Modeling for Tank Cascade System Planning and Management: Case Study of Mamunugama Tank Cascade System, Kurunegala District

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Abstract:　　　The dynamics of tank cascade systems have been studied using simple water balance models. This paper presents the development of a system simulation model for a tank cascade system based on the principles of System Dynamics (SD), a mathematical modeling approach that could be used to study the behavior of dynamic systems. The model was developed for the Mamunugama tank cascade system comprising 06 tanks and 02 anicuts and located in the Kurunegala District, Sri Lanka. Modeling of all the water balance components of the tank cascade system is presented in detail. The model was calibrated using observed water levels at four tanks during the period from October 2020 to September 2021 covering a Maha Season and a Yala Season by comparing them with the model computed tank water levels. The model results provided valuable insights into the water balance components at each tank. The model has the potential to be used as a tool for optimizing the usage of the limited water resources in tank cascade systems for improved agricultural production. It can be used in planning tank rehabilitation, studying the impact of restoring abandoned tanks in addition to planning cultivation seasons in a scientific manner.

Keywords:　　　System Dynamics Modelling, Water Balance Component

1. Introduction

Rainfall and surface runoff have been stored in human-made reservoirs in the dry and intermediate zones of Sri Lanka to provide water for irrigation since ancient times. During rainy periods, direct rainfall and surface runoff are collected and stored in these reservoirs or tanks to provide water for domestic use, livestock, and agriculture. More than 12,000 operational tanks and reservoirs have been identified within these zones, and a similar number remain abandoned [1]. A substantial portion of these small reservoirs is hydrologically linked and form tank cascades. It is noted that about 90% of the cascade systems are concentrated in "main cascade zones" located in 27 river basins [2]. The tank density and the presence of small tank cascades are lower in the lower reaches of river basins. However, not all tanks belong to cascades. In the other dry zone river basins than the 27 mentioned above, the percentage of tanks contained within cascades is lower.

These tank cascades allow surplus flow from the upstream tank(s) and return flow from the upstream command area(s) to reach the tank that is immediately downstream, facilitating the reuse of water in the command area of the downstream tank, and in effect, increasing available water for irrigation [3]. Tank cascade systems help to overcome problems related to irregularly distributed rainfall and make water available throughout the year. Availability of water in several locations of the cascade helps to overcome water scarcity even during dry seasons, which enables maximized land use.

A tank in a cascade receives water from upstream spills and drainage, own catchment, diversion structures, etc. Also, each of their outflows can reach different tanks. There can be 20, 30, or even more tanks and anicuts in a cascade. As such, the calculation of inflows to a tank in a cascade is very complex. Besides, without knowing the storage at the end of the season, it is not possible to plan a cultivation season.

Several water balance studies for tanks based on basic hydrological principles have been carried out [4, 5, 6, 7] to identify the optimum utilization of the storage in village tanks. The study by Sakthivadivel et al. [6] showed that the tank command area to tank water spread area describes the adequacy of the tank storage capacity to serve the command area. They

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further said that this ratio should be less than 2 to serve the command well. Dharmasena & Goodwill [7] found that, in general, 50% of the volume stored in a tank is lost through evaporation, percolation, and seepage, leaving only 50% for irrigation. Though these studies generated useful hydrologic information on small tanks, they were limited in extent and scope. Therefore, there was a need for conducting further systematic studies at the tank cascade level [6].

Jayatilaka et al. [3] attempted to measure water availability in tank cascade systems using a cascade water balance model. Itakura [8] carried out a water balance and water flow study for four small tanks in the Thirappane tank cascade in Anuradhapura District. He recorded that the average runoff was 30 % and 12 % of the rainfall for two Maha seasons and it was 10 % and 4.5 % for two Yala seasons. Matsumo et al. [9] attempted to study the water circulation in a cascade including groundwater movement along the cascade.

The literature survey carried out reveals that many water balance studies have been carried out for cascade tank systems while no efforts have been made towards modelling such systems to investigate how such systems could be managed to maximize benefits from the systems. In this work, a cascade tank system is modelled based on the principles of System Dynamics (SD), a well-known mathematical modeling approach that could be used to study the behavior of dynamic systems. Application of SD modelling for global, regional, and basin-level water resources systems has proven to yield remarkable results [10, 11, 12].

2. Study Area

The Mamunugama tank cascade system, which is shown in Figure 1, comprises 06 tanks and 02 anicuts. It is located in the Ihala Thimbiriyawa Grama Niladari (GN) Division, Polpithigama Divisional Secretariat Division of the Kurunegala District, which is within the dry zone of Sri Lanka. It is in the DL1b agroecological zone, where 75% expectancy value of annual rainfall is greater than 900 mm. The soil in the area is mainly Reddish Brown Earth and Low Humic Gley soils and the terrain is undulating. The aquifer in the area is the Shallow Regolith aquifer region underlain by deep Factures Zone aquifer region. Daily rainfall data collected at the Siyambalangamuwa rainfall gauging station located close to the tank cascade system were used in the study.

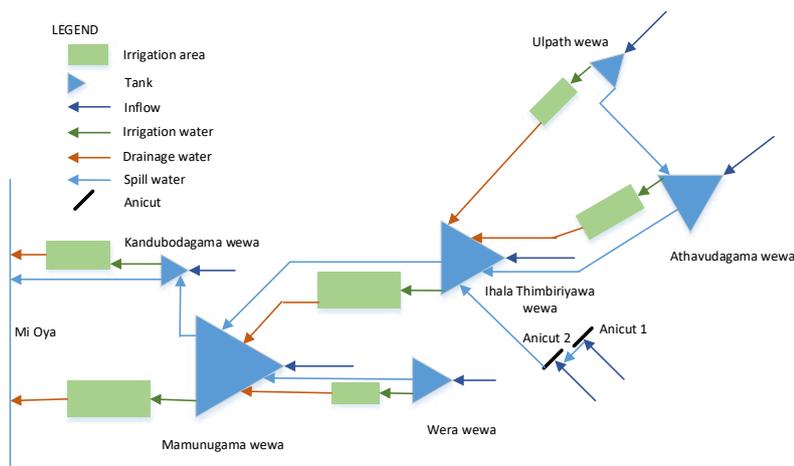**Figure 1 - Location of the Mamunugama TCS**

Figure 2 - Mamunugama Tank Cascade System - Layout

The system model is developed using the Vensim simulation environment, which facilitates the use of the system dynamics modeling objects such as stocks, flows, feedback mechanisms and delays. The cascade model was formulated based on a simple structure, incorporating the dynamic hydrologic processes associated with the set of six tanks and two anicuts. Figure 2 shows the connectivity of the tanks and anicuts in the

cascade system. Details of the tanks in the study tank cascade system are given in Table 1.

As Figure 2 indicates, Ulpath wewa, Athavudagama wewa, Wera wewa, and Kandubodagama wewa are upstream end tanks. Anicut 1 and Anicut 2, which are located in parallel, are also upstream structures. They receive water from their catchments only. The other tanks, viz., Ihala Thimbiriyawa wewa and Mamunugama wewa receive water from their incremental catchment, spillage and seepage from the upstream tank and drainage water from the upstream irrigation area.

Table 1 - Salient Features of Tanks in the Mamunugama Tank Cascade System

Tank	Sluice sill (MASL)	FSL (MASL)	HFL (MASL)	BTL (MASL)
Ulpath Wewa	146.975	149.197	149.697	150.350
Athaudagama Wewa	145.210	147.446	147.856	148.500
Wera Wewa	139.517	142.283	142.633	143.250
Ihala Thimbiyawa Wewa	135.750	138.968	139.468	140.100
Mamunugama Wewa	130.550	133.250	133.770	134.400
Kandubodagama Wewa	130.530	131.630	132.380	133.000

FSL=Full Supply Level, HFL=High Flood Level, BTL=Bund Top Level

Water balance components of the tanks in the tank cascade system are shown in Figure 3. Tanks located at the upstream end of the tank cascade system receive runoff from the catchment and rainfall on the tank water surface as 'inflow' components. The 'outflow' components include evaporation of tank water, seepage through tank bund and bed, water issued for irrigation, and spillway discharge.

All other tanks in the tank cascade system receive the runoff generated in their incremental catchments and the rainfall on the tank water surface. Additionally these tanks receive a fraction of seepage through bund and bed, spillway discharge of the immediately upstream tank(s), and drainage water from irrigation areas located upstream. The outflow components of these tanks are the same as those of start tanks.

Table 2 provides the net (incremental) and gross catchment areas of the tanks in the study tank cascade system.

Table 2 - Catchment Areas of Tanks

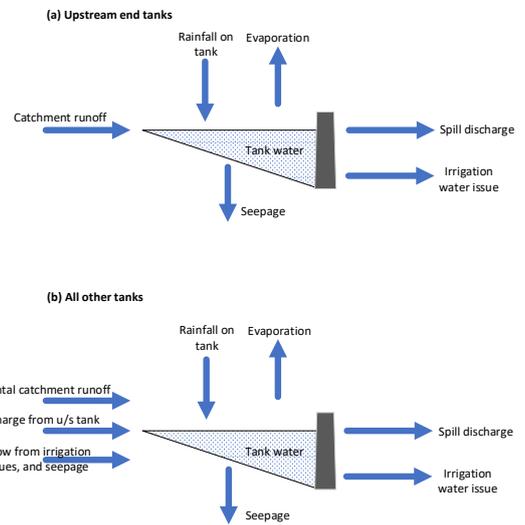| Tank	Net Catchment Area (ha)	Gross Catchment Area (ha)
Ulpath Wewa	25.9	25.9
Athaudagama Wewa	22.3	48.2
Wera Wewa	13.8	13.8
Ihala Thimbiyawa Wewa	83.2	131.4
Mamunugama Wewa	43.1	188.3
Kandubodagama Wewa	38.2	226.5

Figure 3 - Tank Water Balance Components

Water balance equation used for the upstream end tanks (Ulpath wewa, Athavudagama wewa, Wera wewa, and Kandubodagama wewa) is given in Eq (1).

$$S_{i+1} - S_i = I_i + RV_i - Q_i - EV_i - SP_i - O_i \quad \ldots(Eq\ 1)$$

where,

S_i = Tank storage at the beginning of ith time step (m^3)

I_i = Catchment runoff during ith time step (m^3/day)

RV_i = Rainfall volume over tank water-spread area during ith time step (m^3/day)

Q_i = Irrigation water release during ith time step (m^3/day)

EV_i = Evaporation loss during ith time step (m^3/day)

SP_i = Seepage and percolation loss during ith time step (m³/day)

O_i = Spillage during ith time step (m³/day) - Water spills if S_{i+1} reaches tank capacity

For other tanks (Ihala Thimbiriyawa wewa and Mamunugama wewa) water balance equation is given by Eq (2).

$$S_{i+1} - S_i = I_i + RV_i + QV_i + SV_i + OV_i - Q_i - EV_i - SP_i - O_i \quad \text{...Eq (2)}$$

where,

QV_i = Drainage flow from upstream irrigation water issue during ith time step (m³/day)

SV_i = Return flow: seepage and percolation from upstream tank during ith time step (m³/day)

OV_i = Return flow: spillage from upstream tank during i^{th} time step (m³/day)

Other variables as described before.

These water balance simulations are subject to constraints in tank capacities and sluice capacities.

$$S_{min} \leq S_i \leq S_{max} \quad \text{...Eq (3)}$$

where,

S_{min} = Minimum storage capacity of tank (Storage at Minimum Operating Level) (m³)

S_{max} = Maximum storage capacity of tank (Storage at Full Supply Level) (m³)

Other variables have been previously defined.

$$0 \leq Q_i \leq Q_{max} \quad \text{...Eq (4)}$$

where,

Q_{max} = Maximum capacity of sluice of a tank (m³)

Other variables previously defined.

Determination of inflow and outflow components in the water balance equations are described below.

Inflows to upstream end tanks are runoff from the tank catchments and rain falling on tank water-spread areas. The other tanks receive runoff from their incremental catchment areas, rain directly falling on water spread areas, drainage water from immediately upstream command area, part of dam bund and tank bottom seepage from upstream tanks and part of spillage from upstream tanks.

2.1 Runoff from Tank Catchment

Observed inflow data are not available for the tanks in the cascade system. Therefore, daily rainfall (R_i) over catchments was used to generate inflows (I_i) to the tanks using a simple model using the runoff coefficient method. The runoff coefficient was assumed to be varying, its variability depending on catchment wetness and rainfall intensity. The nonlinearity of the runoff generation process can be approximated through a time-varying runoff coefficient, facilitated using an Antecedent Precipitation Index function indicating the degree of catchment wetness [3, 13]. The cascade model estimates runoff from rainfall on the catchment of each tank daily by adopting a modified runoff coefficient method, which allows the runoff coefficient to vary daily depending on the Antecedent Precipitation Index (API), as described by Eq (5) and Eq (6).

$$I_i = C \times R_i \times CA/API_i \quad \text{...Eq (5)}$$

where,

C = Runoff coefficient

R_i = Rainfall over catchment during ith time step (m/day)

CA = Catchment area (m²)

API_i = Antecedent precipitation index on ith time step

Other variables previously defined.

API_i depends on the number of days since the last day with rainfall (n) as given in Eq (6).

$$API_i = \sum_{k=o}^{k=n} 1/(k + 1) \quad \text{...Eq (6)}$$

where,

k = Number of days since the last day with rainfall

Other variables previously defined.

This method provides a means to account for the effect of soil moisture depletion over no-rainfall periods on runoff yield. It accommodates both (a) the effect of field conditions more favorable for runoff generation when there has been rainfall raising soil moisture levels and thus the catchment wetness, and (b) the effect of decreasing soil moisture (or the catchment wetness), which would gradually decrease the runoff yield. The effect of decreasing soil moisture on runoff yield would decrease as the number of days without rainfall increases. Similarly, the increase in API and its effect on runoff yield decreases with the increasing number of days without rainfall once that exceeds a certain

limiting value. In the model, this limit is taken as 11 days.

2.2 Rain Falling on Tank Water-Spread Area

The volume of water received daily due to rainfall over the tank area is determined using daily rainfall and the corresponding tank water-spread area.

Rainfall volume on tank water-spread area is determined as follows:

$$RV_i = R_i \times A_i \qquad \qquad \text{…Eq (7)}$$

where,

R_i = Rainfall over tank during i^{th} time step (m/day)

A_i = Tank water-spread area at the beginning of the ith day (m²)

Other variables have been defined previously.

2.3 Drainage from Upstream Command Area

Part of irrigation water issued to a command area drains to a downstream tank and it is estimated as a fraction of the irrigation water issue from the upstream tank. In general, such flows due to water issues do not reach downstream tanks during the Yala season since such issues are adequate only to satisfy crop water requirements in the command area.

Drainage flow due to irrigation water issues is determined as,

$$QV_j = F_1 \times Q_i \qquad \qquad \text{…Eq (8)}$$

where,

F_1 = A factor (Fraction of water issue reaching downstream tank)

Other variables previously defined.

Fraction F_1 depends on the water use efficiency of the upstream command area. Some tanks receive water issues from a single tank while some receive irrigation issues from several tanks as shown in Table 3. Depending on the extent of the command area and distance of the upstream tank, time j could be equal to time i or longer.

Table 3 - Connectivity of Tanks in the Mamunugama Tank Cascade System

Drainage water from command area of tank	Return flow to tank
Ulpath wewa, Athavudagama wewa, Anicut 1, Anicut 2	Ihala Thimbiriyawa wewa
Ihala Thimbiriyawa wewa, Wera wewa	Mamunugama wewa

Spillage from tank	Spillage to tank
Ulpath wewa	Athavudagama wewa
Athavudagama wewa, Anicut 1, Anicut 2	Ihala Thimbiriyawa wewa
Ihala Thimbiriyawa wewa, Wera wewa	Mamunugama wewa
Mamunugama wewa	Kandubodagama wewa

This return flow is about 20% of the irrigation release for cultivation in the immediately upstream tank [14].

2.4 Return Flow due to Seepage and Percolation

Water that is lost due to seepage and percolation at an upstream tank reaches the downstream tank. The return flow due to seepage and percolation is determined as follows:

$$SV_i = F_2 \times SP_i \qquad \qquad \text{…Eq (9)}$$

where,

F_2 = A factor (Fraction of seepage reaching downstream tank)

Other variables have been previously defined.

Determination of the fraction of the water reaching the downstream tank due to seepage (tank bed and bund) from the upstream tank is very difficult and, thus, fractions (F_2) in the range 0.1 to 0.4 are used in the model as suggested by Jayathilaka et al. [3] at this stage of modeling. The tank connectivity is as given in Table 3.

The tank seepage is estimated by using Eq (10) as suggested by Jayathilaka et al. [3].

$$SP_i = [a_i \ln(h_i) + b_i] S_i \qquad \qquad \text{…Eq (10)}$$

where,

a_i and b_i = parameters of the seepage function

h_i = tank water height (m)

Other variables are previously defined.

The required data to determine parameters of the seepage function relevant to the tank(s) are not available. Thus, taking the values suggested by Jayathilaka et al. [3] for a similar tank cascade system as initial values, the parameters were adjusted at the calibration stage to suit the observed water levels in the study.

2.5 Return Flow due to Spillway Discharge
Return flow due to spillway discharge at upstream tanks is estimated as a fraction of the discharge. Though this fraction could vary from tank to tank, the value of 0.5 was used in the absence of field measurements as suggested by Jayathilaka et al. [3]. The fraction of spill discharge that arrives at the downstream tank has been taken as 0.57 and 0.67 for the Vendarankulama and Bulankulama tanks, respectively, in the study of Shinogai et al. [15] as presented by Jayathilaka et al. [3].

Return flow due to spillage from an upstream tank is determined as,

$$OV_i = F_3 \times O_i \qquad \text{...Eq (11)}$$

where,
F_3 = A factor (Fraction of spillage reaching downstream tank)
Other variables previously defined.

2.6 Irrigation Water Demands
Irrigation water requirements (D_i) of the irrigable area below tanks are estimated using the CROPWAT software (Version 8.0). These are determined for paddy and many other field crops for both Yala and Maha seasons. The water issue for paddy in each season is estimated based on three stages: (a) land preparation, (b) growing stage of the crop, and (c) ripening period of the crop. Since command areas are located close to the dams of tanks, conveyance losses are neglected. However, application efficiencies are used in the model.

At this stage, water requirements for 3.5 month paddy variety cultivation have been estimated. In the Maha season, the land is prepared using rainfall and, therefore, tank water is not generally used in village tanks. In the Yala season, tank water is used for land preparation. The irrigation water release requirements during the growing stage of the crop (stage 2), are determined according to the crop water requirements. During the third stage, i.e. the ripening period of the crop, irrigation water is not required. Irrigation areas under each tank

in the cascade system studies are given in Table 4.

Table 4 - Irrigation Areas in the System

Tank	Irrigation Area (ha)
Ulpath Wewa	4.45
Athaudagama Wewa	8.09
Wera Wewa	6.88
Ihala Thimbiyawa Wewa	14.57
Mamunugama Wewa	14.57
Kandubodagama Wewa	9.31

Source: UNDP Report

In addition to irrigation water demands, drinking water demands can be added to the model. The releases made to satisfy these demands will depend on water availability in the tanks and inflows during the time step.

2.7 Evaporation Loss
Daily evaporation losses are computed by multiplying daily evaporation loss rates by tank surface area, which is a function of water depth that varies with time. The evaporation loss rate is determined by multiplying pan evaporation by pan coefficient. Pan evaporation data at the Mahailluppallama weather station were used in the study.

Evaporation loss is determined as,

$$EV_i = K_p \times E_i \times A_i \qquad \text{...Eq (12)}$$

where,
K_p = Pan coefficient
E_i = Pan evaporation on i^{th} time step (m/day)
Other variables defined previously.

2.8 Seepage and Percolation Loss
Seepage of water through a tank bed and its embankment represents a significant loss of water from a tank [3]. Sometimes, the tank seepage is estimated as a certain percentage of the tank water volume (e.g., 0.5% of the tank water volume per month) [14]. Tasumi et al. [16] argued that a greater percentage of tank water volume would leave as seepage when the tank water level is low than when the tank water level is high. This is due to the changes in the head difference between tank water level and groundwater level in the surrounding area. The seepage interpreted as a percentage of tank storage at the Walagambahuwa tank decreased as the head increased [17]. Tasumi et al. [16] suggested a seepage of about 2.4% of the tank water volume per day. Thus, it is assumed that

the seepage loss is determined based on the volume of water stored in a tank, which is reflected by its water height. In this study seepage loss is estimated by multiplying tank water volume by height, which is represented in a logarithmic function suggested by Jayathilaka et al. [3].

Thus, seepage is estimated as,
$$SP_i = (a \ln h_i + b) \times S_i \qquad \text{...Eq (13)}$$

where,
h_i = Tank water height at the beginning of ith time step (m)
a, b = Seepage parameters (depends on tank)
Other variables defined previously.

2.9 Spillway Discharge
Spillway discharge volume O_i is determined as the tank water volume above the full supply level (tank capacity at the spill level). This is obtained from the tank cascade system simulation model and it depends on the capacity of a tank, water in storage, inflow and outflow.

3. System Simulation Model

The SD based simulation model incorporates the dynamic interaction among different sectors that comprise the water resources system, viz., (i) physical sector such as tanks, weirs, canals, etc., (ii) agricultural sector such as cropping areas, crop types, etc., (iii) economic sector such as crop yields, prices, etc., and hence will support making unique decisions for efficient management of cascade tank systems.

A SD model that incorporates the complexities and interaction among different activities in a cascade tank system will prove the usefulness of the modeling approach in terms of strategic decisions on water sharing to help all water-use sectors of the area. The system model was developed using the Vensim Simulation Environment (Version 8), which facilitates the use of the SD modeling objects such as reservoirs, flows, feedback mechanisms and delays.
Figure 4 presents the SD Model configuration for the water balance of a typical single reservoir in a cascade tank system.
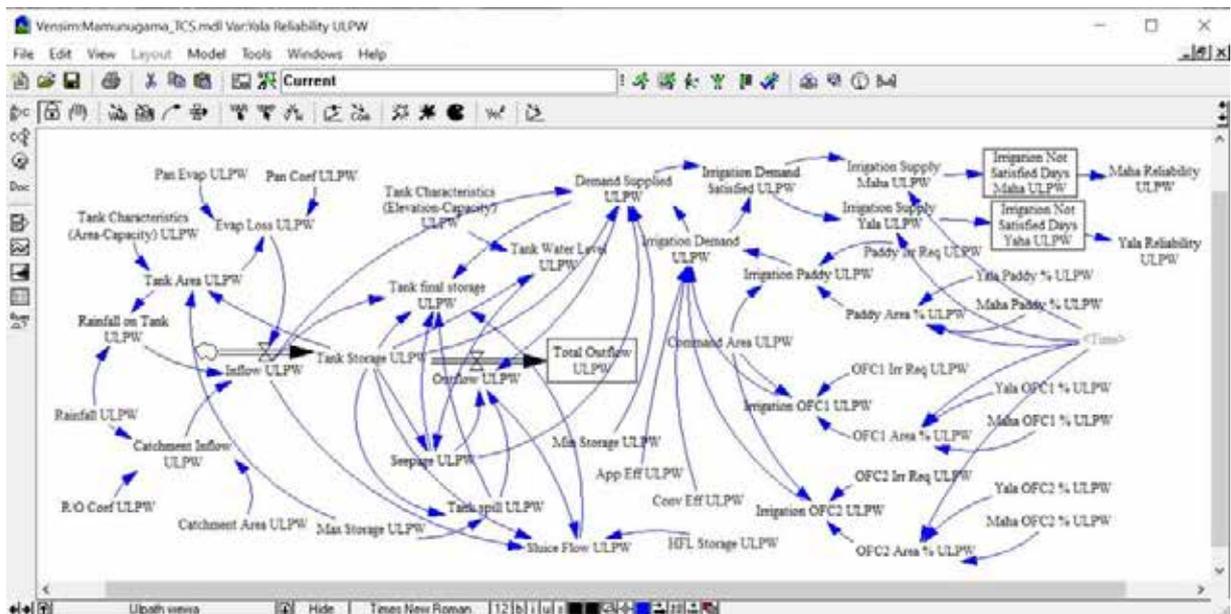

Figure 4 - Vensim Model for Ulpathwewa in Mamunugama Tank Cascade System

In Vensim Environment this model for a single tank is one view (see the left bottom of Figure 4 – Ulpath wewa) in the model. Similarly, for each tank, there is one view. These views are connected appropriately to represent the tank cascade system. In the final model, all the tanks in the system are connected in series and parallel as given in the cascade tank system configuration shown in Figure 2.

All the time series data such as rainfall, inflow, demand etc., are stored in an EXCEL worksheet, which are read by the model as inputs. Similarly, outputs could be either viewed directly in the Vensim Environment or exported to an EXCEL worksheet, which allows the presentation of results in tabular or graphical form.

3.1 Simulation of Water Balance

The SD based simulation model performs water balance computations on a daily basis, starting from the most upstream end tanks in the tank cascade system. The equations solved in the model are given in Eq (1) and Eq (2) subject to constraints given by Eq (3) and Eq (4). The model input consists of rainfall, evaporation, catchment runoff, seasonal cultivation extents, drinking water requirements, crop water requirements, and physical system data such as tank characteristics, etc.

The model carries out a water balance and releases the required irrigation water and drinking water when water in the storage is adequate. If the storage is insufficient, the model calculates the allowable water release, and it will be less than the estimated water release requirement of the day. The water release allowed by the model is denoted as the water issue. In addition to the allowable water issue, the model provides an output at the end of each day including the tank water height, tank storage, and other information on the tank water balance components.

3.2 Calibration of the Model

The inflows to the tanks from their catchments and incremental catchments and rainfall over tanks are known while fractions of seepage and percolation, irrigation water issues and spillway discharges from upstream tanks are initially not known. Those fractions are the calibration parameters in the model and those were determined based on tank water level variations observed at four tanks, viz., Ulpath wewa, Athavudagama wewa, Ihala Thimbiriyawa wewa and Mamunugama wewa, over the period between October 2020 and September 2021 by using trial-and-error method, i.e., by comparing the model resulting water levels of the four tanks with the observed water levels as given in Figure 5 to Figure 8.

Figure 5 - Comparison of Water Levels: Ulpath Wewa

Figure 6 - Comparison of Water Levels: Athavudagama Wewa

Figure 7 - Comparison of Water Levels: Ihala Thimbiriyawa Wewa

Figure 8 - Comparison of Water Levels: Mamunugama Wewa

The model simulations over the Maha and Yala seasons agreed reasonably well with the field observations as shown in Figures 5 to 8.

The calibrated water levels agreed reasonably well with the observed water levels. Inflows from spills and irrigation issues from the upstream tanks were not measured and assumptions had to be made to determine the fractions of such variables that contribute to inflow to the downstream tank. Local conditions such as ground cover and soil parameters influence these fractions. Evaporation rates were also not directly measured but were obtained from long-term records. Such assumptions and approximations contributed to the minor deviations of calibrated values from the observed values.

3.3 Calibration Results

This section presents the calibrated parameter values for the Mamunugama Tank Cascade System.

Part of irrigation water issued to a command area drains to a downstream tank and it is estimated as a fraction of irrigation water issued from the upstream tank. This fraction was found to be varying between 0.15 and 0.4.

Water lost due to seepage through the tank bed and embankment at an upstream tank reaches the downstream tank and the fraction that reaches the downstream tank varied between 0.15 and 0.3.

Return flow due to spillway discharge at upstream tanks is estimated as a fraction, found to be varying between 0.6 and 0.7.

Table 5 - Water Balance Components of the tanks in the Mamunugama Tank Cascade System

Tank	Storage Capacity	Inflow From Catchment	Inflow Rain on tank	Inflow from upstream tanks Spills	Seepages	Draiange	Evaporation loss	Spill	Seepage	Irrigation Demand Supplied	Tank storage Initial	Final
	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3	1000 m^3
Ulpath Wewa	11.47	98.14	10.30	---	---	---	6.60	51.70	22.18	22.13	4.50	10.29
Athavudagama Wewa	50.18	122.83	49.06	25.85	---	---	28.84	34.63	93.94	38.87	12.00	13.44
Wera Wewa	38.26	43.76	12.43	---	---	---	8.82	0.00	41.64	21.04	20.00	4.67
Ihala Thimbiriyawa Wew	99.44	379.19	69.19	13.52	26.78	18.30	49.31	107.32	180.22	124.79	10.00	55.40
Mamunugama Wewa	126.85	180.80	72.46	53.67	88.00	29.16	53.77	0.00	243.48	95.78	10.00	41.07
Kandubodagama Wewa	13.54	165.00	25.91	0.00	---	---	16.58	103.11	19.42	39.70	6.50	18.57

3.4 Water Balance Calculations

The reservoir system simulation results with calibrated parameters over the period 2020/21 Maha and 2021 Yala Season are given in Table 5. The percentages of irrigable areas cultivated during the two seasons are given in Table 6. Only paddy was cultivated during these two seasons. The irrigation water requirements during the two seasons for paddy were determined by using the Cropwat software. The actual dates for starting water issues at all the tanks in the system were used in the estimation of water requirements.

The Ulpath wewa, Athavudagama wewa, Ihala Thimbiriyawa wewa and Mamunugama wewa have satisfied the irrigation requirements during both seasons. The Wera wewa has satisfied 67% and 80% of the irrigation water requirements in the Maha and Yala seasons, respectively. Similarly, the satisfaction of the irrigation water requirements at Kandubodagama wewa is 79% and 96% during the Maha Season and Yala Season, respectively.

Table 6 - Cultivation Areas during the Two Seasons

Tank	Percentage area cultivated Maha	Yala
Ulpath Wewa	100%	28%
Athaudagama Wewa	100%	50%
Wera Wewa	100%	18%
Ihala Thimbiyawa Wewa	100%	56%
Mamunugama Wewa	100%	42%
Kandubodagama Wewa	100%	30%

The volume of water a tank receives due to rain falling on its surface could be as high as about 40% of the inflow it receives from the catchment. The Athavudagama wewa and Mamunugama wewa are examples of such cases. However, the volume of water the Ulpath wewa and Kandubodagama wewa receive is about 10% and 15% of the volume of water received from their catchments.

Figure 9 and Figure 10 show the inflow and outflow components as percentages of their totals. Figure 9 reveals that the catchment inflows are the largest inflow component to all the tanks during the Maha season.

Rainfall over the tank has varied between 10% and 25% of the total inflow. Inflow from spillages from upstream tanks is about 13% of the total inflow for Athavudagama wewa and Mamunugama wewa. The inflow from upstream tank spills for the Ihaha Thimbiriyawa wewa is about 3% only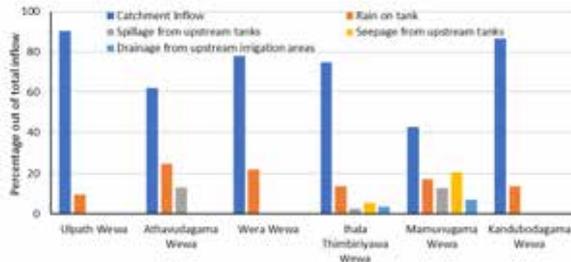. The seepage water Ihala Thimbiriyawa wewa received from upstream tanks is about 5% of the total inflow only. However, 20% of the total inflow received by the Mamunugama wewa is the seepage water from upstream tanks. Drainage water received to the downstream tanks from upstream irrigation areas is less than 7% of the total inflow received by the Ihala Thimbiriyawa wewa and Mamunugama wewa.
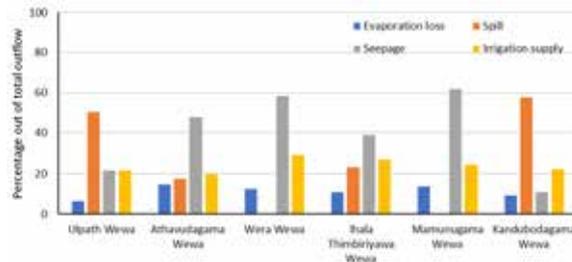

Figure 9 - Inflow Components as Percentages of Total Inflow

Figure 10 - Outflow Components as Percentages of Total Outflow

Figure 10 compares the different tank outflow components which could be used to propose possible improvements to be made for better use of available water. As it illustrates, the spills have been high at the Ulpath wewa and Kandubodagama wewa indicating the requirement for investigating the possibility to enhance the tank capacity to store water. All the tanks downstream of the Ulpath wewa located in series are observed to be spilling, indicating the usefulness of storing the spilled water at the Ulpath wewa by enlarging the tank capacity if possible. The tank bed and embankment seepage loss from the tanks is observed to be a large component compared to the other outflows. Similar results have been observed by Jayathilaka et al. [3] for the Thirappane tank cascade system. However, the seepage losses could be reduced with better maintenance.

The model demonstrates the impact of return flow on the storage of downstream tanks. For example, the flow coming from the upstream tanks and irrigation areas is about 40% of the total inflow to the Mamunugama wewa. This implies that water management of the tank cascade system should consider the hydrological linkage between upstream and downstream tanks and not treat them as a set of independent tanks.

The calibrated model for the cascade can be scientifically used for planning cultivation seasons. This is especially useful when the cultivation pattern is determined according to an agricultural plan, in which suitable crops for both seasons are described. Based on forecasted weather patterns and tank water levels at the planning time, the management can decide the crop types that will make use of the water resources in an optimum manner. The management can also make drought management decisions such as abandoning Yala cultivation and saving water for livestock or fisheries. In rehabilitation planning, the impact of restoring abandoned tanks on the existing hydrology of the cascade can also be studied.

The model helps to manage the cultivation seasons by facilitating the decisions such as the area to be cultivated and crop selection. Especially during the Yala season, the managers can run the model with different combinations of crops and cultivated areas, and advise the farmers about the combination that would maximize farmers' income. The risk of crop losses due to the tanks becoming dry before the end of the cultivation season can be reduced with the model results. It can also be used to understand the impact of restoration of any abandoned tanks to the cascade hydrology, the possibility of increasing the storage of tanks and the resulting impact on the downstream flows and decide on the maintenance activities that would reduce the water losses from the tank.

4. Conclusions

The Mamunugama Tank Cascade System was modelled and calibrated using water levels recorded at four tanks over an annual period. Though the period was short, an acceptable set of values could be obtained for the calibration parameters.

The tank cascade system simulations provided valuable insights into the water balance at each tank. It shows the importance of considering the hydrological linkages between upstream and downstream tanks and not treating them as a set of independent tanks in the management of tank cascade systems.

The model's application to the Mamunugama tank cascade system demonstrated the potential use of it as a tool for optimizing the usage of the limited water resources in tank cascade systems for improved agricultural production.

The paper illustrates the development of a planning and management model for the Mamunugama Tank Cascade System. A model for a different cascade system can be developed easily by using the model component developed for a single tank and connecting them according to the cascade tank system configuration. The model calibration can be further improved by measuring the spills, irrigation issues, and evaporation.

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