011). *Beyond the Truth: Potential for Re-Establishment of Ancient Tank Reserves in the Dry Zone of Sri Lanka*. National Geography Conference, University of Sri Jayewardenepura, Nugegoda.

Perera, M. P., Nianthi, K. W. G. R. & Madduma Bandara, C. M. (2016). Agro-well development and its impact on groundwater table depletion in tank cascades in the dry zone of Sri Lanka. *International Journal of Arts and Commerce 5*(5), 66–77. Available at: http://www.1929-7106 www.ijac.org.uk66-77.

Sengupta, S., Jacob, N. & Khan, H. (2013). *Plan for Restoration of Cascading Tank Systems in Anuradhapura District*. IUCN, Sri Lanka.

Sivayoganathan, C. & Mowjood, M. I. M. (2003). Role of extension in irrigation water management in Sri Lanka. *Tropical Agricultural Research and Extension 6*, 49–55.

Tennakoon, M. U. A. (2015). *Traditional Dry Zone Irrigation – Ecosystematic Concepts Revisited*. Available at: http://www.sapsri.lk/traditional-dry-zone-irrigation-ecosystematic-concepts-revisited-and-reconceptualized/ (accessed 20th Nov. 2017).

Yoshino, M. M. & Suppiah, R. (1984). Rainfall and paddy production in Sri Lanka. *Journal of Agricultural Meteorology 40*, 9–20.

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