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Modifying and Testing of a Cascade Water Balance Model Using a Mini Cascade System with two Tanks

B.V.P.L. Jayakody, M.I.M.Mowjood [1] and E.R.N. Gunawardena[1]

Postgraduate Institute of Agriculture
University of Peradeniya
Peradeniya. Sri Lanka

ABSTRACT. *Models have been used to predict tank water availability, a crucial factor for the survival of rural community in the dry zone of Sri Lanka. A study was conducted for one year in 2001 to improve the already tested Cascade Water Balance Model (CWBM) by incorporating improved prediction equations of tank water evaporation and the seepage, and to apply the modified CWBM to a Tank Cascade System (TCS) of two tanks. Maduragama and Karambewewa tanks in the Maduragama mini cascade in Kala Oya river basin was selected and rainfall, evaporation, irrigation deliveries, tank water height, spill discharge and ground water level were monitored for two cultivation seasons. The results showed that the volume of water in a tank is a good indicator for predicting the seepage flow compared to the tank water height. The derived exponential equation between the seepage and the volume of water has higher degree of determination (r^2 = 0.93) compared to the logarithmic equation (r^2 = 0.73) used in the original CWBM. Evapo-transpiration coefficient of aquatic plant was incorporated in the calculation of tank evaporation. Except at the onset of maha rains, a reasonable overall agreement was obtained between the simulated and observed daily volumes of water in both tanks. The monthly simulation from the modified CWBM is even better compared to the daily simulations. The combined accuracy of the modified CWBM, incorporating the improved equations for seepage and tank evaporation, can predict both daily and monthly tank water levels in small tanks in cascades in the dry zone so that the model can be used in decision making process in water management. The ability to simulate different components of the tank water balance would also be helpful in understanding the dynamics of tank hydrology in cascade systems.*

INTRODUCTION

Village tanks are found as Tank Cascade Systems (TCS), which is defined as a series of small and medium tanks that are connected at successive locations down in one single common water course (Madduma Bandara, 1985; Panabokke, 1999). These tanks are hydro-geologically and socio-economically interlinked in terms of storing, conveying and utilizing water. If the hydrology of one or few tanks is altered by increasing either storage capacity through rehabilitation programs or command area by developing new paddy lands, the entire cascade hydrology changes (Sakthivadivel *et al.*, 1996). Such changes can also have a socio-economic impact on the surrounding communities dependent on the water availability of the system. Therefore, it is important to take the total tank cascade system rather than an individual tank into account when planning, development and operations of small tank systems are considered.

[1] Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.

Overall, the dynamics of the TCS in terms of water availability and utilization has been changed over time due to deforestation, siltation of tanks, construction of agro-wells, etc. The water availability due to these changes has become a critical issue for the villagers of the TCS. Thus, it is important to understand the impact of various changes, that has been occurring in a tank cascade system, on the different component of the water balance and the overall availability of water in the TCS over time and space. Several researchers have developed various models to predict water availability of single as well as TCS in the dry zone (Dharmasena, 2002; Itakura, 1995; Gunawardena, 1999; Jayathilake *et al.*, 2001). All these models differ in the methodology adopted in estimating the components of the water balance. The latest model called Cascade Water Balance Model (CWBM) developed and verified by Jayathilake *et al.* (2001) appears to encompass most of the processes taking place in a TCS. However, it has been recommended that the seepage, which is the biggest component of the water balance of TCS, needs improvement in order to make it more applicable (Jayathilake *et al.*, 2001).

The second biggest component of the water balance, after the seepage is the tank evaporation. Aquatic plants encourage water loss through evapo-transpiration. Gopal (1987) reported that the water loss from aquatic plants is 1.02–9.8 times greater than evaporation from an open water surface, depending on the mat density and other climatic parameters. It is reported in India that the water loss under open water surface was 0.54 – 3.86 mm/day while it was 0.76 – 8.18 mm/day through water hyacinth (Singh and Gill, 1996). These studies show that the water loss through aquatic plants should be taken into account in water balance studies of tanks covered with aquatic weeds.

Therefore, this study was conducted to: a) modify the CWBM by incorporating improved prediction equations of tank water evaporation and the seepage; and b) to test the modified CWBM to a TCS of two tanks for validation.

MATERIALS AND METHODS

Location and site description

This study was carried out at Maduragama mini cascade in Kala Oya river basin in Giribawa and Nawagaththegama Divisional Secretariats of Kurunagala District, Sri Lanka. This cascade comprises of two small tanks called Maduragama (MAD) and Karambewewa (KRB) having 2 and 6 ha of water spread, respectively with an average depth of about 1.5 m. The land use of the upper most catchment of the cascade consists of tropical dry evergreen forest. The catchment of the lower tank is predominantly paddy and is cultivated occasionally due to uncertainty of rainfall. These tanks are surrounded by home gardens, which are almost scrub jungle or occasional plots of annual crops.

The study area is located in the DL1 agro-climatological region of the Dry Zone, which receives 1300-mm rainfall annually. Nearly two third of annual total rainfall occurs in the *maha* season from late September to mid January. The study was conducted during two cultivation seasons from February, 2001 to February, 2002.

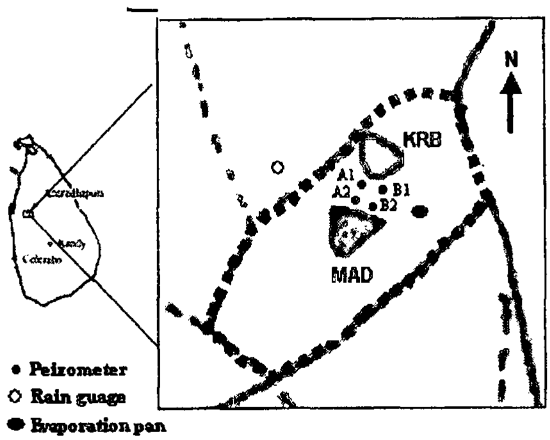

Fig. 1. Schematic diagram of the TCS and the location of measuring equipments.

Tank characteristics

A contour survey was carried out for both tanks. Based on the survey data on each tank, mathematical expressions to relate tank area and tank water volume as functions of the tank water height were formulated. Surfer 7 Software was used for this purpose.

Measurement of the components of tank water balance

Runoff (RO) and direct rainfall (DRF) on tank surface are the major inflow components of the start tank, MAD. The outflow components of the MAD consist of tank evaporation (E), seepage (SP), irrigation water releases (IWD) and spill discharge (SPD). In the second tank, KRB, two more components are contributed from the MAD as inflows in addition to the runoff generated from its own catchments and the rainfall on tank water surface. This additional inflow is treated as two different components; return flow due to seepage and water deliveries, and return flow due to spill.

The CWBM uses daily rainfall and pan evaporation, tank and catchment characteristics, amount of water delivered and user defined parameters to simulate the tank water volumes in each tank in the TCS (Jayathilake *et al.*, 2001). The modified CWBM uses all the predictive equations of the CWBM with the exception of tank evaporation and seepage. The methodology followed to determine the inflow and outflow components of the tank water balance of the CWBM and the modified equations of tank evaporation and the seepage are given below.

Direct rainfall

Daily measurements of rainfall were recorded during the period of the study using non-recording type rain gauges (Fig.1). The volume of direct rainfall on the tank water surface was determined using following equation given in the CWBM.

$$DRF = TWS \times RF \qquad (1)$$

where, DRF = Direct rainfall water (m^3/day), TWS = Tank water surface (m^2), and RF= Rainfall (m/day).

Runoff yield

In the CWBM, the runoff generated from catchments is estimated using Equation 2.

$$RO = (C/API) \times RF \times CA \qquad (2)$$

where RO=Runoff yield(m^3/day), C=Runoff coefficient, API=Antecedent precipitation index, and CA=Catchment area (m^2). Antecedent Precipitation Index is a time-varying runoff coefficient and is described by Jayathilake *et al.* (2001), as a function of catchment wetness as given below.

$$API = \sum_{k=0}^{n} 1/(k+1) \qquad (3)$$

where n - number of days since the last day with rainfall.

Tank evaporation

The evaporation was measured on daily basis using a class A evaporation pan located in the catchment of the lower tank (Fig. 1). Jayathilake *et al.* (2001) have used the data of evaporation pan to calculate the tank evaporation using pan coefficients as shown in Equation 4. But in this study, the impact of aquatic plants was considered thus plant evapotranspiration coefficient was incorporated to calculate the evaporation loss (Equation 5).

$$E = f_p \times E_p \times TWS \qquad (4)$$

$$E_t = f_c \times f_p \times E_p \times TWS \qquad (5)$$

where, E = Evaporation from tank (m^3/day), fc=Plant coefficient, f_p =Pan coefficient, and E_p=Pan evaporation (m/day).

It has been reported that the water losses due to evaporation is 1.6 and 1.9 times higher for a complete coverage of Salvinia and Water hyacinth, respectively when compared to the free water surface (Warusawithana *et al.*, 2003; Kahandawala *et al.*, 2004). In this study, the plant coefficient was adjusted according to the spread of aquatic weeds in the tanks. The coefficient of 1.5 was used for the total coverage (100%) and the value decreased linearly depending on the reduction of the spread of coverage at a given time.

Spill water

As given in the CWBM, the spillway discharge is computed using Equation 6. During the study period of 12 months, only two spilling events were observed. The measured length of the spill and the height of water above the spill were used to estimate the spill discharge.

$$SPD = L \times f_d \times H^{1.5} \tag{6}$$

where, SPD=Spillway discharge (m^3/s), L=Length of the spill (m), H=Spill height (m), and f_d=Discharge coefficient.

Return flow due to spillway discharge

Only a fraction of spill water reaches the lower tank directly. It has been reported that this fraction varies between 0.57 to 0.67 in dry zone cascades (Shinogi *et al.*, 1998). The spill water calculated from Equation 6, was substituted to the equation below to calculate the upstream return flow as an input to the lower tank.

$$RTFS = SPD \times Cs \tag{7}$$

where, RTFS=Return flow due to spillway discharge of the upstream tank (m^3/day), and Cs=User defined coefficient.

Water deliveries for irrigation

Water for irrigation was delivered through sluices of 20cm diameter cement pipes. The time duration and the level of the opening (half or full) were recorded. The Orifice equation, given below was used to calculate the water delivered for irrigation.

$$IWD = CA\sqrt{2gh} \tag{8}$$

where *IWD*=Irrigation water usage (m^3/s), *C*=Coefficient (0.62), *A*= Cross sectional area of the pipe (m^2), *g*= Gravitational Acceleration (ms^{-2}) and *h* = Depth of the water from center of orifice (m).

Return flow due to seepage and irrigation water

The following equation used in the CWBM was used to estimate the return flow from the upper tank catchment (MAD) to the lower tank (KRB) as a component of the inflow. The calculated irrigation release from Equation 8 was substituted to Eq. 9. The user-defined coefficient was determined during the calibration.

$$RTF = C_{rt}\,(SP + IWD) \tag{9}$$

where, RTF = Return flow m^3/day, C_{rt} = User defined coefficient (varied from 0.1 to 0.3), and IWD =Irrigation water deliver (m^3/day).

Tank seepage

A method to calculate the tank seepage is proposed. Depth of groundwater table was measured using four peizometers installed in the command area of MAD as shown in Fig.1. An electronic depth measuring devise was used to measure the water depths. Measurements were taken on daily basis in the morning along with the water level measurements of the two tanks. Water table depths from the peizometers were recorded only for a period of three months during which low rainfall was observed (from 1st February to 31st March, 2001). Darcy's equation, given below, was used to determine the seepage from the first tank (MAD) to the second tank (KRB).

$$SP = K \times A \times I \qquad (10)$$

where, SP = Flow due to seepage (m^3/s), K = Hydraulic conductivity (m/d), A = Cross-sectional area (m^2), and I = Hydraulic gradient (m/m).

The hydraulic gradient along a longitudinal section was calculated by dividing the differences of water level heights of two peizometers by the distance between them. The average of two hydraulic gradient values along longitudinal sections A_1- A_1 and B_1-B_1, as shown in Fig.1, was calculated to represent the hydraulic gradient along the command area. The depth of the water table, mid way along the command area was estimated by dividing the elevation differences between two tank beds by 2. The cross-sectional area of the sub-surface water flow was then calculated by multiplying the depth of the water table by the width of the valley (drainage area). The hydraulic conductivity obtained for the similar soil type in the Dry Zone was substituted for K.

The daily seepage was calculated as described above for the three-month period. A regression analysis was performed between the volume of water in the upper tank and the calculated seepage to derive a relationship.

Tank water depth

The daily tank water levels were measured every morning considering the base of the sluice gate as a datum point. This information was used to determine the respective water–surface area and the volume of water in the tank in each day using the derived relationships of height Vs water surface area, and height Vs volume of water in the tank.

Model input and initial condition

Modified CWBM was applied for each tank. For each tank inputs and out puts were separately considered and predicted. In the process of calibration of the model, initial condition in the tank cascade was assigned based on the measured tank water volumes at 8 am on 31 January, 2001. During the calibration, the model input including daily measurements of rainfall and pan evaporation, tank water height, and tank water released for irrigation were based on the field data recorded over the period 1 February, 2001–28 February, 2002. The user-defined coefficients, f_p, C_{rt}, C_s, and the model parameters C that need to be calibrated were initially assigned values as recommended by Jayatilake *et al.* (2001) and were later adjusted during calibration.

The model performed daily water balance computations for each tank and calculated water balance components and the tank water volume at the end of each day over the calibration period. The simulated tank water volume at the end of each day was compared with the tank water volume measurements taken at the beginning of the following day.

RESULTS AND DISCUSSION

Characteristics of the cascade system

Table 1 shows the physical characters of the TCS. MAD tank is about four times larger than the KRB in terms of volume as well as catchment area. The command area of the MAD is about twice larger than that of KRB.

Table 1. Cascade physical characters

Tank	Full Supply Level (m)	Capacity (m^3)	Water surface (m^2)	Command area (m^2)	Net Catchment (m^2)	Gross Catchment (m^2)
MAD	1.6	32648	65636	39519	524200	524200
KRB	1.25	9300	22311	18000	174000	698200

Seepage

There is a strong correlation between the seepage with the volume of water in the MAD tank as shown in Fig. 2. As indicated by the coefficient of determination (R^2 = 0.93), the exponential equation derived explains 93% of the variation of the seepage with a single parameter, the volume of water in the tank. The strength of the relationship between water height and seepage flow developed using a logarithmic equation was lower (R^2 = 0.80). The exponential equation derived was used in the modified CWBM to predict the seepage flow during the non-recording period for the first tank (MAD) and the entire study period for the second tank (KRB).

Model simulation

The model inputs and user-defined coefficients of the calibrated model are given in Table 2. All the user defined parameters for both tanks have the same values except the runoff coefficient. The higher runoff generated from the upper catchment of the MAD tank is mainly due to the land use. Much of the MAD catchment consist of shrub jungle, where as paddy, which produces less runoff dominated in the catchment of KRB.

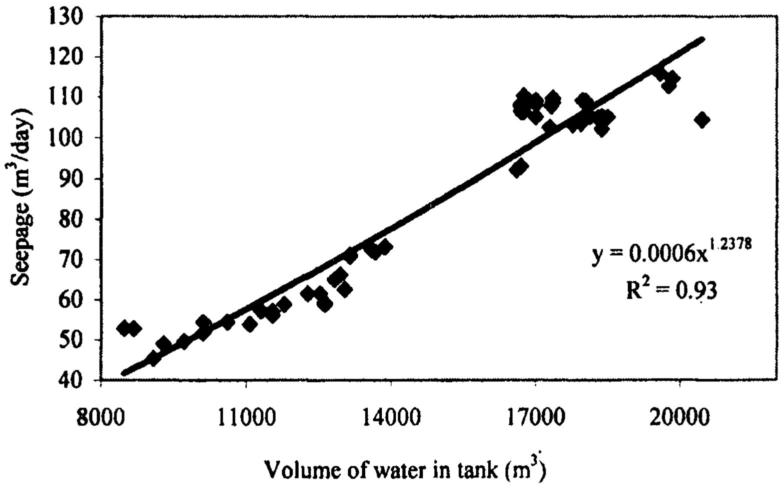

Fig. 2. Relationship between tank volume and seepage in the MAD tank.

Table 2. Input Parameter values for MAD & KRB Tank.

Parameters	MAD	KRB
Type	Upstream	Down Stream
Effective spill level	1.6m	1.25m
Length of spill way	5.0m	5.0m
Runoff coefficient	0.20	0.13
Tank evaporation (fp)	0.8	0.8
Plant evaporation coefficient (fc)	1.5	1.5
Return flow – seepage & Irrigation (crt)	0.2	0.2
Return flow – Spill (Cs)	0.61	0.61

The simulated and observed water volumes for MAD and KRB tanks during the study period are shown in Fig. 3 and 4, respectively. The simulations started on 1 February, 2001 soon after the cessation of *maha* rains. Water level decreases gradually until an unexpected cyclonic rainfall occurred in April. Thereafter, the water levels decreased and tanks became empty (far below the dead storage level) during the prolonged dry period. The water level again increased sharply with the onset of *maha* rains. Except at the onset of *maha* rains, a reasonable overall agreement was obtained between the simulated and observed volumes of water in both the tanks.

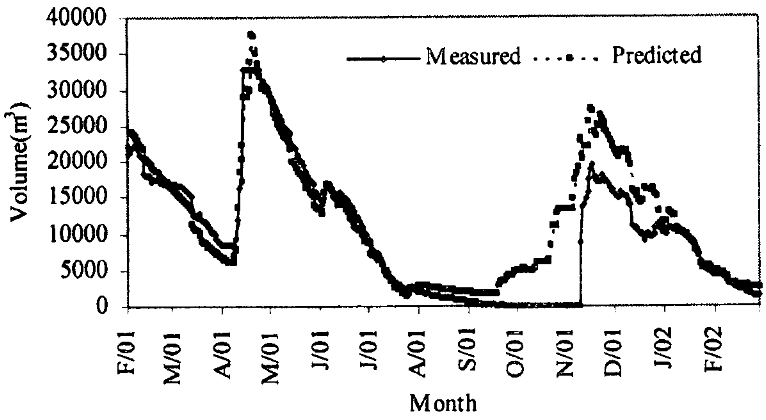

Fig. 3. Daily simulated and observed water volume in the MAD tank.

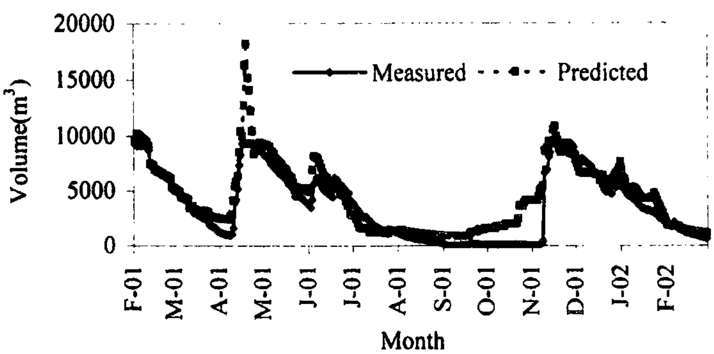

Fig. 4. Daily simulated and observed water volume in the KRB tank.

Monthly simulations

The regression analysis performed between daily simulated (y) and observed (x) water volumes produced $y = 0.9322\,X - 941.75$ ($R^2 = 0.82$), and $y = 0.9113\,X - 368.87$ ($R^2 = 0.84$) for MAD and KRB tanks, respectively. The monthly simulations from the modified CWBM are better than to the daily simulations as shown in Figs. 5 and 6. However, the lower tank tends to simulate a high water volume since the regression line is shifted above the 1:1 line. This may be due to over estimation of inflow and/or under-estimation of the outflow from the KRB tank.

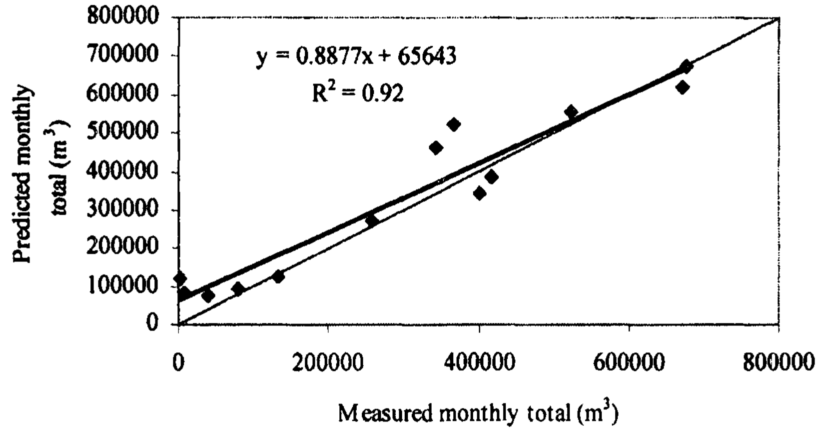

Fig. 5. Monthly simulated and observed volume of water in the MAD tank.

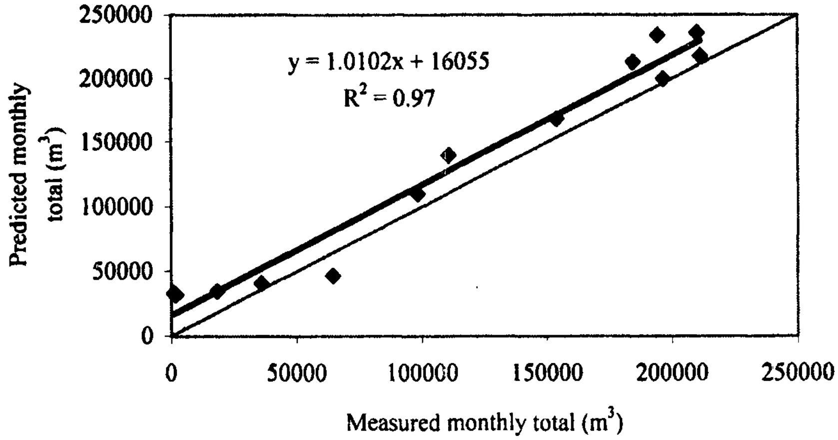

Fig. 6. Monthly simulated and observed volume of water in the KRB tank.

The different components of the water balance for MAD and KRB tanks are given in Tables 3 and 4, respectively. Most of the inflow to the MAD is generated from its own catchment compared to the direct rainfall. Highest amount of water stored is released for irrigation to the tank command area. It is interesting to note that the highest contribution to the lower tank (KRB) as inflow was made from the return flow from irrigation and the spill from the upper tank. Much of this water has again left the KRB tank through the spill. This is to be expected in the upper tanks in the Dry Zone cascades where tank capacity limits the amount of water that can be stored during heavy rainfall events.

Table 3. Monthly water balance for MAD tank.

Month	RF (mm)	RO (m^3)	DRF (m^3)	Total Input (m^3)	E (m^3)	IWD (m^3)	S (m^3)	SPD (m^3)	Total Output (m^3)
Feb-01	42	3285	1606	**4891**	3714	1602	3274	0	**8590**
Mar-01	0	0	0	**0**	4128	3055	2319	0	**9503**
Apr-01	439	38813	23186	**61998**	4820	3402	4591	26734	**39548**
May-01	16	382	543	**925**	6658	5949	4371	0	**16978**
Jun-01	55	4520	1587	**6107**	4132	3955	2426	0	**10513**
Jul-01	14	1115	113	**1228**	2086	4824	598	0	**7509**
Aug-01	11	436	77	**513**	957	0	131	0	**1088**
Sep-01	53	3372	62	**3434**	332	0	17	0	**349**
Oct-01	102	8463	63	**8527**	84	0	2	0	**86**
Nov-01	207	18059	2999	**21058**	1897	8550	2077	0	**12524**
Dec-01	87	5829	2068	**7897**	1780	14302	2070	0	**18152**
Jan-02	40	1785	737	**2522**	1911	6070	1336	0	**9316**
Feb-02	0	0	0	**0**	1195	934	322	0	**2451**
Total	1066	86058	33041	**119099**	33695	52643	23535	26734	**136608**
Percentage of the total input		72	28	**100**					
Percentage of the total output					25	38	17	20	**100**

Table 4. Monthly water balance for the KRB tank.

Month	RF (mm)	RO (m^3)	DRF (m^3)	RTFS (m^3)	RTF (S &I) (m^3)	Total Input (m^3)	SPD (m^3)	S (m^3)	IWD (m^3)	E (m^3)	Total Output (m^3)
Feb-01	42	667	927	0	731	**2326**	0	1068	2914	2124	**6106**
Mar-01	0	0	0	0	806	**806**	0	411	1613	1469	**3493**
Apr-01	439	8397	7493	13367	1199	**30456**	21150	891	0	1701	**23743**
May-01	16	82	196	0	1548	**1826**	0	884	2478	2705	**6067**
Jun-01	138	2372	1769	0	957	**5099**	0	708	4521	2038	**7267**
Jul-01	14	239	69	0	813	**1122**	0	244	1279	1155	**2678**
Aug-01	11	93	45	0	20	**158**	0	52	0	476	**528**
Sep-01	53	725	51	0	3	**779**	0	3	0	118	**121**
Oct-01	142	2566	70	0	0	**2636**	0	1	0	65	**67**
Nov-01	265	4876	3751	0	1594	**10222**	3761	1012	375	1405	**6554**
Dec-01	99	1391	1488	0	2456	**5335**	0	952	3423	1146	**5521**
Jan-02	43	407	477	0	1111	**1995**	0	471	5934	967	**7372**
Feb-02	0	0	0	0	188	**188**	0	121	576	616	**1313**
Total	1261	21814	16338	13367	11427	**62946**	24911	6819	23115	15985	**70830**
Percentage of the total input		35	26	21	18	**100**					
Percentage of the total output							34	10	33	23	**100**

CONCLUSIONS

The result from the study showed that the volume of water in a tank is a good indicator for predicting the seepage compared to the tank water height. The combined accuracy of the modified Cascade Water Balance Model, incorporating the improved equations for seepage and tank evaporation, can predict both daily and monthly tank water levels in small tanks in cascades in the Dry Zone, so that the model can be used in decision making process in water management. The ability to simulate different components of the tank water balance would also be helpful in understanding the dynamics of tank hydrology in cascade systems. The impacts of different changes can be predicted in advance using the above model and as a result irreversible damages to the cascade systems can be prevented.

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