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Hydrological and water balance studies to evaluate options for climate resilience in smallholder irrigation systems in Sri Lanka

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Abstract

Smallholder agriculture shares a great portion of Sri Lanka's economy and provides a livelihood to 20% of the country's labour force. However, smallholder agricultural systems are considered highly vulnerable to climate variability and change. As such, improving their climate resilience is critical to ensuring sustainable development of the country. In the country's dry zone, agricultural systems are supported by thousands of small and large irrigation tanks in cascades, whose water supply potential keeps fluctuating widely between years and seasons due to rainfall variability which is a unique characteristic of this zone. In this study, we assessed the hydrological potential of the catchments of these tanks in a typical irrigation system and provided a framework to design an optimal strategy to enhance climate resilience of such systems for improved agricultural production, using a water balance model. The results show that climate-induced impacts on hydrology coupled with population growth and agricultural expansion increase irrigation water demands in the near future. Moreover, demand-side interventions will be more effective than supply-side adaptation in reducing the demand-supply gap. The study recommends evaluating more adaptation measures under expert guidance, uncertainty assessments of future climate and socio-economic pathways, and incorporating a cost-benefit assessment in the model.

Keywords: Adaptation; Agriculture; Cascade tanks; Climate change; Climate variability; Scenarios

Highlights

- Climate change coupled with population growth and agricultural expansion increases will increase the irrigation water deficits in the cascade tank systems in the near future.
- Demand-side interventions in water management are more effective than supply-side management in reducing the demand-supply gap.
- The study provides a framework to design an optimal strategy to enhance climate resilience in smallholder irrigation systems to improve agricultural production and food security with the use of hydrological and water balance assessments.

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1. Introduction

With the ever-growing demand for food and increasing competition for water, adaptation in the agriculture sector with a central focus on water management is vital to ensuring food security in future (Ashofteh *et al.*, 2017). Suitable adaptation can moderate economic consequences and improve food security, even though the risk cannot be fully eliminated. Adaptation practices and use of technology has proven to be beneficial not only in improving farmer resilience and food security, but also provide co-benefits for environmental health (Lobell *et al.*, 2013) and climate change mitigation (Dinesh, 2016). However, it is important to critically assess the sustainability of the adaptation strategies before implementation.

Sri Lanka is a tropical country in South Asia, which is identified as one of the most vulnerable areas in the world to climate change (Schellnhuber *et al.*, 2013). Observed climate change in Sri Lanka is primarily characterized by rising temperatures, erratic rainfall patterns and extreme climate events (Baba, 2010).

Nearly 90% of freshwater withdrawals in Sri Lanka is committed to agriculture. It is noted that the livelihoods of more than 70% of the population are directly or indirectly based on agriculture. The sector employs about 35% of the total labour force. However, the agriculture sector's share in Sri Lanka's economy has declined in recent times, especially since the introduction of economic reforms in 1977 (Bandara *et al.*, 2014). About 25% of the population in Sri Lanka are food insecure and the country ranks high with regard to the prevalence of undernourishment and food inadequacy (Thibbotuwawa & Leonard, 2017).

Sri Lanka's agriculture sector is facing key challenges related to water security resulting from climate change and variability. The dry zone, which contributes to more than 70% of the country's landmass, 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 has experienced cycles of alternating droughts and floods, which have severely affected the economy of smallholder farmers supported by these irrigation systems.

About 145,000 ha of agricultural lands are irrigated by village tanks compared to 305,000 ha by major irrigation facilities (Department of Census and Statistics, 2018). Therefore, village irrigation supports a significant number of farmer families in the dry zone. In addition, services provided by village tanks are greater in number and diversification 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.

Dry zone agricultural systems are characterized by smallholder farming. Smallholder agriculture contributes 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. 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 is 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 over. However, paddy cultivation during the minor cropping season (Yala/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 practise adaptation strategies based on water management to ensure the sustainability of agricultural production.

Most village tanks are in cascades. Seasonal cultivation planning at present is carried out at the tank level and there is no methodology developed for water management at the cascade level. However, the tank network is hydrologically connected such that the downstream tanks in a cascade receive drainage water and spill water from upstream tanks and command areas. If the cropping season is planned at cascade level, cropping intensity and farmers' income can be increased while minimizing crop losses. In recent times, the interest in seasonal planning at cascade level rather than for individual tanks has increased.

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. Yet 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 cascade 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 in the study area should follow an integrated approach, looking at the cascade as a whole, considering plausible future pathways shaped by climate, demands, water availability, technology, etc.

The objective of this study is to facilitate well-informed decision-making in the development of the cascade to improve the climate resilience of smallholder farming systems in a sustainable manner. The study aims to develop a framework to design the best strategy to improve the productivity of available water resources in order to improve agricultural production sustainably under plausible future scenarios of climate variability and change. To achieve this, the study evaluated different water demand and supply-side adaptation options.

2. Study area

Anuradhapura District of Sri Lanka is characterized by the presence of tank cascade systems, which, by definition, are connected series of tanks organized within a catchment that stores, utilizes and conveys water from a watercourse (Madduma Bandara, 1985; Itakura & Abernethy, 1993). Ranorawa Cascade in Anuradhapura District of Sri Lanka represents a typical village irrigation system in the country and was selected as the study area. The cascade is located in the Thalawa sub-basin of Moderagam Aru Basin in Anuradhapura District as shown in Figure 1. It extends over an area of 22.911 km^2 and consists of a series of 17 connected minor tanks (see Annexure 1) falling within the Ranorawa and Pemaduwa Agrarian Service Centers (ASCs) in the agro-ecological zone DL1b. Agriculture is the main livelihood in the region.

2.1. Rainfall

The study area is located in the dry zone of Sri Lanka, where characteristically, the average annual evaporation exceeds the average annual rainfall implying water stress during certain periods of the year (Sakthivadivel *et al.*, 1996). Figure 2, showing the annual rainfall in Nochchiyagama and Ranorawa stations from 1986 to 2015 (data in Ranorawa station is available starting from 2011 only), suggests that

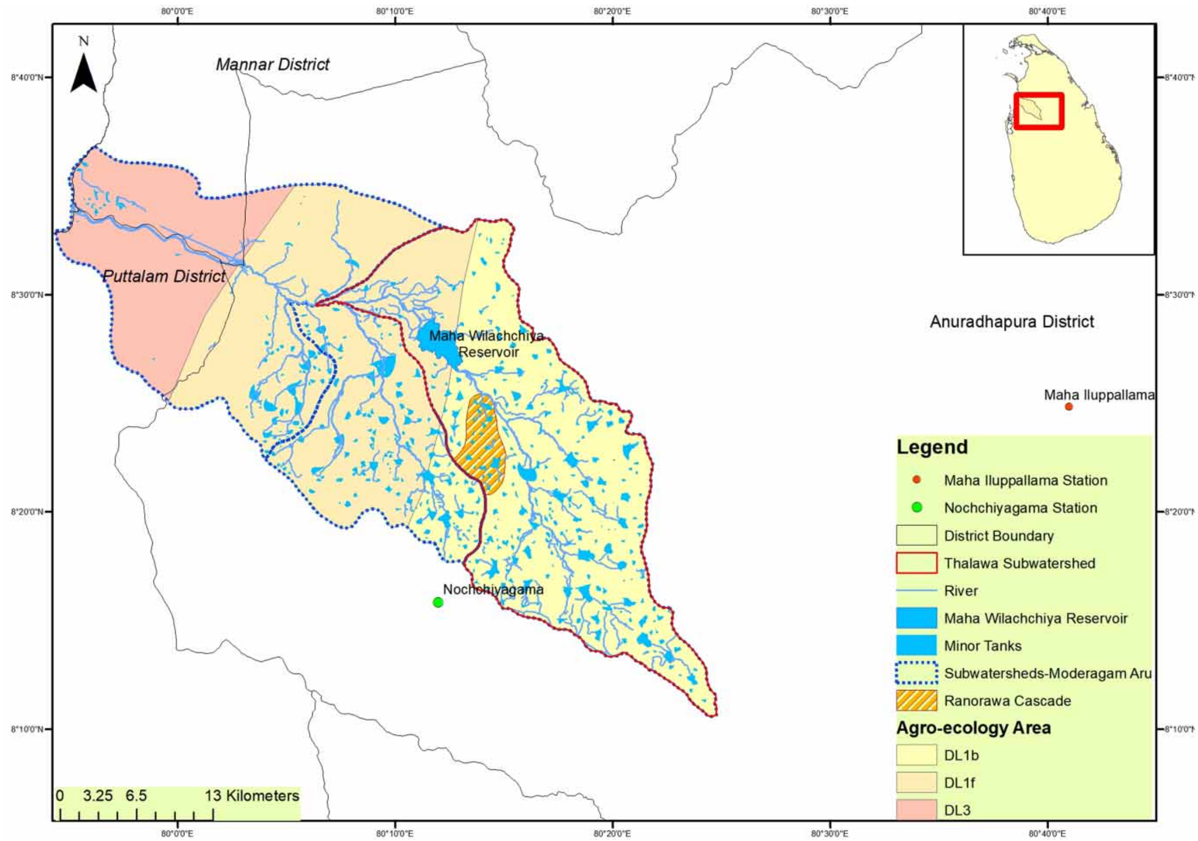

Fig. 1. Location of Ranorawa Cascade in the Moderagam Aru Basin.

there is high intra-annual variability of rainfall in the region. The cascade receives the highest contribution to its annual rainfall during the North-East monsoon period (December–February). The major cropping season (from October to March) begins with the onset of the Second Inter-monsoon and benefits mostly from North-East monsoon (December–January) rains. Nearly 70% of the annual rainfall is received in the major cropping season. April to September, which is the minor cropping season, is relatively dry, accounting for only about 30% of annual rainfall.

2.2. Climate change and climate variability

The changes in magnitudes and temporal distribution in rainfall and temperature under climate change scenarios in future is projected to adversely affect the paddy cultivation in Anuradhapura District. Studies show that the wet season (October–February) paddy irrigation requirement across most of Sri Lanka will increase by the year 2050 under climate change scenarios. Accordingly, in Anuradhapura, paddy irrigation requirement will increase by 15–18%. Furthermore, shifts and shortening of the rainy season are also projected for the entire country (De Silva *et al.*, 2007). It is identified that

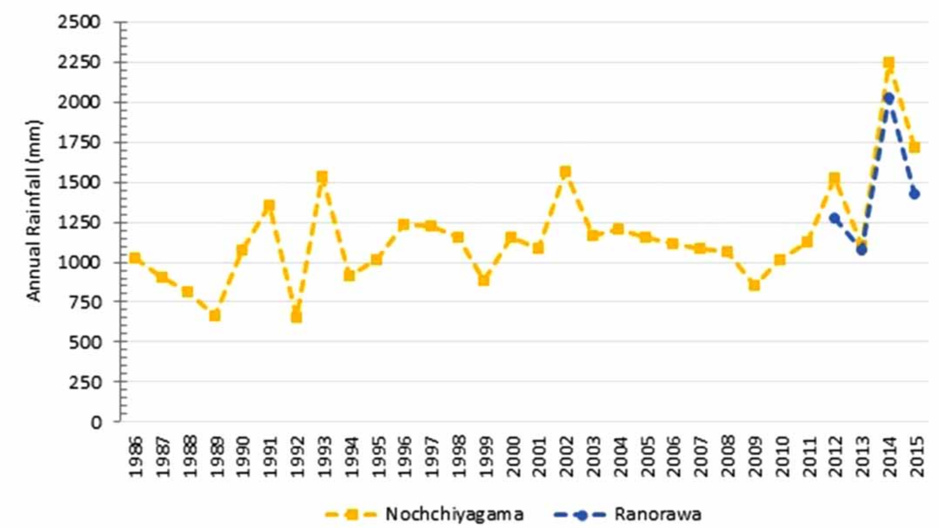

Fig. 2. Annual rainfall of Nochchiyagama and Ranorawa stations. *Source*: Department of Meteorology, Sri Lanka.

Anuradhapura District is among the highest vulnerable districts to climate hazards in the country (Eriyagama *et al*., 2010).

Sakeena (2013) surveyed farmers in Maha Wilachchiya Divisional Secretariat (DS) Division (which is in the Thalawa sub-basin) to understand their perception of climate change. Farmers have revealed that the changes in the weather pattern have become increasingly unfavourable for paddy cultivation in recent times.

2.3. Land use and soil

Land use data according to the distribution in 2016 were obtained from the Land Use Policy Planning Department and soil data derived from a map published by the Survey Department, Ceylon in 1967 is given in Figure 3. Ranorawa Cascade predominantly has reddish brown earth and low humic gley soils and most of its area is under forest cover and scrublands.

3. Data and methodology

3.1. Overview

The Soil Conservation Service (SCS) Curve Number method was used to develop the rainfall–runoff relationship which was used to simulate future runoff by inputting future projected rainfall data. This is a simple method and it is widely used in estimating floods of small to medium-sized ungauged drainage basins (Ara & Zakwan, 2018).

The method is based on empirical formulae, tables, and curves. It requires rainfall and the curve number (CN) of the catchment to determine the runoff generated in the basin. CN is a dimensionless

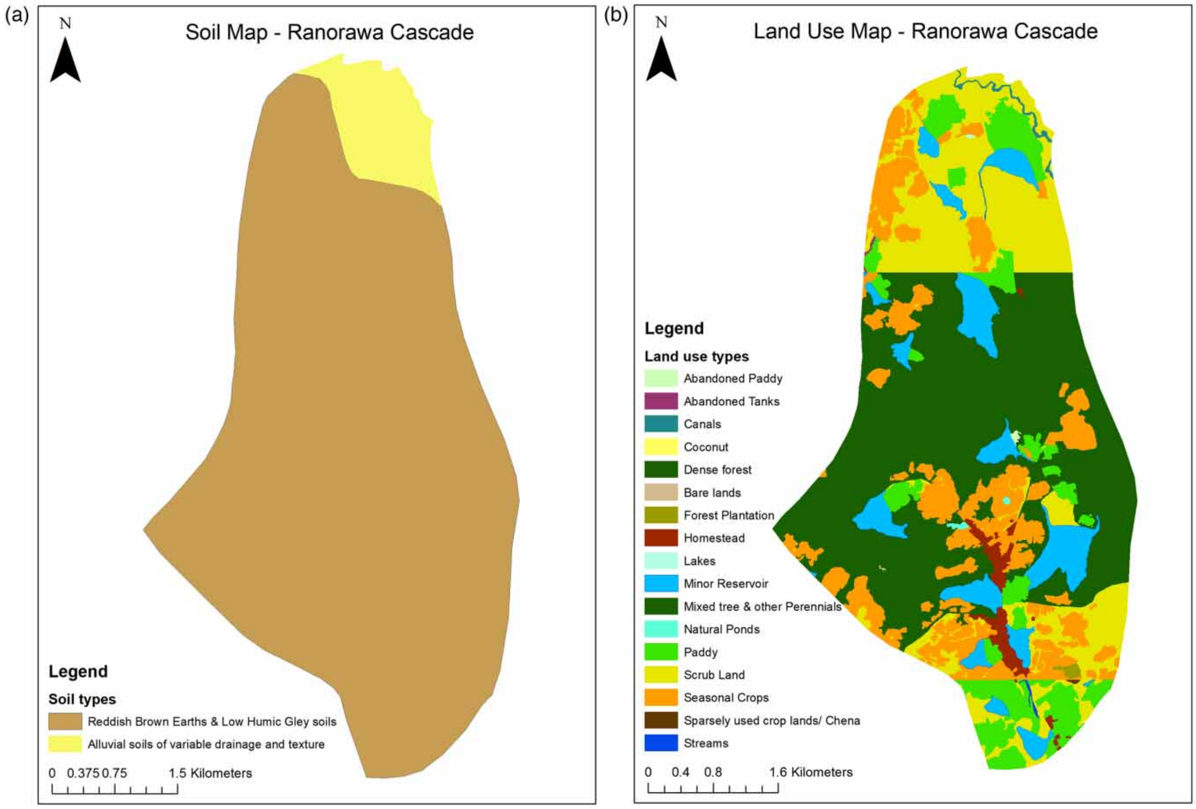

Fig. 3. Soil and land use maps of the Ranorawa Cascade.

empirical parameter representing basin characteristics determined by the combination of land use, soil and the antecedent moisture condition (AMC) of the soil. Therefore, as the first step, the study area was categorized into different combinations of soil types and land use in a GIS platform and their corresponding CN (corresponding to normal AMC) was determined from the literature. Using HEC-Geo HMS in ArcGIS, a CN map of the study area was produced, and the spatially averaged CN was calculated. The CN for wet and dry AMCs were calculated using standard equations.

An event-based analysis was carried out to determine runoff generated from individual rain events from 1986 to 2015. AMC at the beginning of each event was found considering the total 5-day antecedent rainfall. The daily runoff generated was calculated following standard relationships used in the method. The annual virgin runoff generated was plotted against the annual rainfall in the sub-watershed and their best fit relationship was obtained as the rainfall–runoff model for the Thalawa sub-watershed, which is given in Figure 4.

Land use and soil data given in Figure 3 were used in developing the rainfall–runoff relationship. CropWat software developed by the Food and Agriculture Organization (FAO) was used to calculate the irrigation water requirements (IWR) for the baseline and the future under climate change scenarios. Water Evaluation and Planning (WEAP) software was used to simulate 15 scenarios including reference (business-as-usual), future climate and population dynamics (climate change, high growth, low growth),

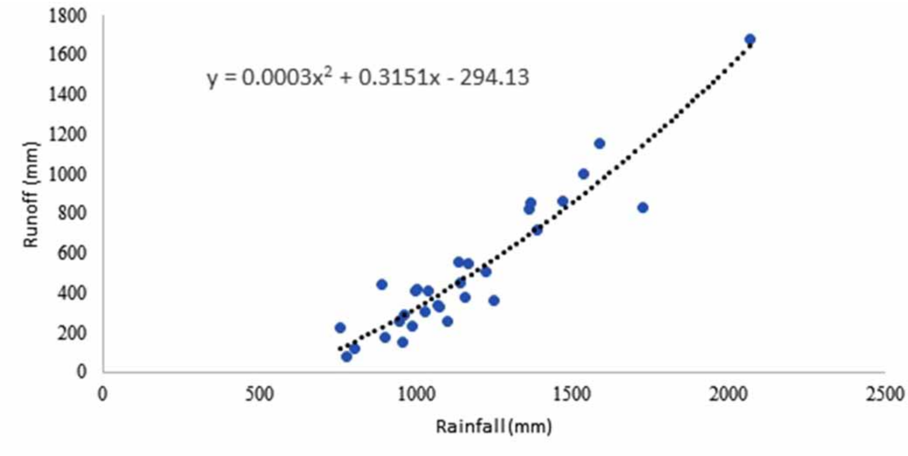

Fig. 4. Rainfall–runoff relationship for the Thalawa sub-watershed.

supply-side management (storage augmentation, improved canals) and demand-side management (introducing high-value crops (HVC) for the dry season) and few combinations. Water balance components were compared to strategize reducing unmet demands in future and improving water productivity in the cascade under multiple future pathways which are potentially beyond the control of basin managers.

3.2. Future climate projection

Daily rainfall and temperature (daily maximum temperature, Tmax and daily minimum temperature, Tmin) for the historical run (1976–2005) and the future up to 2044 were obtained using multiple General Circulation Models (GCMs) from the Coupled Model Intercomparison Project 5 (CMIP5). A description of the selected GCMs is given in Table 1. The future data were extracted under RCP4.5 and RCP8.5. Historical daily rainfall from Nochchiyagama station and daily temperature data from Maha Iluppallama station was obtained from the Department of Meteorology (see Figure 1 for station locations).

Among various bias-correction methods ranging from simple scaling approaches to more complex methods employing probability mapping, linear scaling method was chosen, which has been proven to be efficient for hydrological analysis at monthly resolution (Shrestha *et al.*, 2017).

Table 1. Selected GCMs for projecting future climate in the Ranorawa Cascade under RCP4.5 and RCP8.5.

GCM	Institution	Resolution	Vintage
CNRM-CM5	Centre National de Recherches Meteorologiques and Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	1.4° × 1.4°	2010
HadGEM2-AO	National Institute of Meteorological Research/Korea Meteorological Administration	1.25° × 1.875°	2009
MRI-CGCM3	Meteorological Research Institute	1.125° × 2.25°	2011
IPSL-CM5A-MR	Institut Pierre Simon Laplace	1.25° × 2.5°	2009

Source: Flato *et al.* (2013).

3.3. Introduction to the WEAP system

WEAP, a software developed by the Stockholm Environment Institute, is widely used as a tool for integrated water resources planning. It is operated in many capacities; as a database that maintains water demand and supply information, as a forecasting tool that can simulate demands, supplies, runoffs, infiltration, inflows, outflows, storage changes, etc., and also as a policy analysis tool that can assess different water management (both demand- and supply-side management) and development options (Sieber, 2015).

WEAP can be used in a variety of environments such as municipal systems, agriculture systems, at the catchment scale, river basin/sub-basin scale or in complex river systems. The main principle behind its operation is water balance accounting. This tool can be used to address issues, inter alia, water rights and allocation priorities, water conservation and productivity, streamflow and groundwater simulations (facility to link with ModFlow), hydropower generation, environmental flow requirements, economic analysis. It has been proved a robust tool to assist decision-makers in integrated water resources management and development in different settings (Levite *et al*., 2003; Hamlat *et al*., 2013; Li *et al*., 2015).

In setting up a WEAP model, in the first step, *current accounts*, the current water supply and resources and water demands of the system were simulated. This also functions as a calibration step in the model development and is a representation of the actual water supplies against the demands showing the deficit, if any, resource condition, pollution loads and basin outflows. Then a 'reference' or a 'business-as-usual' scenario is established based on existing hydrological, demographic, economic and technology trends.

As the next stage of model development, different *scenarios* represent alternative assumptions about the future pathways due to the impact of policies, climate, technology, economy, lifestyles on water demand, supply, hydrology and pollution in the system. These scenarios can simulate a large number of what-if situations.

Finally, for *evaluation*, the scenarios can be compared against each other and/or the current accounts in aspects of water sufficiency, social economic and environmental satisfaction and sensitivity to different variables and parameters.

3.4. WEAP setup of the Ranorawa Cascade

3.4.1. Current account setup. A year in this model is different from the calendar year in that it is a hydrological year from October (onset of the rainy season) to September. A monthly time step was selected for the analysis. Yet, whenever possible, daily data were used and converted to monthly values.

The year 2015 was selected for the current accounts for this study. The main consideration of this selection was data availability. Analysing the annual rainfall data from 1986 to 2015, the year 2015, which received an annual rainfall of 2,069 mm, was considered as a *very wet year*. Correspondingly, the agricultural activity in 2015 was relatively high compared to average conditions with a cropping intensity of 1.5.

3.4.1.1. Supply and resources.

Reservoirs: The details of the 17 minor tanks are presented in Annexure 1. Storage capacities and the storage–depth relationships by the Department of Agrarian Development (DAD) and the Provincial Irrigation Department (PID) were obtained. To produce these data, the DAD and PID conducted engineering surveys of minor tanks in Ranorawa Cascade under the Climate Smart Irrigated Agriculture Project of Sri Lanka. The model uses net evaporation data (the difference between evaporation and rainfall) to calculate the evaporative losses from tanks, that varies with the water surface area of the tank.

Monthly evaporation data of Maha Iluppallama station published by the Department of Irrigation was used. Seepage loss was assumed using the logarithmic function given below, which is an empirical equation derived by Jayatilaka *et al.* (2001):

$$y = -4.3625 ln(x) + 0.4292$$

where, y = daily seepage as a percentage of the tank volume and x = relative water height = tank water height/tank water height at FSL (Jayatilaka *et al.*, 2001).

Reach: A rainfall–runoff model for the Thalawa sub-basin given in Figure 4 was developed to estimate the runoff per unit area, which was assumed to be uniform over the cascade area (runoff values used are also provided in Annexure 2). Rainfall data were available at Ranorawa station (see Figure 1 for location) for the year 2015 which was input to the above model to estimate runoff per unit area in the cascade. The net catchment area of each tank was obtained by the DAD and PID which was used to calculate the runoff to each tank. The rainfall and evaporation data are given in Annexure 2.

Groundwater: A shallow regolith aquifer is found in the study area which is common for small tank cascades in north central and north western provinces. Groundwater is used in home gardens, and for domestic and livestock use but not for paddy irrigation. The storage capacity of the aquifer was approximated by the product of the following three parameters; the average aquifer thickness which is around 10 m (Panabokke & Perera, 2005), the cascade area (without rock land type) and the specific yield of the aquifer which was assumed to be 0.04. The total storage is estimated as equal to area × aquifer thickness ×specific yield of the aquifer.

3.4.1.2. Water demands. Agriculture, domestic and livestock are the three dominant water use sectors in the cascade. Paddy is primarily cultivated in the cascade, but during dry minor cropping seasons, other field crops are grown in place of paddy. However, in 2015, which is categorized as a very wet year, only paddy cultivation was done in both cultivation seasons.

Agriculture use: Net irrigation requirement (per unit area) was calculated from CropWat model which required climate data and crop parameters as input data. A field irrigation efficiency and a conveyance efficiency of 60 and 80%, respectively, were assumed, which are the loss rates commonly used in operation studies in the region. Twenty per cent of conveyance loss was assumed to replenish groundwater through seepage flows and the evaporation in irrigation canals were considered as insignificant (Mohammadi *et al.*, 2019). The command area under each tank was also obtained by the DAD and PID. The net irrigation requirement, the losses and the command areas under each tank obtained in the above manner were used to estimate the monthly irrigation water demand from each tank. Ideally, a cropping intensity of 2 was assumed, suggesting that the entire command area is cultivated during both seasons, which, however, is not the reality. Return flow from the paddy fields distributes between inflow to the downstream tank and groundwater. Common practice is to assume that 15–20% of the irrigation released from the tank is contributing as return flow (or drainage flow) to the downstream tank. This value as a percentage of the total return flow was about 50%. Therefore, it was specified in the model that the return flow from paddy fields flows in equal proportions to groundwater and the downstream tank. Spillage from the upstream tank was directed to the downstream tank through a stream. It is possible to encounter cases where spill water flows to more than one downstream tank or drainage flow and spillage flows to different tanks in a cascade. In such situations, the flows were defined accordingly in the model. Investigations revealed that there are no proper canal structures catering for spill water in the cascade, rather the spillage flows in natural paths.

Domestic use: Domestic water use was assumed as 70 L per day per capita (Reed, 2005). The population under each tank was also obtained by the DAD and PID (see Annexure 1). It was assumed that domestic and livestock consumption is 100%, suggesting no loss, which was a reasonable assumption for rural areas.

Livestock use: Livestock data were collected from ASCs representing the cascade area. Goats, dairy cattle and buffalo are the main livestock types in the cascade and their respective annual water demand was assumed as 2,737.5 L per goat, 14,965 L per dairy cattle and 14,400 L per buffalo (Engineering ToolBox, 2010; Kumar *et al*., 2019).

A schematic of the WEAP model of the Ranorawa Cascade developed in the above-discussed manner is given in Figure 5.

3.4.2. Modelling of future scenarios. A reference scenario and 14 other future scenarios representing climate change, population growth, implementation of demand and supply-side management measures, and a few of their combinations were simulated using the WEAP model.

3.4.2.1. Reference or baseline scenario. The period from 2016 to 2044 was defined as the time period for the reference scenario. The climate and hydrology of this period were assumed to be similar to that of the 1987–2015 period. Rainfall data were obtained from observed data of Nochchiyagama station and temperature and evaporation from Maha Iluppallama station. Socio-economic trends were assumed to remain unchanged. Population growth rates were obtained from the Census of Population and Housing, 2012 report and are given in Table 2. Growth in crop area was assumed to be 1% based on historical records. Runoff, irrigation requirement and reservoir evaporation for each year were calculated in the same manner described for current accounts. The scenario setup as above was considered as the reference or business-as-usual scenario.

3.4.2.2. Climate change. Two scenarios were developed to represent climate change, namely, climate change under RCP4.5 emission scenario and climate change under RCP8.5 emission scenario. Under these scenarios, the net irrigation requirement varied depending on changes in rainfall and temperature under the selected climate change scenarios. Therefore, the net irrigation requirement was recalculated from CropWat under the two scenarios. Furthermore, catchment runoff was modified according to the projected rainfall under climate change scenarios.

3.4.2.3. Population growth. The observed population growth in Anuradhapura District from 1981 to 2012 is 1.3%. Two growth scenarios have been considered in this study:

1. A high growth scenario of 1.8%
2. A low growth scenario of 0.5%.

Effects of population growth are reflected in water demand rates in both the domestic and agriculture sectors. Per capita agricultural command area for each tank for the baseline case was calculated and this rate was maintained for the future as well. The command area under each tank was assumed to grow relative to population growth.

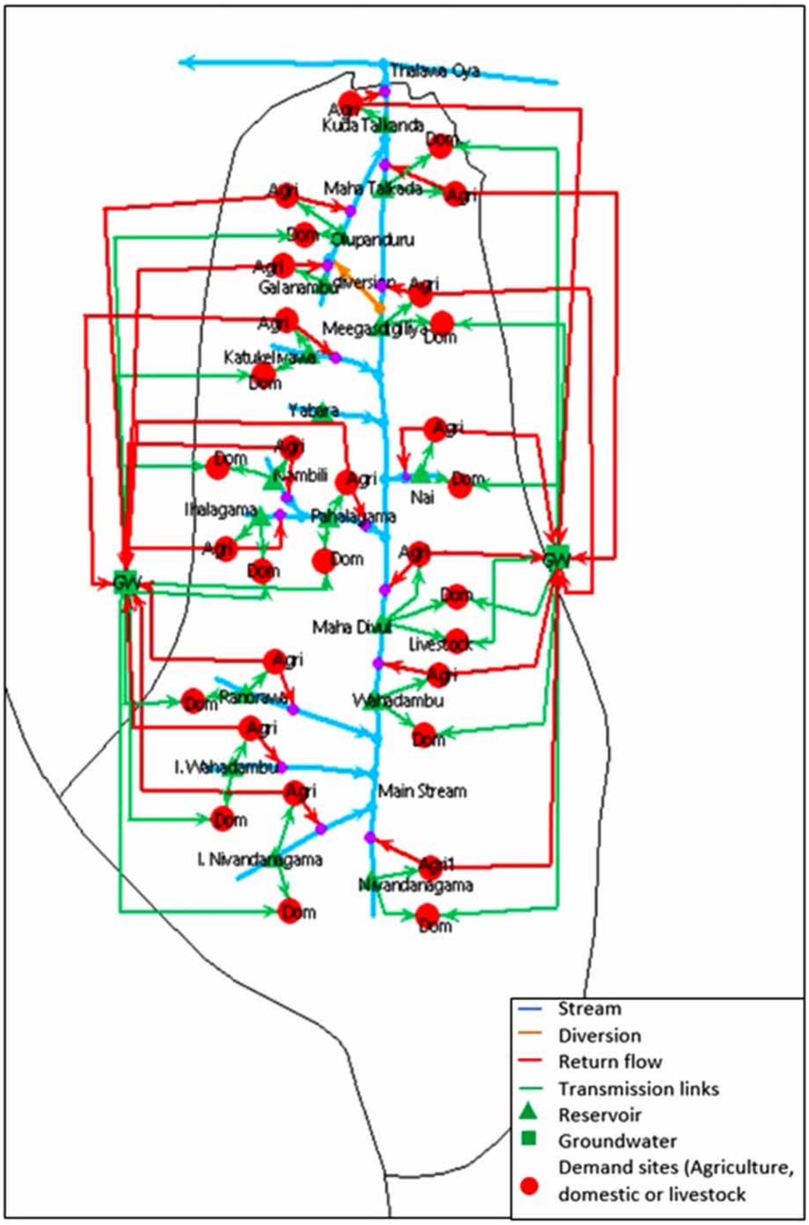

Fig. 5. Schematic view of the Ranorawa Cascade in the WEAP model. *Note:* The same groundwater aquifer is represented as two nodes in the figure for clarity.

3.4.2.4. Improved water use efficiency in crop cultivation. These scenarios capture the effects of alternate cropping patterns during the dry season where high-value crops replace some of the paddy areas. The selected other field crop (OFC) was maize. A cropping pattern of 70% maize and 30% paddy during the minor cropping season was introduced under these scenarios. Two scenarios were developed, high-value crops A (HVC A) and high-value crops B (HVC B), respectively, having 70 and 80% field

Table 2. Population growth rates in Anuradhapura District.

Category	Growth rate
Human population	1.30%
Cattle	−1.49%
Buffalo	−3.19%
Goats	−1.33%

Source: Department of Census & Statistics (2012).

irrigation efficiency for maize. The conventional irrigation method for maize is furrow irrigation, which, in general, yields an efficiency of nearly 70%. However, efficiency improvement techniques such as alternate-row furrow irrigation method (Kang *et al*., 2000) can substantially reduce field irrigation losses in maize cultivation. As such, acting on the conservative side, the latter scenario of 80% field irrigation efficiency was developed assuming the practice of improved furrow irrigation techniques.

3.4.2.5. Improved canal systems. For this scenario, it was assumed that all transmission canals within the cascade system will be improved by lining. It was assumed that this will improve the transmission efficiency of the system from 80% to 95%.

3.4.2.6. Storage augmentation. This scenario represents the restoration of abandoned tanks and storage augmentation (rehabilitation) of existing tanks. Two minor tank rehabilitation scenarios were assessed with, respectively, two levels of storage augmentation: 8 and 15% (depending on the unmet demand under each tank, the storage augmentation was either 8% or 15%). The third scenario under storage augmentation considered tank rehabilitation along with the restoration of four abandoned tanks, Nai Wewa, Nambili Wewa, Galanambu Wewa and Kuda Talkanda Wewa. The paddy areas under these tanks were also made active under this scenario. This increased the total command area in the cascade, thus the total water demand. The details of the tanks are given in Annexure 1.

Finally, a few combinations of the above scenarios were also simulated using the model. A summary of the scenarios is given in Table 3.

4. Analysis and results

4.1. Projected climate and irrigation water requirement under climate change scenarios

The box and whiskers plots given in Figure 6 show the distribution of rainfall in the baseline and near future under RCP4.5 and RCP8.5 in the cascade. The near-future mean annual and seasonal (major and minor cropping seasons) rainfalls are projected to be higher than those observed during the baseline period. Correspondingly, the average yield from the basin will rise, explaining the lowered annual and minor cropping season irrigation water requirement (IWR) as shown in Figure 7. However, during the major cropping season, the average IWR is projected to rise (see Figure 7). This is attributed to the increase in temperature projected for the near future under RCP4.5 and RCP8.5.

It is further drawn from Figure 6 that the inter-annual variability of annual and major cropping season rainfall is projected to increase under both RCPs while a decrease is projected for the minor cropping season. In

Table 3. Summary of simulated future scenarios.

Scenario type	Scenario name	Description
Climate change (CC)	1. Climate change (RCP4.5)	Following changes in rainfall, Tmax and Tmin, under RCP4.5 emission scenario
	2. Climate change (RCP8.5)	Following changes in rainfall, Tmax and Tmin, under RCP8.5 emission scenario
Population growth	3. High growth (HG)	1.8% growth in human population and agriculture area
	4. Low growth (LG)	0.5% growth in human population and agriculture area
Adaptation strategies – Demand-side management	5. High-value crops A (HVC A)	Maize–paddy combination of respectively 70–30% shares of the total command area during the Minor Cropping Season with field irrigation efficiency of 70% for maize
	6. High-value crops B (HVC B)	Maize–paddy combination of respectively 70–30% shares of the total command area during the Minor Cropping Season with field irrigation efficiency of 80% for maize
Adaptation strategies – Supply-side management	7. Improved canals	Transmission loss reduced up to 5%
	8. Storage augmentation A	Tank rehabilitation – Augmentation of the storage capacity of tanks by 8%
	9. Storage augmentation B	Tank rehabilitation – Augmentation of the storage capacity of tanks by 15%
	10. Storage augmentation C	Tank rehabilitation and restoration of abandoned tanks
Combination scenarios	11. High growth and climate change (HG and CC-RCP4.5)	Combination of high growth and climate change – RCP4.5 scenarios
	12. High growth and climate change (HG and CC-RCP8.5)	Combination of high growth and climate change – RCP8.5 scenarios
	13. Low growth and climate change (HG and CC-RCP4.5)	Combination of low growth and climate change – RCP4.5 scenarios
	14. Low growth and climate change (HG and CC-RCP8.5)	Combination of low growth and climate change – RCP8.5 scenarios

more than 50% of the time in the near future (under both scenarios), projected annual rainfall is greater than the mean annual rainfall recorded during the baseline period, indicating that most of the future years will be wetter than the average baseline conditions. Similar projections are made for the major cropping season rainfall under both RCPs and minor cropping season rainfall under RCP4.5. The minimum annual and seasonal rainfalls are projected to increase compared to baseline under both RCPs in the near future.

4.2. Water balance in the near future under the reference scenario

In all future scenarios, unlike in the agriculture sector, demands in domestic and livestock sectors are fully met as they are fed by groundwater in addition to surface water. Figure 8 shows different water balance components under the reference scenario. The total water demand in the basin during the period from 2015 to 2044 under this scenario is 118.78 million m^3. The largest share of 99.22% of the total water demand in the catchment is from the agricultural sector and the domestic and livestock sectors account for only 0.70% and 0.08%, respectively. In the agriculture sector, supply shortages are expected every year. Nearly 47% of the total yield (or runoff) in the near future flows out of the cascade uncaptured and unutilized while there exist unmet demands as evident from Figure 8. The existing surface storage capacity thus has a need for augmentation.

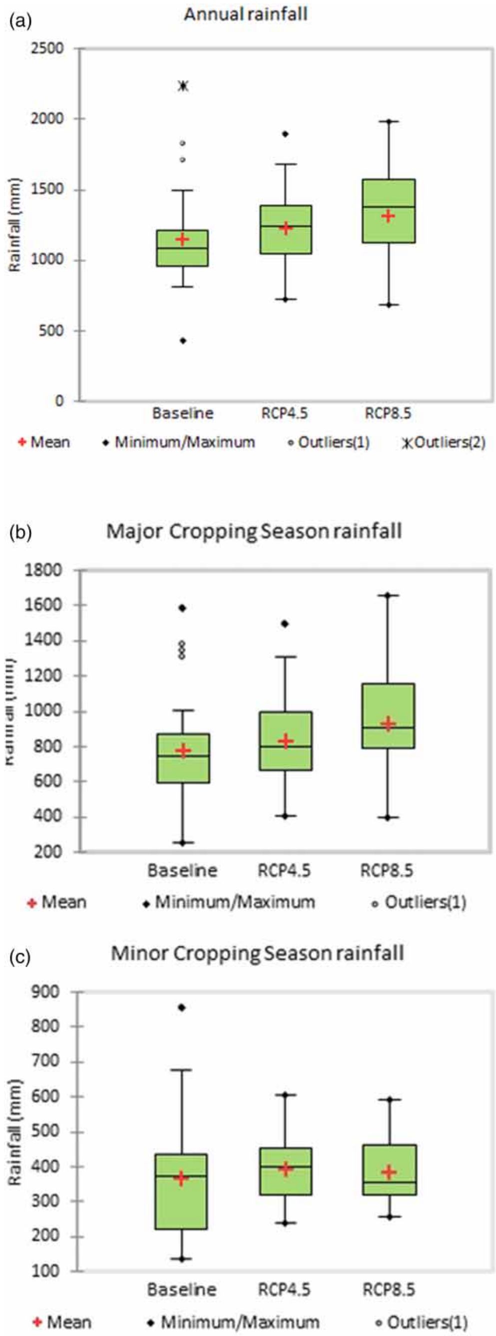

Fig. 6. (a) Annual, (b) major cropping season and (c) minor cropping season rainfall distribution in the baseline period and under climate change scenarios in the near future in the Ranorawa Cascade.

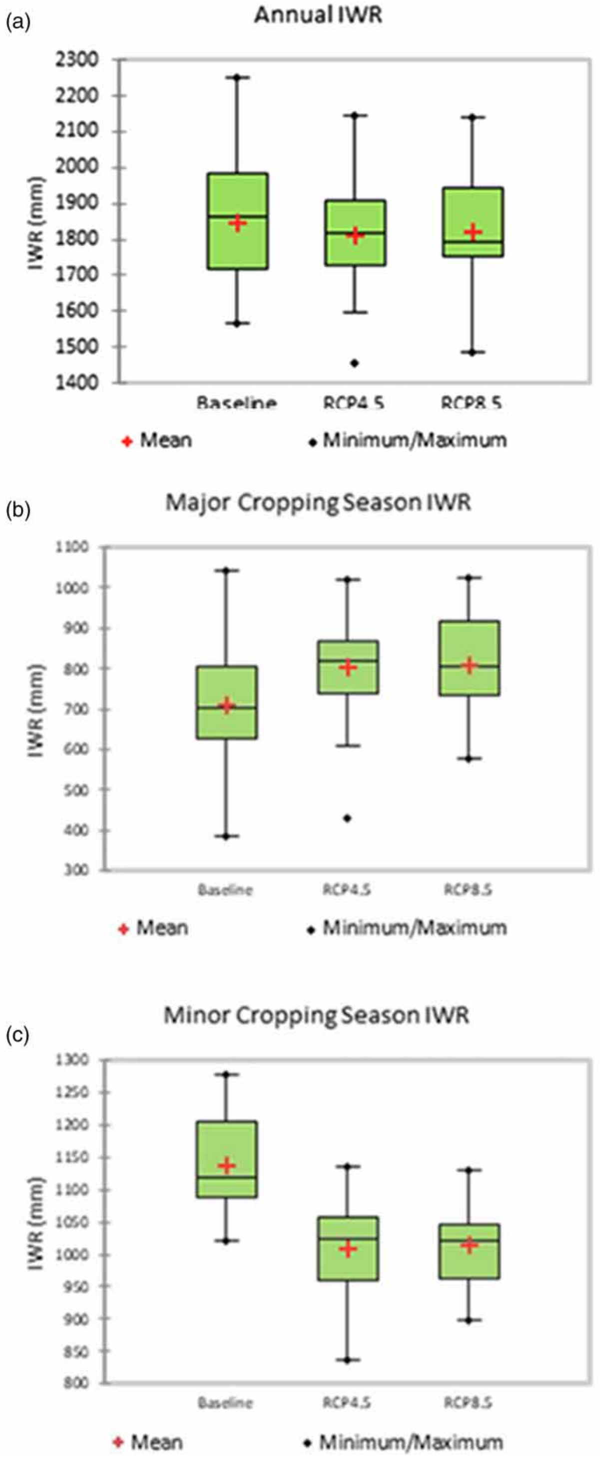

Fig. 7. (a) Annual crop, (b) major cropping season and (c) minor cropping season irrigation water requirement during the baseline period and near future under climate change scenarios in the Ranorawa Cascade.

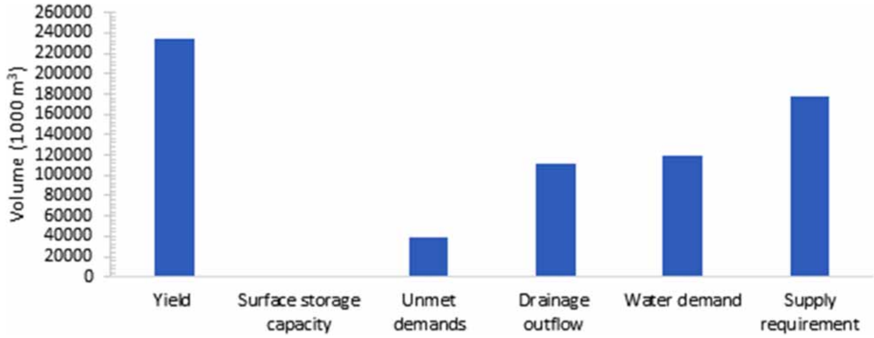

Fig. 8. Water balance components under the reference scenario.

Considering the agricultural sector, in the reference scenario, a cropping intensity of 2 was defined. The normal practice is to cultivate only a proportion of the command area during the minor cropping season (cropping intensity is less than 2) depending on the climate forecasted for the season. In such a scenario, the shortages may be nullified in several wet and very wet years. This identifies the need to simulate scenarios that could potentially nullify (or reduce) unmet demands while achieving the full (or improved) annual agricultural production potential. More importantly, the unmet demands fluctuate from year to year due to variability in hydrologic condition both intra- and inter-annually. There is no significant increasing or decreasing trend observed in unmet demand under this scenario even though the cropland area has continuously increased. The unmet demands projected under this scenario are given in Figure 9.

Based on the results of the reference scenario, other future scenarios were developed, and the results are discussed in the following section.

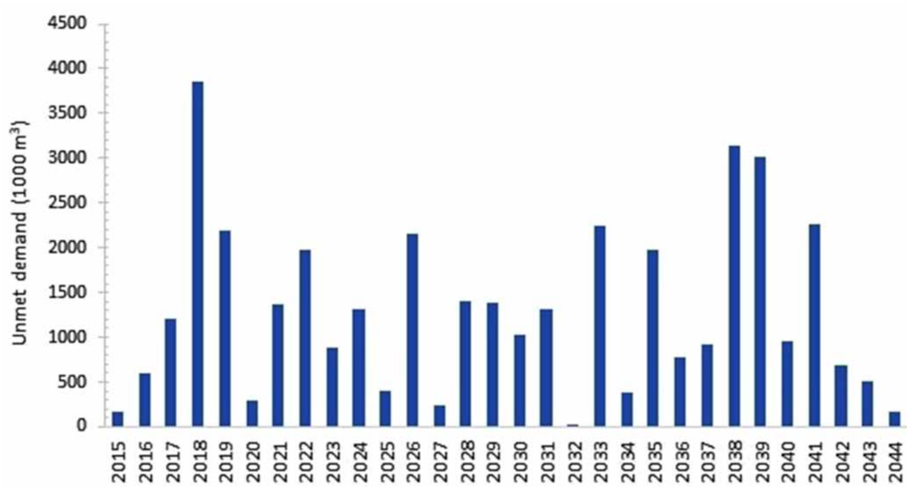

Fig. 9. Unmet demand in the agriculture sector for the reference scenario in Ranorawa Cascade.

4.3. Water balance in the near future under other future scenarios

4.3.1. Water demands and supply potential. Several scenarios were generated to represent future climate change and population growth and the corresponding expansion of agricultural lands, demand-side and supply-side adaptation and a few of their combinations (refer to Table 3 for details). In this section, water balance components such as the supply requirement, unmet demands, groundwater storage and outflow from the basin under each of these scenarios are compared against those in the reference scenario, in order to understand possible strategies to reduce unmet demands in future and improve water productivity in the cascade under different future pathways which are potentially beyond the control of basin managers (such as climate change and population growth). Table 4 presents the annual water balance results under each scenario. The following discussion, where the projected water balance components for the near future (2016–2044) are compared against the reference case (1985–2015), is based on those results in Table 4.

Table 4. Water balance components under different scenarios in Ranorawa Cascade projected for 2016–2044.

	Water yield (1,000 m^3)	Surface storage capacity (1,000 m^3)	Unmet demands (1,000 m^3)	Drainage outflow (1,000 m^3)	Water demand (1,000 m^3)	Supply requirement (1,000 m^3)
Reference	233,832.87	1,880.65	38,845.43	110,914.24	118,782.83	142,539.40
Climate change (RCP4.5)	258,995.88	1,880.65	24,788.20	113,848.88	116,963.42	140,356.10
Climate change (RCP8.5)	294,339.39	1,880.65	24,874.45	140,563.29	117,707.74	141,249.28
High growth	233,832.87	1,880.65	83,736.36	101,591.03	176,840.66	212,208.80
Low growth	233,832.87	1,880.65	59,522.99	106,759.38	146,040.32	175,248.38
HVC A	233,832.87	1,880.65	11,283.01	117,838.26	78,304.47	93,965.36
HVC B	233,832.87	1,880.65	10,855.96	118,069.17	77,208.17	92,649.80
Improved canals	233,832.87	1,880.65	30,492.35	116,225.71	118,782.83	142,539.40
Storage augmentation A	233,832.87	2,031.10	38,074.68	108,557.34	118,782.83	142,539.40
Storage augmentation B	233,832.87	2,162.75	38,091.34	108,526.17	118,782.83	142,539.40
Storage augmentation C	233,832.87	2,559.69	52,296.32	94,535.29	147,332.18	176,798.62
HG and CC-RCP4.5	258,995.88	1,880.65	66,627.67	102,536.77	174,377.57	209,253.08
HG and CC-RCP8.5	294,339.39	1,880.65	66,751.38	129,334.20	175,737.61	210,885.14
LG and CC-RCP4.5	25,899.59	1,880.65	42,734.92	107,385.60	143,649.99	172,379.99
LG and CC-RCP8.5	294,339.39	1,880.65	41,752.28	133,697.54	144,448.74	173,338.48

As both domestic and livestock sectors are fed by groundwater in addition to surface water, their needs were fully satisfied in all scenarios considered. As such, all unmet demands are solely from the agricultural sector.

Under the scenario representing climate change, the yield (surface runoff) is projected to increase, corresponding to the projected increasing trend in annual rainfall (discussed in Section 4.1) compared to the reference scenario. This is the only scenario (excluding combination scenarios) tested in this study which results in a change in the yield of the cascade. In response to the increased yield, projected climate change will significantly decrease water demand, supply requirement and eventually unmet water demands averaged over the near future, even in the absence of any adaptation measures. However, it is advisable to consider uncertainties associated with these climate projections.

Furthermore, under climate change scenarios, drainage outflows will rise by nearly ten-fold compared to the reference period, while there still exist unmet demands in the cascade system. This suggests that existing storage fails to capture the enhanced rainfall projected for the study area. However, it is also important to study daily or weekly pattern of rainfall to observe the inter- and intra-annual distribution of rainfall and study peaks and troughs (extreme events), patterns and trends in projected rainfall. Following such an assessment, only well-informed water management decisions can be made concerning capturing the unaccounted water that drains out, to reduce water shortages within the cascade without compromising downstream demands.

The water demand is expected to increase by nearly 50 and 23% under high and low growth scenarios, respectively. Correspondingly, the unmet demands rise more than twice for the high growth scenario while roughly by a factor of 1.5 for the low growth scenario compared to the reference scenario. The unmet demands are highest under the high growth scenario out of all the scenarios evaluated. Moreover, the drainage outflows from the basin are reducing under these growth scenarios compared to the reference scenario. The impact of such changes to environmental flows and downstream demands should also be assessed.

Two scenarios were selected to represent demand management interventions. They included growing a high-value crop, which was maize in this case, in the minor cropping season using traditional irrigation techniques (HVC A) and improved techniques (HVC B). A significant reduction in water demand (34 and 35%, respectively, under HVC A and HVC B) was observed leading to reducing the demand shortages by nearly 70% when compared to the reference scenario. Even though the changes in cropping pattern were only in the minor cropping season, unmet demands in both minor and major cropping seasons were projected to decrease by 2044 when compared to the reference scenario. This can be attributed to the changing carryover reservoir storage from season to season.

Improved canals will reduce the annual demand shortages by nearly 22%. However, 30.5 million m^3 of demand is not satisfied while the drainage outflows from the cascade are enhanced compared to the reference scenario.

The first two storage augmentation scenarios analysed the rehabilitation of the minor tanks only. Storage augmentation to the extent of 8 and 15% were respectively assumed under these scenarios. Desilting and raising of spillway crest are the possible options to achieve storage augmentation in tanks. However, it is common knowledge that desilting is very costly and, as such, it is recommended to conduct a benefit-cost analysis of desilting of tanks to decide on the optimum volume of desilting. WEAP allows such assessments in its economic module, which, however, is beyond the scope of this study. By the simulation results presented in Table 4, under these two scenarios, the unmet demands reduce only by nearly 2% compared to the reference scenario with insignificant difference between 8 and 15% augmentation scenarios.

The 'storage augmentation C scenario' incorporated the restoration of abandoned tanks in addition to rehabilitation of existing ones. It has resulted in an expansion of cultivation lands with the addition of the command areas under restored tanks. As such, the water deficit is higher as compared to the reference (base case) scenario despite the capacity augmentation. However, the agricultural production will increase in the cascade corresponding to the increase in the command area. This questions the feasibility of storage augmentation, which requires a cost-benefit analysis considering the benefits of increased agricultural production from tank restoration against the cost of tank capacity enhancement. All three storage augmentation scenarios result in reduced drainage outflows. It is advisable to accompany this result with a follow-up study to validate their sustainability.

The above-discussed results infer that demand-side management strategies, such as changing the crop pattern in the dry season, are more effective than the supply-side management strategies in reducing the unmet demand in Ranorawa Cascade in the near future.

Under the scenario representing the combination of climate change and high growth (population and corresponding growth of agricultural lands), the demand shortages have increased and drainage outflows have reduced compared to the reference scenario. In this combined scenario, the positive impact of the increase in catchment yield resulting from the climate change scenario is thereby levelled off by the increasing pressure on water resources under the growth scenarios. Even though in terms of unmet demands, the combination scenario is favourable compared to the individual growth scenarios, it is still resulting in higher water shortages in the cascade than the business-as-usual case. This highlights the critical need for suitable adaptation measures as it is highly unlikely that business-as-usual will be the case in the near future in the study area in terms of climate, population growth and land use change.

Results thereby show that under climate change and population dynamics (resulting in land use change), the introduction of high-value crops during the minor cropping season can substantially reduce the unmet demands and increase cropping intensity compared to the reference scenario. However, it is essential to conduct an assessment of the socio-economic benefits of introducing OFCs in place of paddy, giving due attention to their market conditions. In this pilot study, we have only tested maize cultivation in place of paddy. However, several combinations of OFCs with improved irrigation efficiencies, considering expert opinion, can also be evaluated along with their economic assessment to select the best combination of adaption strategies for a given cascade.

4.3.2. Groundwater storage. The fluctuations of groundwater storage are given in Figure 10. It is important to notice that the introduction of high-value crops decreases the groundwater storage, attributed to reduced return flows. Moreover, the improved canals exhaust the groundwater storage due to reduced seepage and percolation. As such, the results corroborate previous studies by Meijer *et al.* (2006) which shows lining will have negative impacts by lowering groundwater levels due to a reduction in seepage from canals. Under other scenarios, the groundwater storage is replenished.

5. Conclusions and recommendations

In light of the anticipated vulnerability of smallholder agriculture in the Ranorawa Cascade, this study aimed to assess the agricultural water demand-supply scenarios under plausible future pathways of climate and population dynamics and to evaluate the performance of a few adaptation methods to reduce water stress. A water balance study was carried out using the WEAP model for the study area comparing the projected supply, demand, storage and outflows under several scenarios for the time horizon of 2016–2044. It also involved the use of SCS CN method to compute the catchment runoff based on historical daily rainfall data for 20 years from 1986 to 2015.

Under the reference (business-as-usual) scenario, a significant increasing or decreasing trend in water shortages was absent, even though a constant growth rate in population and agricultural extent was assumed, and this is attributed to high inter- and intra-annual variability in the rainfall and the resulting streamflows from the catchment.

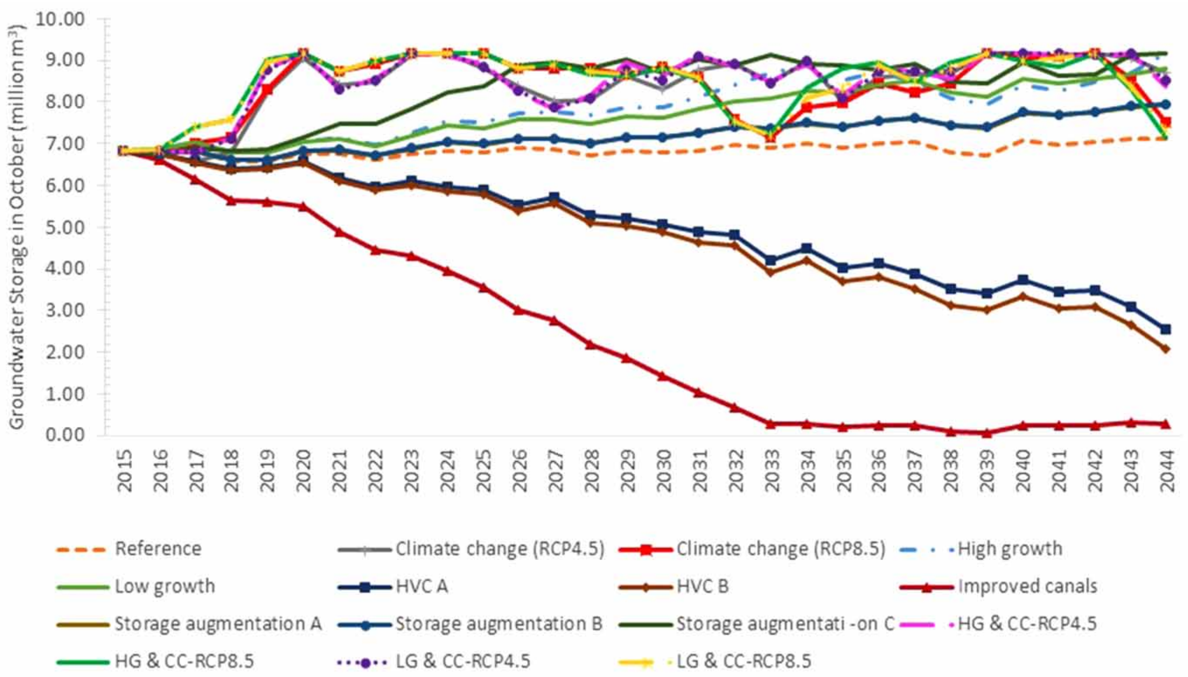

Fig. 10. Groundwater storage in the near future under different scenarios in the Ranorawa Cascade.

The high growth scenario resulted in the highest unmet demands while the lowest was observed under a scenario representing the introduction of high-value crops (HVC B). High growth, low growth, storage augmentation C and combined high growth and climate change scenarios resulted in increased unmet demands compared to the reference scenario. Of the adaptation measures tested, storage augmentation A and B scenarios were the least effective in reducing demand shortages.

The model was used to evaluate the impacts of various future scenarios of changes in socio-economic and environmental conditions involving climate change, population growth, expansion of agricultural lands and water management interventions on the water supply-demand balance in Ranorawa Cascade. Moreover, combinations of some of these scenarios were also simulated. Results show that climate change-induced higher rainfall can be beneficial, but its inter-annual variability could be a management challenge. The study, which only evaluated the average conditions, shows a favourable situation compared to the reference scenario, even though the demands are not fully met. However, management and development strategies should focus on tackling extreme floods and droughts. This requires more powerful climate modelling and forecasting techniques and uncertainty assessments.

Population and agricultural area growth results in a significant increase in irrigation water deficits, which however is moderated to a certain extent when combined with the climate change scenario. The results indicate that demand-side adaptation, e.g., growing high-value crops, is more effective than the supply-side adaptation strategies in reducing unmet demand sustainably and improving incomes and domestic food security.

The study further reflected that scenarios introducing high-value crops and improved canals lower the groundwater shortage pertaining to reduced seepage and percolation, which questions their sustainability.

Furthermore, in interventions that reduce the surface drainage outflow (such as in the storage augmentation scenarios), the decision-makers should pay attention to check whether the minimum downstream flow requirements, including environmental flows, are satisfied. The same WEAP model could be expanded to facilitate such assessment, ideally by up-scaling to the river basin level.

Research framework and outcome facilitates planners to design an optimum mix of solutions to sustainably address the vulnerability of smallholder agriculture in the country and to improve resilience against climate change and population dynamics. This hydrology-based planning of cascade development for agricultural improvement marks a major departure from the conventional engineering-centric approach of focusing on desilting and increasing the storage capacity of the tanks followed in the past which resulted in undesirable consequences for downstream water bodies.

The study is recommended to be extended to incorporate cost-benefit assessment of the scenarios, especially when restoring tanks and introducing high-value crops. Furthermore, in developing the 'high-value crops' scenarios, more detailed prior assessments are required to decide which mix of OFCs to grow, to what extent, and which smart irrigation techniques are most suitable under different settings, etc., with inputs from the experts in the agriculture sector and other stakeholders. It is further recommended to run several climate change scenarios since future climate change pathways are associated with deep uncertainties. As such, the model should be further developed incorporating the above recommendations before making water management decisions in the cascade to improve agriculture productivity and to ensure sustainability in the long run.

The water balance study involved several assumptions pertaining to the extent of irrigation return flows; the conveyance efficiency of irrigation canals, storage–elevation relationships of some tanks, field irrigation efficiency, groundwater outflows, recharge, etc., in the absence of actual values of these variables from field tests. These assumptions will have significant implications for some of the model outputs, including changes in groundwater condition (stock) and the water (demand-supply) balance. It is recommended that field investigations are carried out to determine the value of these variables. The robustness of the model can be improved by calibrating it against observed streamflows. However, such a calibration could not be done as Thalawa catchment is not gauged.

Groundwater monitoring data are very scarce in Sri Lanka. Monitoring of groundwater in the command area, along with field studies to determine the hydraulic conductivity of the soils would therefore be essential. Further, monitoring of the performance of the tank system vis-à-vis the total inflows, the volume of water released to the command areas (daily and seasonal), evaporation, the water level fluctuations in the tank, infiltration from the tank bed and conveyance efficiency of the canals need to be carried out for selected tanks, as this can improve the accuracy of future planning of tank cascade development programmes.

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Data availability statement

Data cannot be made publicly available; readers should contact the corresponding author for details.

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