48

Research Report

Predicting Water Availability in Irrigation Tank Cascade Systems: The Cascade Water Balance Model

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and
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International Water Management Institute

Research Reports

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This report draws from a study conducted as part of a collaborative research program between the International Water Management Institute (IWMI) and Japan International Research Center for Agricultural Sciences (JIRCAS), based on the Thirappane tank cascade system in Anuradhapura, Sri Lanka. This project was funded by JIRCAS. The authors gratefully acknowledge the useful comments provided by reviewers. The support received from Mr. Lal Muthuwatte in preparing figures and tables and from Ms. Gayathree Jayasinghe and Mr. A. D. Ranjith with data analysis and interpretations are acknowledged with thanks.

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Contents

Summary

In the dry zone of Sri Lanka and in other similar regions, better water management in irrigation tank cascade systems is vital in achieving higher productive use of available water. To develop and implement management practices aimed at improving effective use of water, studies leading to the development of models that can predict available tank water in irrigation tank cascade systems are invaluable.

This report presents a water balance model *Cascade* that can predict tank water availability in the Thirappane tank cascade system in Anuradhapura, Sri Lanka. The model determines tank water availability on a daily basis, for the purpose of improving productive use of the water resources in a tank cascade system. It represents the physical system using a node-link system configuration, and incorporates water balance components of different types of irrigation tanks including rainfall runoff, rainfall on tank, evaporation of tank water, tank seepage and percolation, irrigation water release, spillway discharge and return flow from upstream tanks. An important feature of the Cascade model is that it employs a modified runoff coefficient method for estimating runoff from rainfall, which incorporates an Antecedent Precipitation Index (API) function as an indicator for catchment wetness, providing a simplified method for the representation of the nonlinear runoff-generation process. The model calculates tank seepage and percolation based on functions derived from an analysis of the observed tank water reduction during time periods without rainfall.

The Cascade model was calibrated using field data collected at four tanks over a period of 21months, which represented different agrometeorologic conditions encountered at the Thirappane tank cascade system under both maha (wet) and yala (dry) growing seasons. The model was applied over a 10-year period for predicting tank water availability for rice crops in the Thirappane tank cascade system.

The results demonstrated the applicability of the model for evaluating feasibility of a cropping scenario, and thus the potential use of the model in the development of management options for minimizing the effects of water shortage on crops. The model provided valuable insights into the processes that determine tank water balance, and clearly manifested the relative magnitudes of the tank water balance components and their temporal variations. Further, it demonstrated the availability of water from upstream tanks as return flow in the immediately downstream tanks, and thus the increased potential usage of water resources facilitated by the tank cascade system.

Using a relatively modest input and a simple water balance modeling approach, the Cascade model provides a valuable means to determine water availability in the Thirappane tank cascade system. The model has shown its potential to become a useful tool in the process of optimizing usage of the limited water resources in tank cascade systems for improving agricultural production.

Predicting Water Availability in Irrigation Tank Cascade Systems: The Cascade Water Balance Model

C. J. Jayatilaka, R. Sakthivadivel, Y. Shinogi, I.W. Makin, and P. Witharana

Introduction

With the increasing demand for improved agricultural production to sustain growing population, the need to maximize the productive use of the limited water resources has been widely recognized. In the dry zone of Sri Lanka and in other similar regions, better management of water stored in irrigation tanks (reservoirs) is vital to achieve this.

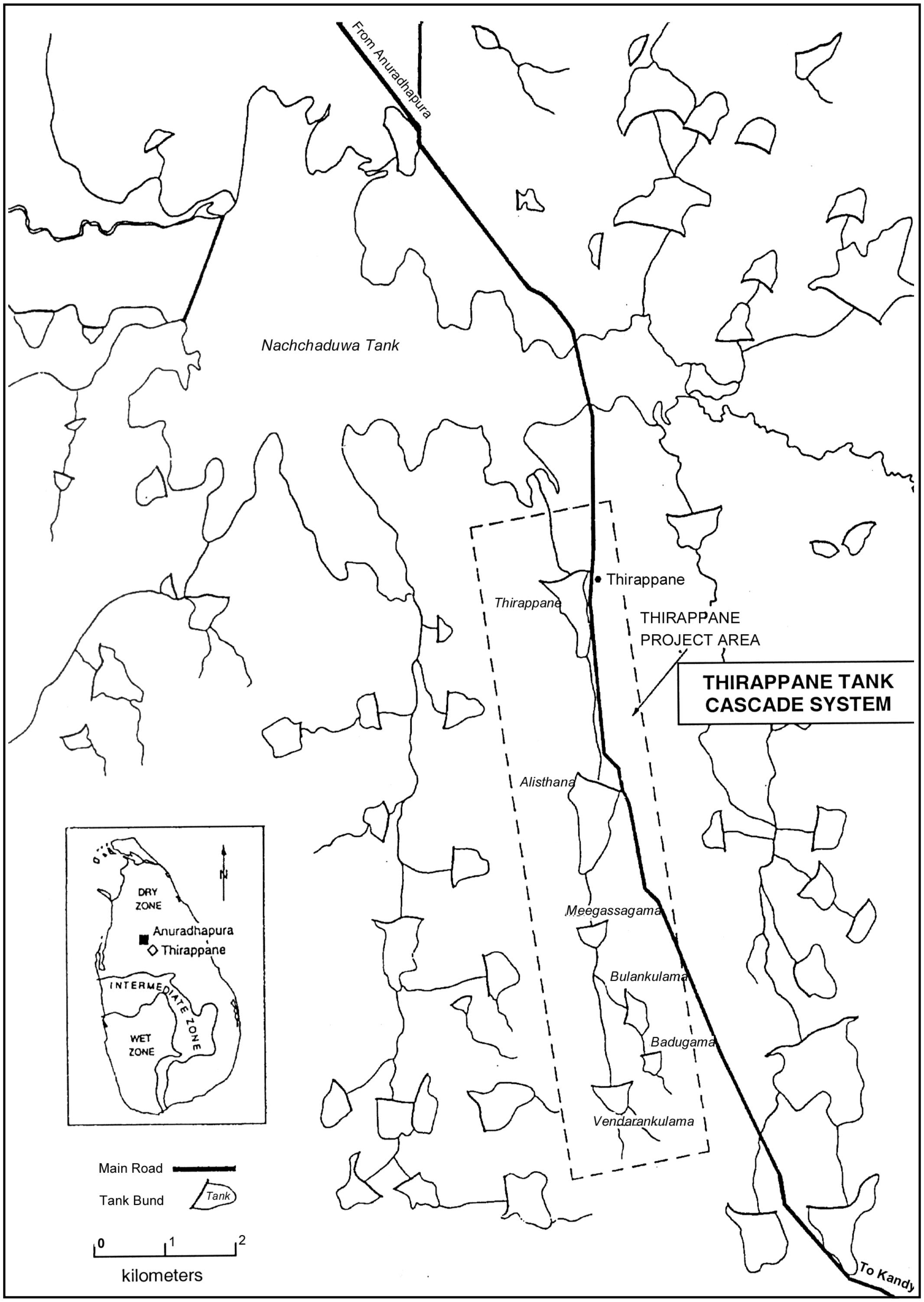
Thousands of irrigation tanks have sustained agricultural production over more than 2000 years in the dry zone of Sri Lanka, providing an economical means for surface storage of runoff during the rainy season for subsequent release as irrigation water according to the requirements of rice and other crops. Many of the irrigation tanks are interconnected forming cascades, allowing surplus flow from the upstream tank(s) and return flow from the upstream command area(s) to reach the tank that is immediately downstream. This facilitates reuse of water in the command area of the downstream tank, and in effect, increases available water for irrigation. Several hundreds of such tank cascade systems (TCSs), with small tanks in the cascade numbering from 3 to 30, have been identified in the dry zone of Sri Lanka (Tasumi et al. 1999), which occupies about 60 percent of the island, where rainfall is less reliable.

To develop and implement management practices aimed at improving effective use of water, studies leading to the development of models that can predict required tank water in cascade systems are invaluable. It is imperative that any such model developed should be of a complexity commensurate with the generally available data, in order to provide a practical tool for improving effective water usage in tank cascade systems.

The report presents a simple water balance model *Cascade* developed to predict tank water availability in the Thirappane tank cascade system, in Anuradhapura, Sri Lanka (figure 1). The report includes calibration of the model and its application to predict tank water availability for rice crops over a 10-year period.

This report draws from a study conducted as part of a collaborative research program between the International Water Management Institute (IWMI) and the Japan International Research Center for Agricultural Sciences (JIRCAS). The aim of the study was to develop a model with the capability to account for the dynamic hydrologic components of the tank cascade systems similar to that of the Thirappane TCS commonly found in the dry zone of Sri Lanka. It was intended to keep the model structure as simple as possible and the data requirement to be minimal for increasing the potential practical use of the model. The expectation was that the Cascade model would provide the basis for the development of a useful practical tool with the capability to predict tank water availability in similar tank cascade systems in Sri Lanka and in other countries.

FIGURE 1.
Location of the Thirappane tank cascade system.



The Study Area and Field Measurements

The Thirappane TCS, the focus of this study, is located about 20 km south of Anuradhapura in Sri Lanka (figure 1). It is typical of hundreds of irrigation tank cascade systems that are found in the dry zone of Sri Lanka. The Thirappane TCS is situated within the catchment area of the much larger Nachchaduwa reservoir, which was built in the ancient times. There are six inter-linked tanks in this TCS and the distance from the most upstream to the most downstream tank is only 8 km (Itakura 1995).

The Cascade model was developed considering four tanks in the TCS namely, Vendarankulama, Bulankulama, Meegassagama and Alisthana (figure 1), where field measurements have been collected as reported by Shinogi et al. (1998). A small tank named Badugama, which was not functioning during the period considered in this study (P. Witharana, personal communication), was included as part of the catchment area of the immediately downstream tank Bulankulama.

Rice, the staple food of Sri Lanka, is the main irrigated crop during both maha (wet) and yala (dry) growing seasons in the Thirappane TCS, in common with much of the agricultural land in the North Central Province of Sri Lanka. Although the command areas of minor tanks in small cascades such as the Thirappane TCS are small (less than 40 ha), each command area is important for sustaining the livelihood and the vital agricultural production of the village that forms part of the tank system.

The rainfall and evaporation statistics for the study area based on the meteorological data from the Maha Illuppallamma Agricultural Research Station, located about 13 km from the study site is used in this study (Shinogi et al. 1998). The average annual rainfall for this area is about 1,490 mm, and the average annual potential evapotranspiration is estimated to be much higher, 2,453 mm. Except during three months (October–December) of the year, average monthly potential evapotranspiration exceeds average monthly rainfall. During the growing season maha (October–March), total rainfall is 1,036 mm and the potential evapotranspiration is slightly higher, 1,084 mm. The difference is much greater in the yala season (April–September), during which the total rainfall is only 454 mm while the total potential evapotranspiration is 1,369 mm.

It is clear that much of the rainfall occurs during the maha season. The rainfall events normally tend to be of high intensity and short duration resulting in rapid runoff. In order to sustain crops during no-rainfall periods, the runoff produced during rain events need to be stored in tanks, and subsequent water issue for irrigation should be regulated ensuring optimum usage of water available in the tank cascade system.

The field measurements to obtain important hydrological and physical characteristics of the Thirappane TCS have been carried out based on an observation network since 1997 (Shinogi et al. 1998). These measurements have provided vital observed data required for this study on daily rainfall and pan evaporation, tank water height, and water issue for irrigation. Initially, this study utilized the observed data recorded from 22 July 1997 to 21 February 1998. As more data became available, the data set was extended to 18 April 1999, thus 21 months of observed daily data were finally used. However, the data sets obtained at the head-end tanks in the cascade, Vendarankulama and Bulankulama, were not complete as rehabilitation work was carried out.

Except during the rehabilitation work, the tank water levels were observed twice a day, manually in all four tanks considered in this study. The volume of water released for irrigation was measured at Parshall flumes located downstream of the tank sluices. The daily rainfall measurements were made at each tank with the use of manually recorded rain gauges and the pan evaporation data collected at the Meegassagama tank was used in this study. The points of above field measurements at each tank in the TCS are shown in figure 2.

The field measurements also included soil surveys, which allowed classification of the soil series. The main soil types commonly found in the North Central Province, Reddish Brown Earth (RBE) and Low Humic Gley (LHG), cover most of the area in the Thirappane TCS (table 1). The types of land use and the physical characteristics of the catchment areas are also given in table 1.

FIGURE 2.
The study area and locations of field measurements.

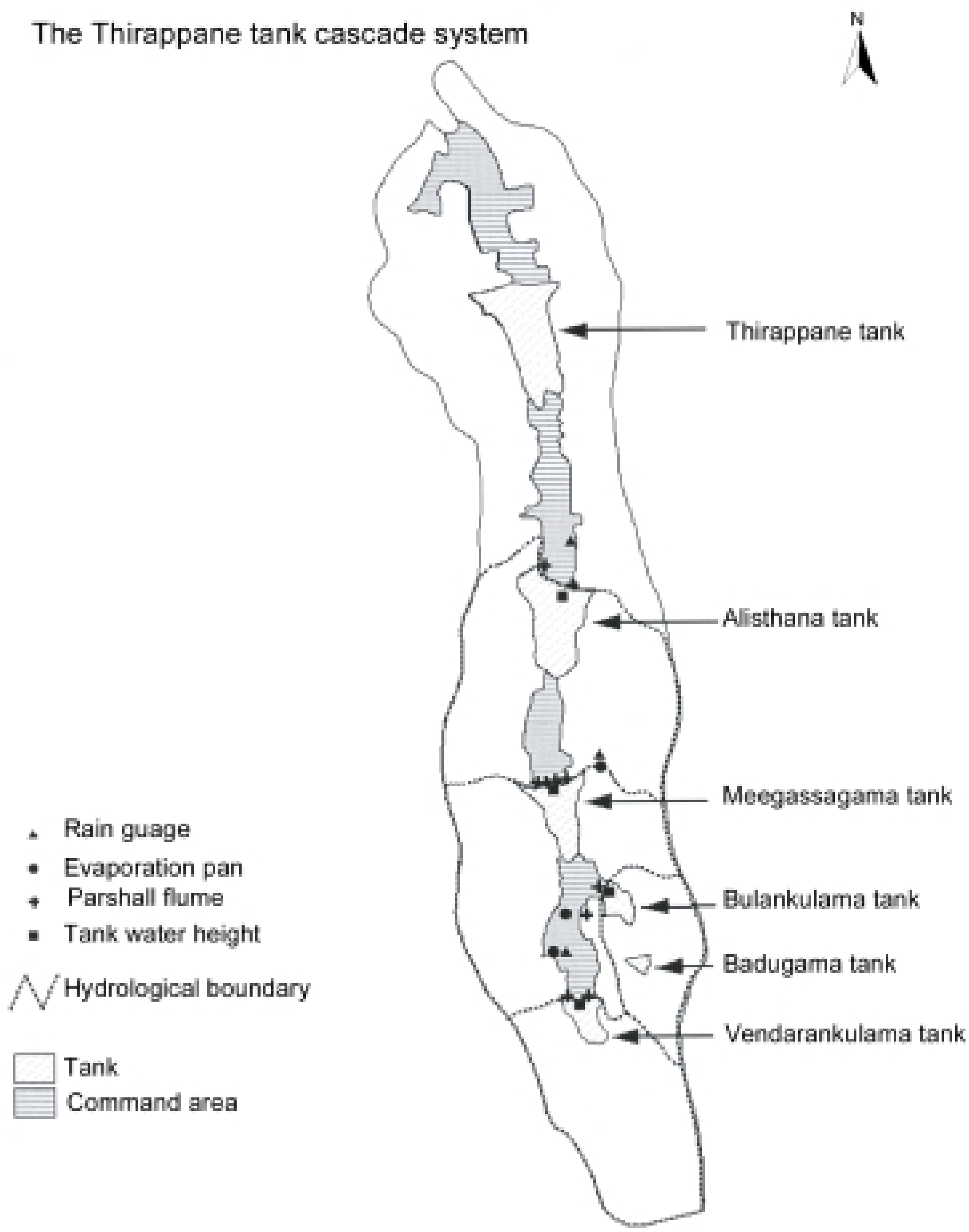


TABLE 1.
Thirappane tank cascade system: Catchment area description.

(a) Catchment area, average slope and aquifer thickness.

Tank	Catchment area (m^2)	Average slope (%) N-S	Average slope (%) E-W	Average thickness of the aquifer (meters)
Vendaramkulama	2.40E06	2.97	0.36	8.2
Bulankulama	1.13E06	0.30	0.36	5.0
Meegassagama	3.33E06	0.69	0.41	5.0
Alisthana	3.25E06	0.85	0.91	6.0

(b) Land use (percentage area).

Tank	Cropped land*	Dense forest	Scrub land	Degraded forest	Barren land	Teak plantation
Vendaramkulama	2	40	6	0	5	47
Bulankulama	6	57	8	7	11	9
Meegassagama	27	40	16	11	1	5
Alisthana	16	50	11	20	4	0

*Includes paddy land, homestead gardens, and chena land.

(c) Soil type (percentage area).

Tank	Well drained, reddish brown earth soils	Moderately to imperfectly drained reddish brown earth soils	Poorly drained low humic gley soils	Rock outcrops
Vendaramkulama	62	22	10	6
Bulankulama	63	15	8	13
Meegassagama	67	16	17	1
Alisthana	78	9	9	4

Model Development

The development of the Cascade model was initiated considering the structure and the processes included in the Reservoir Operation Simulation (Extended) Systems (ROSES), a software package developed by Usgodaarachi et al. (1996) to simulate the operation of water resources systems on daily basis. The Cascade model was formulated based on a simple structure, incorporating the dynamic hydrologic processes associated with a set of four tanks in the Thirappane TCS.

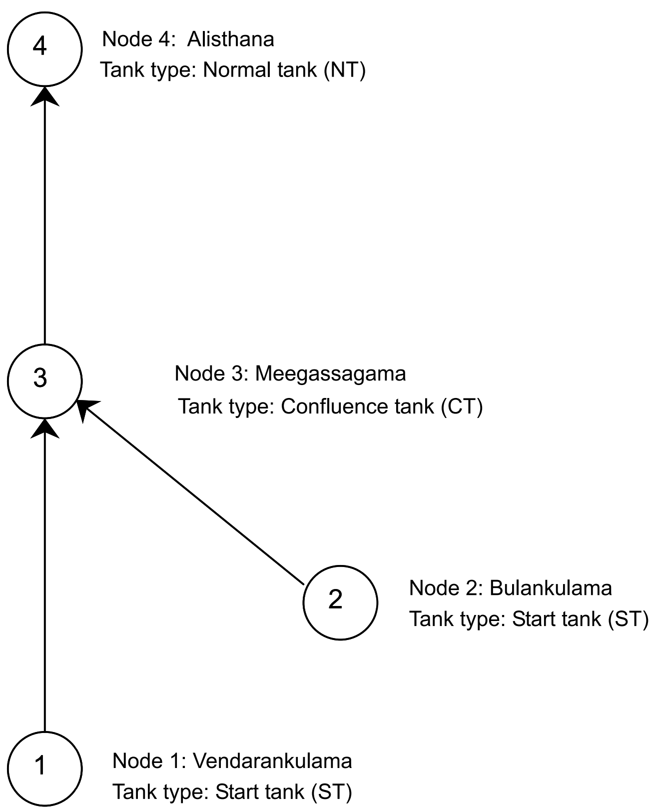
Representation of the Physical System

The configuration of the tank cascade system is represented in the model using a commonly accepted node-link system configuration that can delineate relative positions of tanks and their interconnections (figure 3). The nodes indicate tanks and the links indicate the interconnection between tanks. The links do not necessarily represent any physical link such as a canal or stream; they indicate the direction of flow between the tanks.

As the initial step in setting up the model for a given cascade, each tank should be assigned a *node number* and *tank type* depending on its relative position within the cascade. Three types of tanks are identified–Start tank (ST): a tank with *no* inflow from upstream tanks; Normal tank (NT): a tank with inflow from one upstream tank; and Confluence tank (CT): a tank with inflow from more than one upstream tank.

In the Thirappane TCS, Vendarankulama and Bulankulama have been identified as STs, and Meegassagama and Alisthana were assigned as CT and NT, respectively (figure 3). The node numbering begins with the STs in the upstream end of the cascade and continues sequentially towards the downstream end. The CTs should always have a node number higher than those of the upstream tanks linked to them. The NT should be assigned a node number greater than that of the tank located immediately upstream. The last node number in the cascade should be equal to the number of tanks in the cascade.

FIGURE 3.
Representation of the Thirappane tank cascade system in the model.



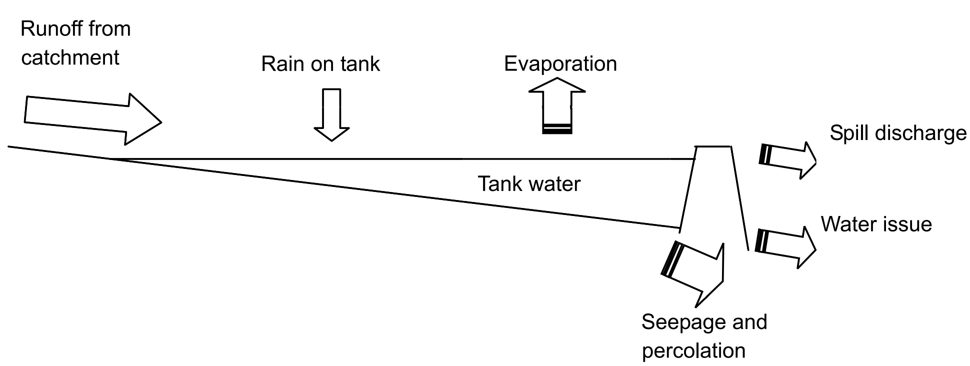
Tank Water Balance Components

The effective water balance components of the tank cascade system simulated by the Cascade model are shown in figure 4. In start tanks, which are normally located in the upstream end of the cascade, runoff from the catchment, and rainfall on the tank water surface, form the 'inflow' components. The 'outflow' components include: evaporation of tank water, seepage through the tank embankment and percolation through the tank bed, which is referred to as 'tank seepage,' water issue for irrigation, and spillway discharge.

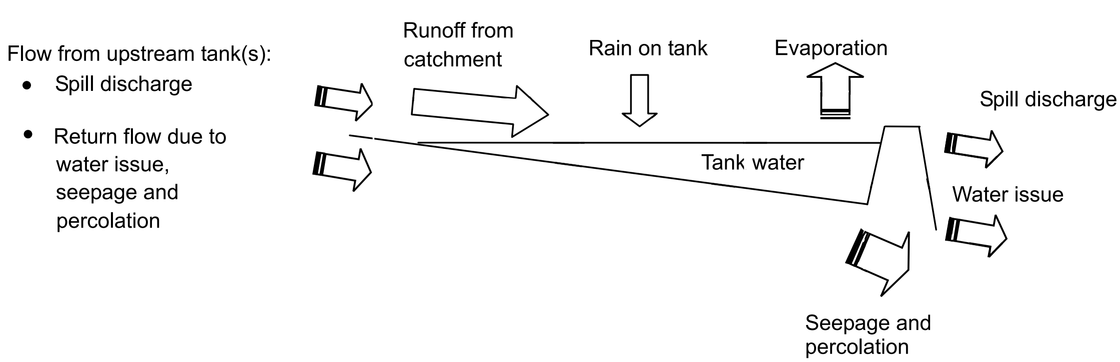
In normal and confluence tanks, in addition to the runoff generated in their own catchments and the rainfall on tank water surface, a fraction of the outflow from the immediately upstream tank(s) can flow in, increasing the total available tank water (figure 4). This additional inflow is treated as two different components: return flow due to seepage

FIGURE 4.
Schematic of the tank water balance components.

a. Start tank



b. Normal/Confluence tank



and water issue, and return flow due to spillway discharge. In normal tanks, these flow components occur from the immediately upstream tank, whereas, in confluence tanks, inflow from the immediately upstream tanks (more than one) that are linked to the confluence tank needs to be incorporated. The outflow components of normal tanks and confluence tanks are similar to those of start tanks. In all three types of tanks, the fraction of outflow can only reach the immediately downstream tank as return flow.

The relevant information on the node-link system configuration needs to be specified as part of the input to the model that describes the physical system. Based on the survey data at each tank, mathematical expressions for representing (1) tank area, (2) tank water volume as functions of the tank water height, and (3) tank water height as a function of tank water volume need to be formulated. The cubic expressions derived for the Thirappane TCS depicting above relationships are given in Jayatilaka et al. (2000).

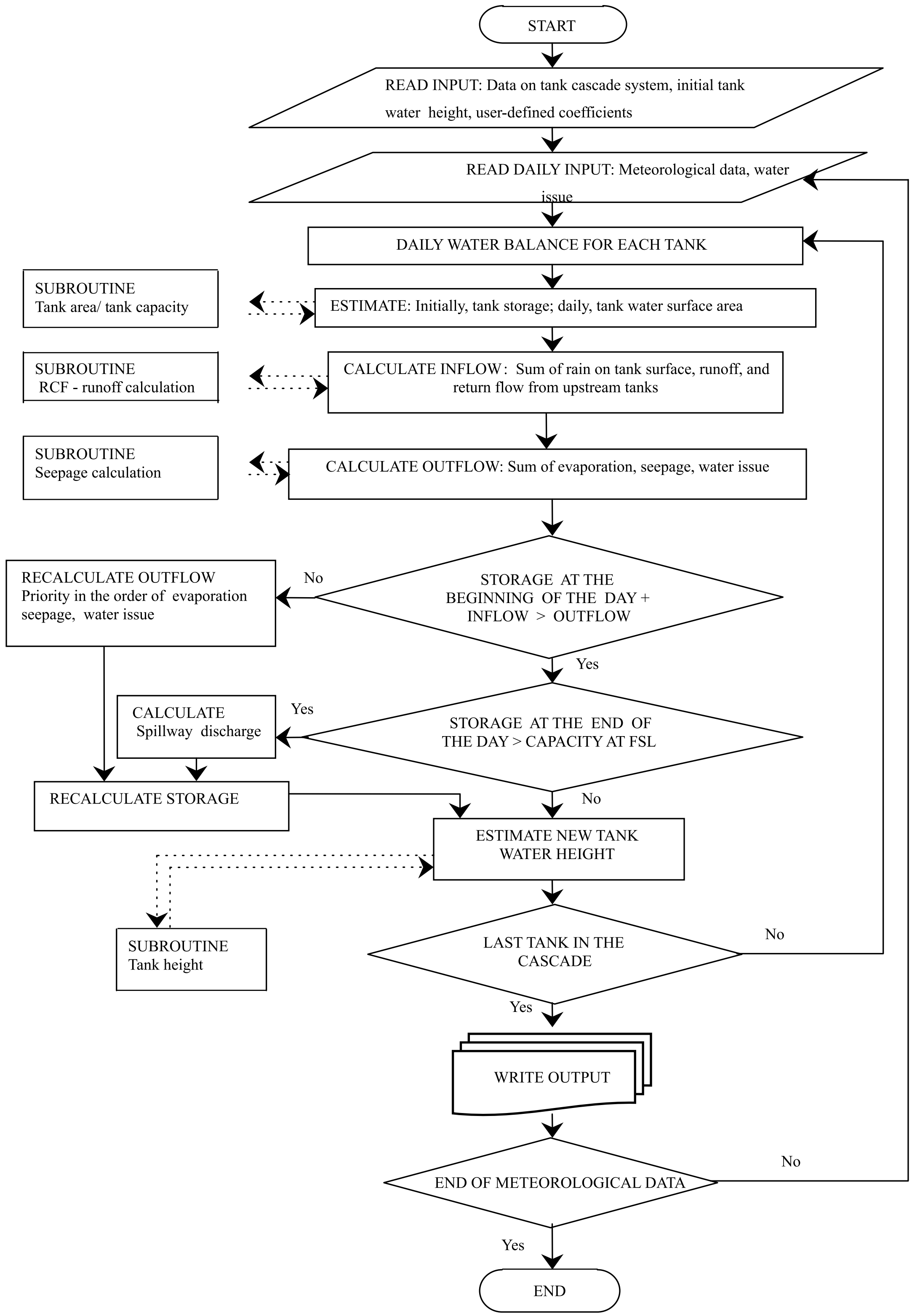
Simulation of Daily Tank Water Balance

The components of the tank water balance represent complex hydrological processes associated with the tank cascade system. For example, generating runoff from rainfall on a catchment is a complex process that involves interaction of effective climatic, geologic, and topographic factors; vegetation characteristics; and the antecedent conditions of the catchment. Accurate simulation of these complex processes can impose a substantial input data requirement and a detailed mathematical representation of the physical system and the relevant processes on the model. The Cascade model approximates the physical system and the effective water balance components with the use of several expressions and assumptions as described in Appendix A.

Starting from the most upstream end of the tank cascade, the model performs water balance computations for each tank on a daily basis based on the processing procedure illustrated in the flowchart presented in figure 5. The model input consists of meteorological data and water release for irrigation on a daily basis and information on the physical system. In the process of calibration of the model, water released for irrigation measured in the field is used as the model input. In using the model for predictions, the required water release needs to be estimated considering the water requirements for land preparation and the crop water requirements during the growing stage, based on cultivation extents of different types of crops in the command area. In either case, through the daily water balance computations, the model allows release of the required irrigation water when the storage is adequate. If the storage is insufficient, the model calculates the allowable water release, and it will be less than the measured water release for the day (when calibrating the model) or the estimated water release requirement of the day (during predictions). The water release allowed by the model is denoted as the water issue (model), when presenting the results. In addition to the allowable water issue, the model provides output at the end of each day including the tank water height, tank storage, and information on the tank water balance components.

An important feature of the Cascade model is that it employs a modified runoff coefficient method for estimating runoff from the catchment. As runoff generation is a complex process influenced by several factors, the use of either a constant or a simple seasonal variation (eg., as used by Itakura 1995 or Kachroo and Liang 1992) for representing the runoff coefficient is not adequate. The method adopted by the Cascade model incorporates an Antecedent Precipitation Index (API) function, which in an indirect way, acts as an index of the wetness of the catchment. This allows variation of the runoff coefficient, providing a simplified method for the representation of the nonlinear runoff-generation process. As the effect of the antecedent soil moisture level on runoff yield is accommodated through the method adopted, the requirement for detailed field

FIGURE 5.
Flowchart of the Cascade model.



measurements on soil moisture levels and the need for complex mathematical techniques in the model for simulating flow in the unsaturated soil zone are eliminated.

The runoff generation in response to rainfall can be delayed after a prolonged dry period, as the soil moisture needs to be replenished before runoff can occur. The model handles the initial loss of rainfall that occurs in such conditions with the use of a *delay* parameter. The delay and the runoff coefficient (RCF), which represent the combined effect of the factors affecting runoff generation in the catchment, such as the soil type, topographic slope and vegetation, are the two parameters used in the model that need calibration.

The model calculates the tank seepage based on functions derived from an analysis of the observed tank water loss during time periods without rainfall (Appendix A). Normally, the tank seepage is estimated as a certain percentage of the tank volume (e.g., 0.5 percent of the tank volume per month used by Ponrajah 1984; 2.4 percent of the tank water volume per day as given in Tasumi et al. 1999). Based on the results obtained at all four tanks in the Thirappane cascade, this study clearly indicated 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. Similar observations have also been made at the Walagambahuwa village tank as reported by Dharmasena (1985). The observed trend in variation of the seepage rate is consistent with the larger head difference that can occur between tank water and the groundwater in the surrounding area when the water table is low under dry conditions in the cascade. In contrast, in wet conditions when the tank water level is high and the water table is near the surface, the resulting head difference can be comparatively low resulting in low percentage reduction of tank water due to seepage.

The analysis on the tank seepage also led to the derivation of a function (Appendix A) that can be used for seepage and percolation calculations in similar small irrigation tanks in the absence of observed measurements to obtain parameters relevant to each tank. This function can be further improved by extending the seepage analysis further involving more field data under different agrometeorological conditions in the cascade. The option to use such a function for the tank seepage estimation would further enhance the potential application of the model.

Calibration of the Model

The process of calibration of the model was based on two stages, involving field measurements collected as described by Shinogi et al. (1998) at four tanks of the Thirappane TCS. The initial calibration (stage1) was based on the data set available at the time, which included daily records of the field measurements from 22 July 1997 to 21 February 1998. In the second stage (stage 2), calibration was extended until 18 April 1999, involving 21 months of observed data. The extended data set spanned over two maha and one yala growing seasons, thus representing both dry and wet conditions in the tank cascade system. The use of the entire data set facilitated the model to be calibrated under different seasonal field conditions in the tank cascade.

The functions used in the Cascade model for the estimation of the tank water reduction due to seepage have been derived utilizing relevant information from the data set used in stage 1 of the calibration process. The parameters of these seepage functions kept unchanged as the model calibration was extended to stage 2. This, to a degree, allowed verification of the applicability of the seepage functions over the changing field conditions in the tank cascade.

Model Input and Initial Condition

In the process of calibration of the model, initial condition in the tank cascade was assigned based on the measured tank water levels at 8 am on 22 July 1997. During the calibration stage 1, 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 22 July 1997–21 February 1998. The user-defined coefficient, *fp*, which converts pan evaporation rate to tank water surface evaporation, was taken as 0.8. The user-defined coefficients *fr* (return flow coefficient), *fs* (return flow fraction due to upstream tank spilling), and the two model parameters RCF and delay that need to be calibrated were initially assigned values as recommended in Appendix A, and were later adjusted during calibration.

The model performed daily water balance computations for each tank in the cascade and calculated water balance components and the tank water height at the end of each day over the calibration period. The simulated tank water height at the end of each day was compared with the tank water height measurements taken at the beginning of the following day. The calibration was finalized in stage 2 involving field data collected over 21 months (until 18 April 1999), based on a qualitative comparison of the match between the observed and simulated tank water heights over the calibration period. This was considered to be more appropriate for comparing simulated results with the measured data than using a numerical criterion due to the lack of a complete data set over the periods of rehabilitation work and its effects over the following periods at the two head-end tanks. The model input, user-defined coefficients, and the parameters of the calibrated model are given in table 2. The observed data and the simulated results are presented in figures 6–9. The first graph in each figure shows the observed and predicted tank water height along with the model input on daily rainfall, pan evaporation data. The second and third graphs illustrate tank water balance components. The fourth graph includes the predicted and observed tank water volume, and the measured tank water issue along with the water issue allowed by the model, which is denoted as water issue (model). The temporal variations of the water balance components are also presented in figures 6–9. The total water balance over the 21-month calibration period is presented in figure 10 and table 3.

Model Simulations

The modeling results presented in this study span a 21-month period, which represented different agrometeorologic conditions encountered at the tank cascade system under both maha and yala growing seasons. The simulations started on 22 July 1997, when the rainfall in the yala season ended, and dry conditions prevailed in the tank cascade system until the rainfall in mid-September. The field observations indicated low initial storage in all tanks corresponding to tank water heights ranging from 0.48–1.21 m (table 2). The water levels decreased and tanks became empty during this no-rainfall period. The model simulations over this dry period agreed well with the field observations as shown in figures 6–9.

The generation of runoff in response to rainfall following the dry period was delayed due to depleted soil moisture levels in the catchments at the end of the long dry spell. This condition was clearly visible from the tank water level measurements particularly in tanks downstream of Vendarankulama. The model accounted for the delay in runoff generation in catchments by adjusting the delay parameter in the runoff calculation procedure, the final values of which are given in table 2. The gradual increase of the tank water height in the

TABLE 2.
The Cascade model input parameters.

a. User-defined coefficients.

fp	fr	fs
0. 8	0.10	0.5

b. Input data on tanks.

Tank	Node no:	Tank type	Effective spill level (m)	Length of the spillway (m)	Initial tank water height (m)	RCF	Delay (mm)
Vendarankulama	1	ST (Start Tank)	3.00	30.0	1.21	0.21	80.0
Bulankulama	2	ST (Start Tank)	2.50	30.0	0.48	0.30	290.0
Meegassagama	3	CT (Confluence Tank)	2.75	55.0	0.97	0.132	240.0
Alisthana	4	NT (Normal Tank)	3.75	30.0	0.81	0.31	260.0

TABLE 3.
Model calibration: Tank water balance components.

a. Inflow components as percentage of the total inflow to the tank during the calibration period.

Tank	Rain on tank surface (%)	Runoff (%)	Return flow from upstream tanks (%)	Inflow from upstream tank spilling (%)
Vendarankulama	17.4	82.6	0.0	0.0
Bulankulama	15.3	84.7	0.0	0.0
Meegassagama	26.0	60.1	12.5	1.4
Alisthana	25.2	70.6	2.8	1.4

b. Outflow components and net storage increase as percentage of the total inflow to the tank during the calibration period.

Tank	Evaporation (%)	Seepage (%)	Spill discharge (%)	Water issue (%)	Storage increase (%)
Vendarankulama	11.0	75.2	2.9	4.4	6.5
Bulankulama	8.0	83.9	0.0	7.9	0.3
Meegassagama	22.6	41.6	5.3	16.1	14.4
Alisthana	20.4	46.8	0.0	21.8	11.0

FIGURE 6.
Model calibration: Observed and simulated tank water height, volume, and simulated tank water balance components–Vendarankulama.

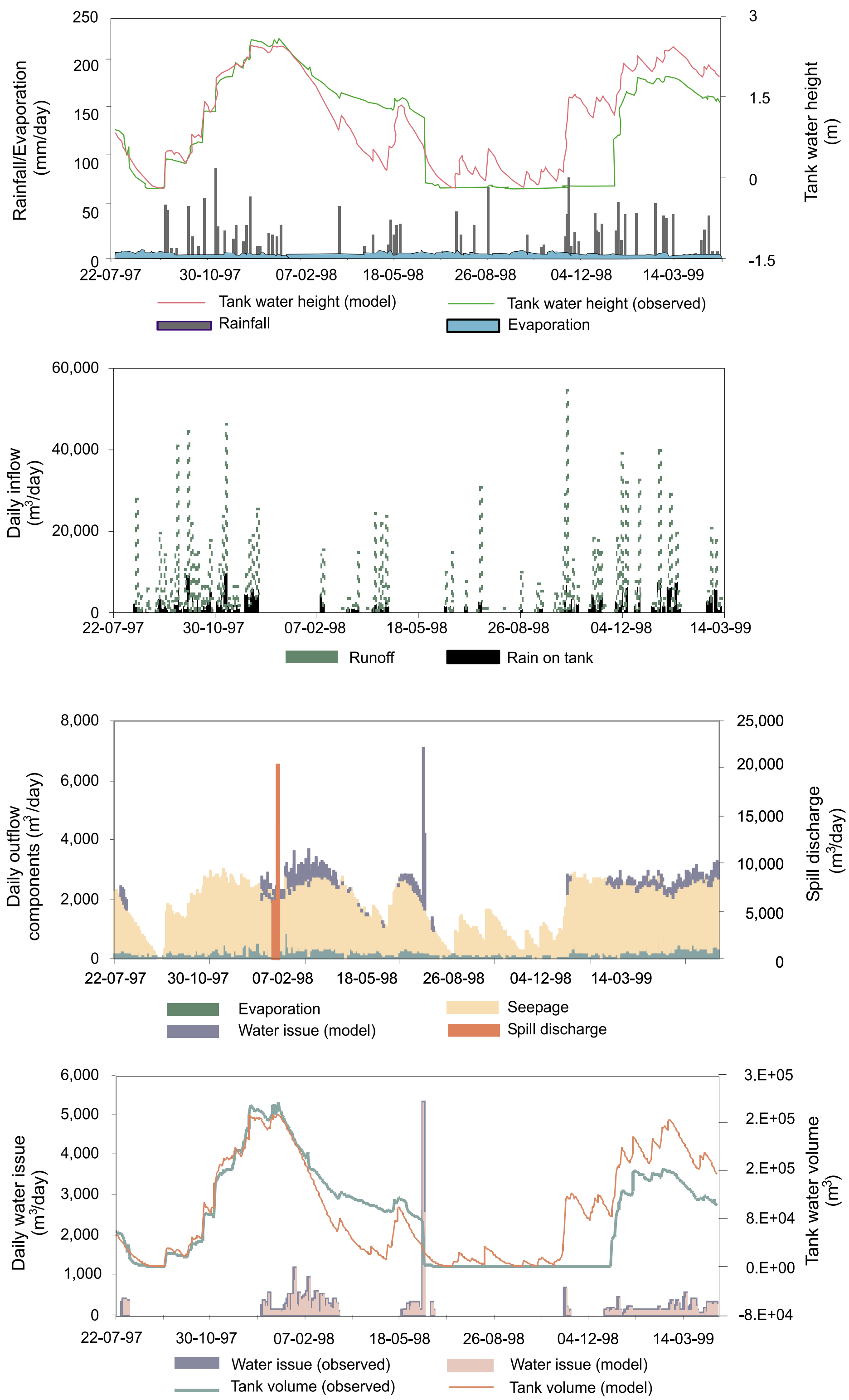


FIGURE 7.
Model calibration: Observed and simulated tank water height, volume, and simulated tank water balance components–Bulankulama.

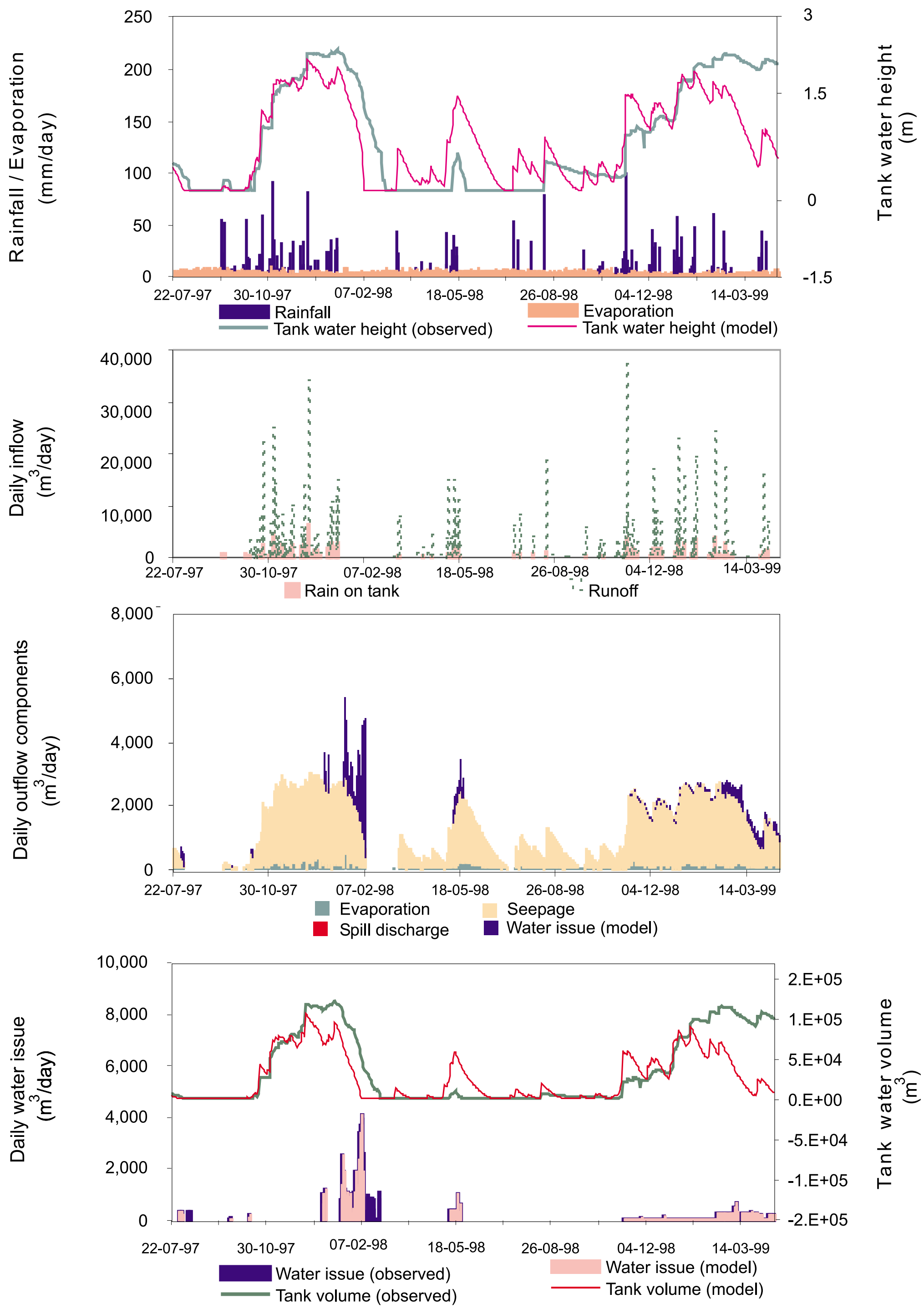


FIGURE 8.
Model calibration: Observed and simulated tank water height, volume, and simulated tank water balance components–Meegassagama.

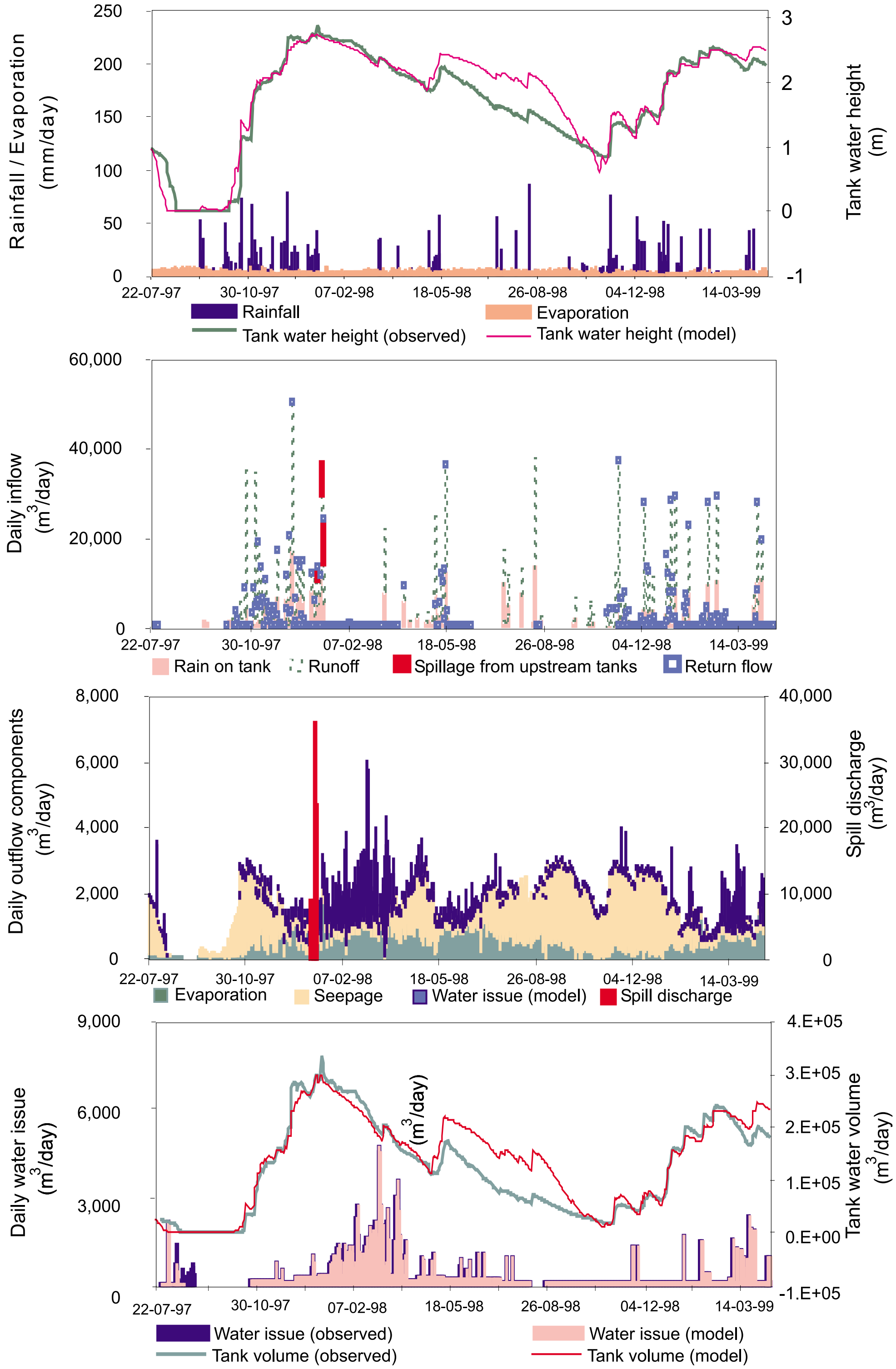


FIGURE 9.
Model calibration: Observed and simulated tank water height, volume, and simulated tank water balance components–Alisthana.

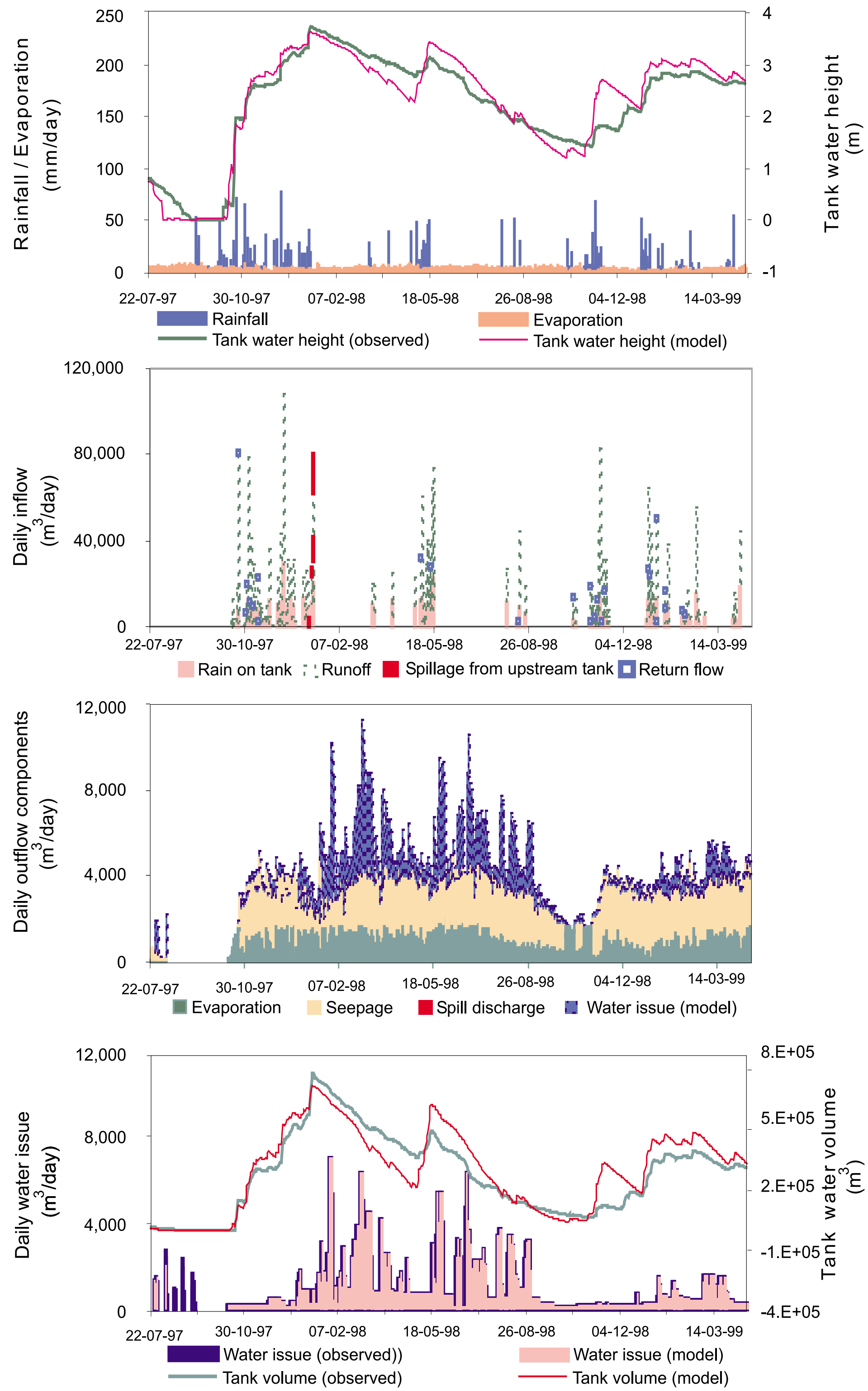
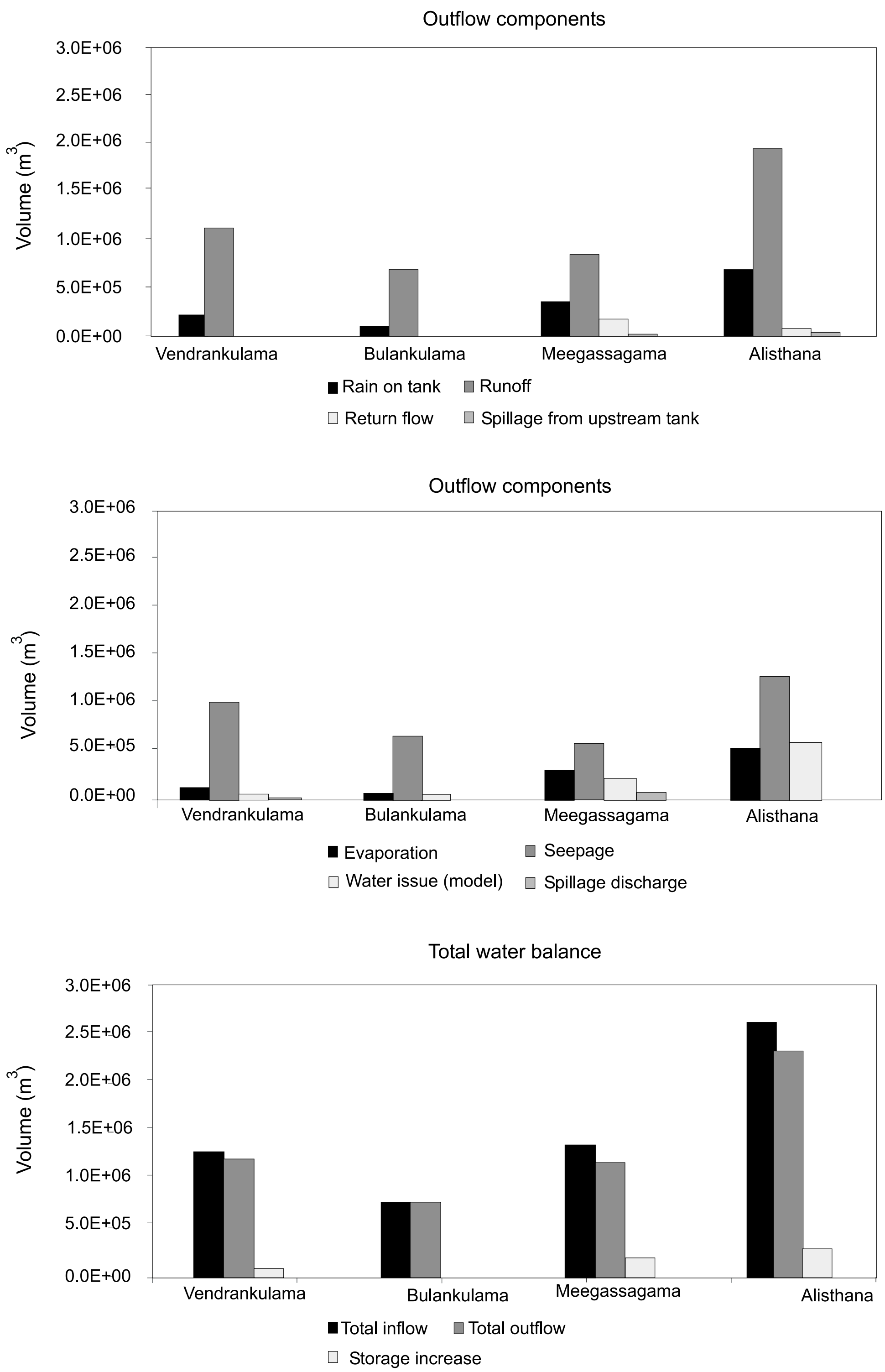


FIGURE 10.
Total water balance of the tank cascade system over the calibration period.



maha (97/98) season and the changes in tank storage in the following periods in response to rainfall variations were simulated by adjusting the runoff coefficient (RCF), which is also included in table 2.

During the 97/98 maha season, the simulated tank water height showed a close agreement with the observed data in all the tanks, particularly in the early part of the rainfall period (figures 6–9). Towards the end of the maha season rainfall period, the model underestimated the tank water height at the Bulankulama tank. This condition was commonly observed at the Bulankulama and Vendarankulama tanks towards the end of the 97/98 maha season.

The agreement of the model simulations with the field observations over the rest of the calibration period was considerably better in the downstream tanks when compared with the upstream tanks. The apparent discrepancy between the model results and the field measurement can be explained by considering the field conditions and physical attributes of the catchments (table 1) and the assumptions associated with the Cascade model.

Vendarankulama Tank

This tank is located at the foot of a hill in the upstream end of the cascade. The catchment area of the Vendarankulama is relatively steep (slope of 2.7 percent in the N-S direction) compared with other catchments within this cascade (table 1). Cultivated land in this catchment accounts for a small fraction of the total area (2%) in comparison with other catchments (6–27%). Teak plantations cover 47 percent of the area. This indicates a marked difference compared with other catchments, in which the teak plantations cover only 0–9 percent of the area. The predominant soil type in the cascade, well-drained reddish brown earth, covers 62 percent of this catchment.

The delay in runoff generation in response to the maha 97/98 rainfall was simulated at the Vendarankulama tank with the use of a delay parameter (80 mm) that was considerably low compared with the range of the values (240–290 mm) used at the other tanks in the cascade. The RCF value used at the Vendarankulama tank (0.21) is well within the range of values used for the downstream tanks (0.132–0.31).

Given the catchment area is accurate, the value of RCF would reflect the resulting effects of the factors influencing runoff generation such as vegetation, slope, and soil type. The initial loss of rainfall after the prolonged dry spell indicated by the delay parameter would also be influenced by these factors. The steeper slope could have influenced the low delay in runoff generation observed in this catchment. The larger area with teak plantations and the smaller cropped area could have influenced both RCF and delay parameters, as discussed by Dharmasena (1994) in studying the effect of land use on rainfall–runoff relationships and runoff threshold values.

The simulated tank water height at the Vendarankulama tank agreed well with the observed data until February 1998. The model simulated spillway discharge at the end of the rainfall period in January 1998. The field observations over this period also indicated tank spilling. However, the agreement of the model results with the observed data shown in figure 6 was obtained with the use of a weir crest level of 3 m in the model. This is slightly higher than the crest level indicated by the survey data (2.9 m). In all the tanks considered, with an exception of the Alisthana tank, it was necessary to use spill crest levels different from those indicated by the survey data. It can be envisaged that the field practices such as the use of sand bags to raise the spill level, and in some cases, extension of the sections of the spillway, and other field conditions could have contributed to the changes in the effective spill crest level. In addition, it is not clear whether the survey data used in this study represent the existing physical conditions accurately.

From February to June 1998, the model underestimated the tank storage. This could be due to an inadequacy of the function used for the estimation of tank seepage, which was derived using the observed data until February 1998.

On 26 June 1998, the tank was emptied for rehabilitation work as indicated by the measured water issue in figure 6. There has been an uncontrolled water issue over the rehabilitation period, and the tank remained dry until the end of December 1998. As the water issue data was not supplied to the model over this period, the model did not allow any water release, but simulated an increase in tank storage in response to rainfall. Therefore, a direct comparison of the simulated and measured tank water height is not possible over the period during and after the rehabilitation work. However, the trend shown in the simulated tank water height agreed well with the observed trend since the end of the rehabilitation work in December 1998 (figure 6).

Tank water balance

As a start tank, Vendrankulama received inflow only due to rainfall on the tank surface (17.4%) and runoff from its catchment (82.6%), as shown in table 3, which illustrates the total tank water balance over the calibration period. The seepage loss dominated the outflow from the tank, and accounted for the 75.2 percent of the total inflow to the tank. The evaporation was low particularly during low storage conditions; nevertheless, the evaporation was estimated to be 11 percent of the total inflow. The water issue allowed by the model agreed well with the available measured data, and accounted for 4.4 percent of the total inflow. The total spillway discharge and the net storage increase over the simulation period were 2.9 and 6.5 percent of the total inflow, respectively.

Bulankulama Tank

The Bulankulama tank is also located near the upstream end of the cascade and it contained another small tank, Badugama, within its catchment. The area with rock outcrops (13%) is larger in this catchment compared with that of the other catchments (1–6%). This could promote additional runoff generation, and thus, would have influenced the RCF values used at this tank (0.30), which is towards the higher end of the range of the values used (0.132–0.31) in the cascade. The slope of the catchment is milder (0.30% in the N-S direction) than that of the other three catchments, and cropped area is small (6%), compared with the downstream catchments. This attribute, together with other attributes of this catchment (table 1) may have influenced both the RCF and the delay parameters (290 mm) used in simulating runoff.

The simulated water height at the Bulankulama tank showed a reasonable agreement with the measured data until the tank water reached the highest level indicated by the measured data during the maha (97/98) rainfall period (figure 7). The simulated results were based on an effective spillway crest level of 2.5 m. The spill level of 2.2 m as indicated by the survey data will not allow tank water level to reach 2.4 m as indicated by the observed data. The requirement to use a higher effective crest level could be an indication of the existing field conditions of the spillway, or the effect of the field practices to raise the spill level, or an inconsistency in the field measurements.

The Bulankulama tank was kept dry when the rehabilitation work was carried out from 5 October 1997 to 1 May 1998. With the exception of some indication of water accumulation in July 1998, the tank remained empty until July 1998. Due to the incomplete water issue information supplied to the model, it is not feasible to compare the model results with the observed data during this period.

The model simulations over the rest of the calibration period did not show a close agreement with the measured data. The reasons for the apparent discrepancy are not clear. It is possible that the changes resulting from the rehabilitation work were not adequately represented in the model. And the possibility of inconsistency in the data used in formulating expressions such as the tank height vs. tank capacity relationship cannot be ruled out. In addition, it can be envisaged that the inadequacy of the seepage function could also have contributed to the apparent differences.

Tank water balance

As a start tank, Bulankulama received inflow due to runoff from its catchment (84.7%) and rainfall on the tank water surface (15.3%). The tank seepage loss dominated the outflow and was estimated to be 83.9 percent of the total inflow. The total water release for irrigation allowed by the model accounted for 7.9 percent of the total inflow. The model indicated drying up of the tank in February 1998, earlier than what was indicated by the field data. As a result, the water issue allowed by the model was less than that was indicated by the field measurements (figure 7). The evaporation component accounted for 8 percent of the total inflow. In this tank only 0.3 percent of the total inflow was added to the net storage increase.

Meegassagama Tank

The confluence tank Meegassagama is located downstream of the Vendarankulama and Bulankulama tanks. Therefore, it received return and spill flows from both upstream tanks as inflow, in addition to the rainfall on the tank and runoff from its own catchment. The catchment area of this tank is fairly large compared to the two tanks upstream, and is even slightly larger and higher than that of the Alisthana tank which is located immediately downstream (table 1). The cropped area is relatively large–27 percent of the catchment area, and rock outcrops represent a small area (1%) of this catchment. The slope in the N-S direction of this catchment is greater than that of the Bulankulama, but is milder than that of the other two catchments.

At this tank, the parameter used for simulating the delay in runoff generation in the 97/98 maha season was 240 mm. A close agreement between the model results and the measured data was obtained using RCF as 0.132, which is the lowest in the range of values used in the tank cascade (table 2). As noted earlier, the catchment area of this tank is the largest amongst the four tanks considered. The need for a low RCF value could be a consequence of the effects of the factors affecting runoff generation. Another plausible explanation is that the low RCF value may have compensated for an overestimation of the catchment area that is effective in contributing runoff to the Meegassagama tank. In improving the model, it would be useful to re-draw the effective catchment area of this tank and to check the validity of the survey data in determining tank capacity from tank height.

The overall match between the model results and the field measurement was considerably close; however, over the relatively dry period from mid-June to November 1998, the model simulations deviated from the measured data (figure 8). This may have resulted from underestimating the tank seepage rates by the seepage function used in the model. The seepage function, which has been derived using relevant data from July 1997 to February 1998, indicated unrealistic (negative) values when the tank storage was near its full capacity. Under such conditions, a very low seepage rate (0.1%) was assumed in the model. This assumption needs to be used until the seepage function is improved involving more data on tank seepage components under high tank storage conditions.

The model simulated spillway discharge with an effective spill crest level at 2.75 m, which is lower than that was indicated by the survey data (2.9 m). It is possible that field conditions at the spillway or an inconsistency in survey data could have contributed to this difference in the spill crest level.

Tank water balance

Based on the simulated results the inflow components of the Meegassagama tank were: Runoff (60.1%), rainfall on tank water (26%), return flow due to upstream tank seepage and water issue (12.5%), and return flow due to upstream tank spilling (1.4%). This shows that over the calibration period, return flow and spill flow from the upstream tanks accounted for a total of 13.9 percent of the total inflow into this confluence tank. This highlights the concept of reuse of water in the tank cascade.

Except in the dry period in the beginning of the simulations, this tank had a considerable storage throughout the calibration period. Due to this condition, rainfall on tank water surface represented a significant component of the total inflow (26%).

The seepage component dominated the outflow, accounting for 41.6 percent of the total inflow, but was considerably lower than that of the two upstream tanks. The evaporation in this tank accounted for 22.6 percent of the total inflow. This can be attributed to the tank water surface area corresponding to the relatively high tank water storage over most of the calibration period compared with the previous two tanks, which were dry or had very little storage over considerably long time periods. The water release allowed by the model was estimated to be 16.1 percent of the inflow. This agreed well with the measured data except at the beginning of the calibration period when the model indicated an empty tank earlier than that was indicated by the field data. The net storage increase in this tank accounted for 14.4 percent of the total inflow, whereas spillway discharge was estimated to be 5.3 percent of the total inflow.

Alisthana Tank

The Alisthana tank is located downstream of the Meegassagama tank, and is the last node considered in this study. The predominant soil type, red brown earth, covers a relatively large area of this catchment (78%). Cropped land accounts for 16 percent of the area and there are no teak plantations. The slope of the catchment is much smaller than that of the Vendarankulama catchment, but it is higher than the other two upstream catchments (table 1).

The delay in runoff generation in response to maha (97/98) rainfall was simulated with a delay parameter of 260 mm. A close agreement between the simulated tank water height and the observed data was obtained throughout the calibration period (figure 9) with RCF set at 0.31, the highest in the range values used in the cascade.

Tank water balance

As a normal tank, Alisthana received return flow from the immediately upstream tank (Meegassagama) in addition to the inflow from its own catchment and rainfall on tank surface. Runoff from its catchment was estimated to be 70.6 percent of the total inflow. As this tank had considerable storage during most of the calibration period, rainfall on tank surface accounted for 25.2 percent of the total inflow. Return flow due to water release and seepage at the upstream tank was estimated to be 2.8 percent and, return flow from upstream tank spilling was 1.4 percent.

The seepage dominated the outflow and was estimated to be 46.8 percent of the total inflow. However, in this tank and in the Meegassagama tank, the seepage component was considerably low compared with the two upstream tanks. The high storage conditions were often observed at these downstream tanks, and as indicated by the seepage functions, seepage under such conditions will be relatively low.

The high storage conditions also promote tank water reduction due to evaporation, and at the Alisthana tank the evaporation was estimated to be 20.4 percent of the total inflow. Except in the early part of the calibration period, tank storage was sufficient to provide for the water issue requirements at this tank. The water issue allowed by the model was 21.8 percent of the inflow. The net storage increase was equal to 11 percent of the total inflow.

Discussion on Calibration

Except for the apparent differences in the latter part of the simulation period at the two head-end tanks, a reasonable overall agreement was obtained between the simulated results and the measured data. However, a close match between the observed data and model simulations is an indication of the combined accuracy in simulating the different hydrologic components by the model. For example, if rainfall runoff is underestimated while the tank seepage is also underestimated, the simulated tank water height may still show a close agreement with the observed data. Therefore, it is important, whenever possible, to verify the validity of the simulated results considering the field evidence and understanding of the physical system.

The apparent discrepancy between the model results and the observed data can be attributed to several factors. At least in part, the observed differences highlight the need for further improvement of the seepage functions involving additional data representing different seasonal conditions at the tank cascade. The simulated results also depend on the validity of the model input in representing field conditions. There is uncertainty concerning the degree to which the model input is representative of the field conditions. Siltation and other problems associated with village irrigation tanks can affect the water-holding capacity of tanks. As such, the validity of the mathematical relationships in the model used for estimating tank capacity and tank area can change. Given the uncertainty caused by the above factors, the agreement obtained between the observed data and the simulated results over the calibration period can be regarded as an indication of the applicability of the simple water balance modeling approach used in the Cascade model.

The increase in the simulated tank water level in response to rainfall events over the calibration period agreed well with field observations, providing confidence in the method adopted in simulating runoff yield from catchment. The runoff coefficient (RCF) and delay parameters could reflect the combined effect of the factors such as land use, soil type, and slope of the catchment. This was clearly evident at the Vendarankulama tank where a distinctly low delay parameter was required to simulate runoff generation in its catchment area that was relatively steep. By comparing simulations with additional observed data at Thirappane and at other similar tank cascade systems, it may be possible to gain further insights into the effect of catchment characteristics on parameters such as RCF and delay. As shown by Dharmasena (1994) by studying the effect of land use on rainfall–runoff relationships and runoff threshold values, such studies may enable derivation of the values of the delay and RCF parameters based on catchment characteristics. This can eliminate the calibration requirement of the model.

The model simulations clarified the relative magnitudes of the water balance components at each tank. The results showed that tank inflow was mainly comprised of runoff from the catchment (60–85%). The significance of tank seepage became clearly evident, as it accounted for 42–84 percent of the total inflow to the tank. The lower values were observed in the downstream tanks, which had considerably high tank storage over most of the calibration period. In comparison, the total water release for irrigation was relatively low, and was within the range 4–22 percent. The results confirm tank seepage as the main outflow component, which, in an indirect way, supplements the water requirement of vegetation in the surrounding and command areas of a tank. The results indicated that about 14 percent of the total inflow to the confluence tank Meegassagama was derived from the return and spill flows from the upstream tanks, and thus, demonstrated the reuse of water from upstream catchments in the immediately downstream tanks facilitated by the tank cascade system. Thus the simulated results showed the capability of the model to provide valuable insights into the water balance at each tank.

Application of the Model

Using the model parameters obtained through the calibration process, the Cascade model was applied to predict water availability for rice crops in the Thirappane TCS over a 10-year period. The extent of paddy cultivation in the Thirappane TCS from 1988 yala to 1997 yala given in table 4 was used to estimate the demand for irrigation water release in each tank. The model was then used to predict whether the available tank water storage would be sufficient to provide for the time-varying irrigation water requirement at each tank.

This application of the Cascade model provides an example of how the model can be utilized to evaluate the feasibility of providing the required irrigation water for a cropping scenario, and thus illustrates a vital initial step in the process of improving effective water usage in a tank cascade system.

Model Input

The model input includes daily meteorological data and the water release required for irrigation. The daily rainfall and pan evaporation data over the time period considered in this model application was taken from the records at the Maha Illuppallama Research Station, which is situated at about 13 km from the Thirappane tank cascade system. This was part of the long-term data set prepared by filling in the missing data using records at another met station, Maradankadawala, situated 6.4 km from the study site, as described by Jayatilaka et al. (2000). For the estimation of irrigation water release requirement, a procedure appropriate for the type of crops and field practices of the model application should be adopted. The method adopted for estimating the required daily irrigation water release based on paddy cultivation extents is given in the following section.

Irrigation Water Requirement

The irrigation water requirement at each tank needs to be estimated considering the field practices of the two growing seasons maha (relatively wet season from October to March) and yala (relatively dry season from April to September). The water issue requirement in each season is estimated based on three stages: (1) land preparation; (2) growing stage of the crop; and (3) ripening period of the crop.

In the maha season, land is prepared using rainfall in October, and therefore, tank water is not

TABLE 4.
Paddy cultivation extents (area in ha) of the Thirappane tank cascade system.

Season	Paddy cultivation extent (ha)			
	Vendarankulama	Bulankulama	Meegassagama	Alisthana
Yala 88	0.0	0.0	6.1	0.0
Maha 88	10.1	8.1	28.3	18.2
Yala 89	0.0	0.0	0.0	0.0
Maha 89	8.1	6.1	28.3	16.2
Yala 90	0.0	0.0	0.0	0.0
Maha 90	6.1	6.1	28.3	14.2
Yala 91	0.0	0.0	6.1	0.0
Maha 91	12.1	8.1	28.3	16.2
Yala 92	0.0	0.0	2.6	2.0
Maha 92	19.0	10.1	28.3	24.3
Yala 93	0.0	0.0	0.0	6.1
Maha 93	19.0	14.6	28.3	20.2
Yala 94	0.0	0.0	0.0	0.0
Maha 94	0.0	0.0	0.0	0.0
Yala 95	0.0	0.0	0.0	0.0
Maha 95	0.8	0.0	0.0	0.0
Yala 96	0.0	0.0	0.0	0.0
Maha 96	10.1	3.2	6.1	0.0
Yala 97	0.6	8.1	6.1	5.5

required. In the yala season, tank water is released for land preparation in April. The volume of water released and the time period could vary. It is assumed that a 15-day period starting from 16th of April and a total of 125 mm of water would generally indicate the land preparation water requirement in the yala season. The irrigation water release requirements during the growing stage of the crop (stage 2), which is considered to be a 90-day period, is determined according to the crop water requirements as indicated in the process described below. During the third stage, the ripening period of the crop (15 days), irrigation water is not required.

Irrigation water demand in the growing stage

Using daily rainfall and pan evaporation data, the daily net irrigation water requirement (WR in m/day) at the paddy field is calculated using equation (1).

$$WR = cf_1.E \;-\; cf_2.\,R \qquad \ldots\ldots.. \quad (1)$$

where, E is pan evaporation (m/day), R is rainfall (m/day), cf_1 is pan coefficient for paddy fields and cf_2 is the coefficient to convert rainfall to effective rainfall. cf_1 was assigned the values suggested by Kitamura (1984) for the pan coefficient for the paddy fields in the dry zone of Sri Lanka, taking rice-growing period as 90 days in both seasons (table 5). cf_2 was taken as 0.8 in the yala season and 0.65 in the maha season as used in the ROSES model (Usgodaarachi et al. 1996).

If WR, calculated using equation (1), is less than or equal to zero, then the required Daily Irrigation Water Issue (WI) is taken as zero. If WR > 0.0 then, WI is calculated (in m^3/day) from equation (2).

$$WI = WR.PA / IE \quad \text{..................} \quad (2)$$

where, PA is the paddy cultivation area (m^2), IE is the irrigation efficiency (assumed as 0.6) and WR is the daily net irrigation water requirement (m).

TABLE 5.
Pan coefficient for paddy fields in Sri Lanka (Kitamura 1984).

Growing period day number	Pan coefficient	
	Wet season (Maha)	Dry season (Yala)
11	0.8	0.9
21	0.8	0.9
31	0.9	0.9
41	1.1	1.0
50	1.2	1.1
60	1.4	1.2
70	1.4	1.2
80	1.4	1.2
90	1.4	1.2

Initial Condition

The Cascade model was to be set up for predictions from the beginning of the yala season in 1988. There were no observed tank height data available to assign water level in tanks, and therefore, the initial condition had to be approximated. In order to minimize the effect of any errors in the assumed tank water height on model predictions, initial condition was assigned on the 1 August 1987, leaving a considerable time period before the start of predictions in yala 1988.

Considering the relatively dry period normally observed in the cascade towards the end of the yala season, a small tank water height, 0.1 m, was assumed in each tank. It was expected that the model simulations during the last two months of the 87 yala season and the 87/88 maha season would adjust tank water height to a realistic value by the start of predictions in yala 1988.

Model Predictions

Using the model parameters and the user-defined coefficients of the calibrated Cascade model, tank water availability in the Thirappane cascade was predicted based on the daily water balance computations over a 10-year period, from 1 August 1987 to 30 September 1997. The results obtained are presented in figures 11–14.

The model simulated the delay in runoff generation at the beginning as a prolonged dry spell was assumed in the cascade at that time, and predicted the subsequent increase in tank storage and its changes in response to rainfall. In addition to the initial period, the delay in runoff generation was simulated after a prolonged dry spell, which was assumed when two conditions, (1) no rainfall and (2) empty tank, occurred simultaneously over 50 consecutive days at a given tank.

In general, the model predictions indicated that two upstream tanks became dry more often (almost every year) during the prediction period compared with the two downstream tanks. After the initial dry spell, delay in the generation of runoff occurred only once at the Bulankulama tank when a prolonged dry spell occurred in April in 1992. This condition however, did not occur in the other tanks, as conditions for prolonged dry spells were not satisfied.

FIGURE 11.
Predicted tank water height, volume, and tank water balance components–Vendarankulama.

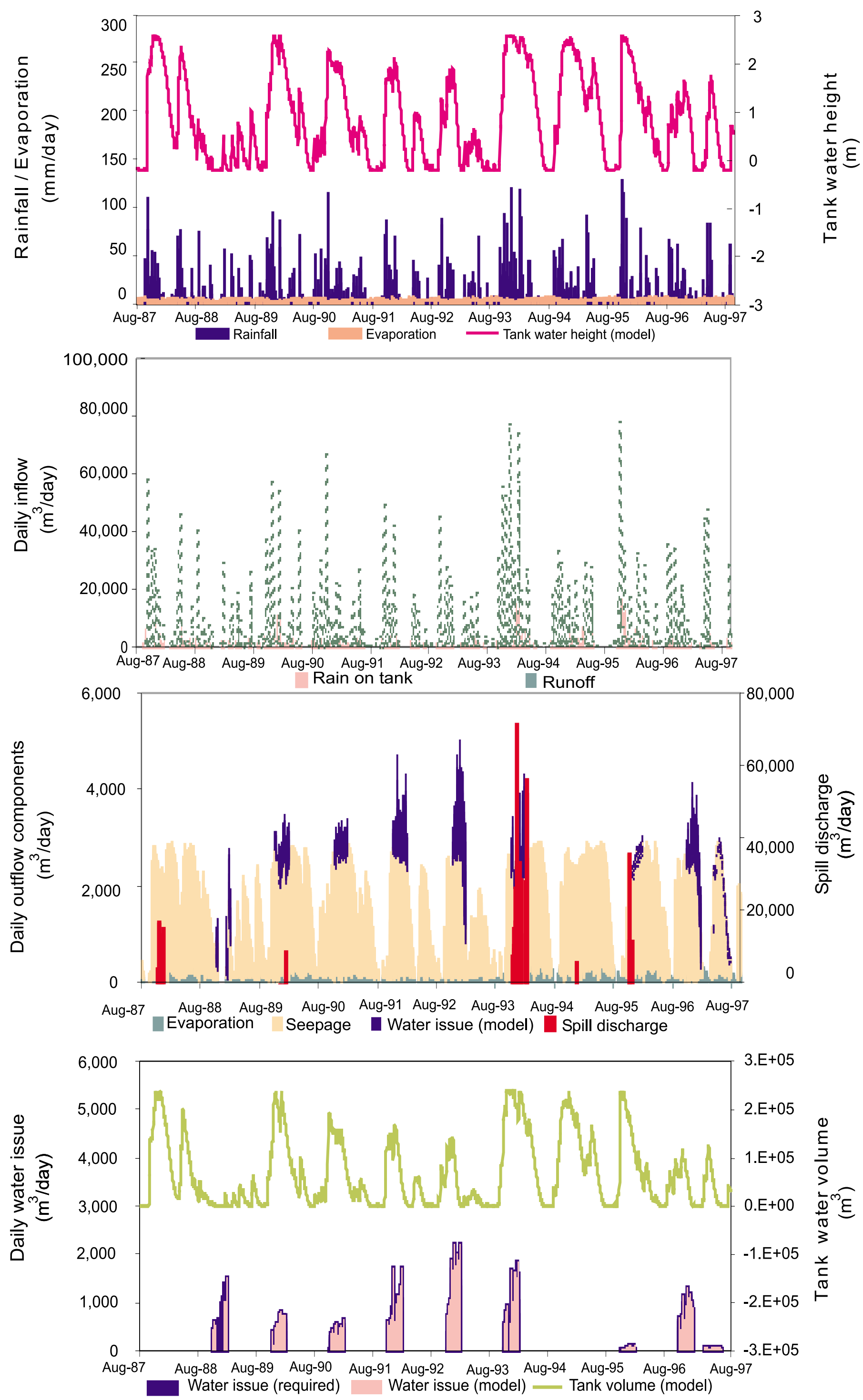


FIGURE 12.
Predicted tank water height, volume, and tank water balance components–Bulankulama.

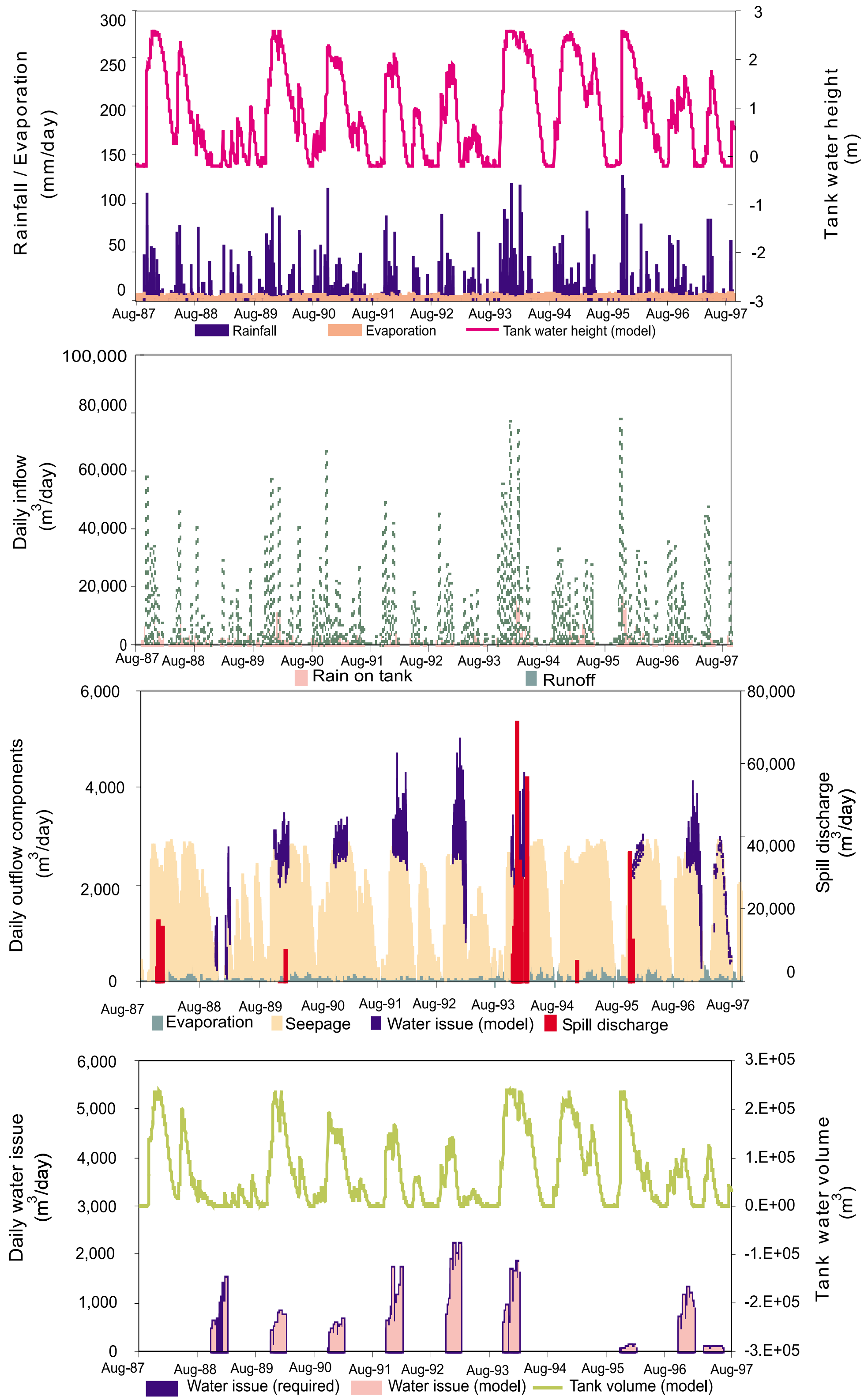


FIGURE 13.
Predicted tank water height, volume and tank water balance components–Meegassagama.

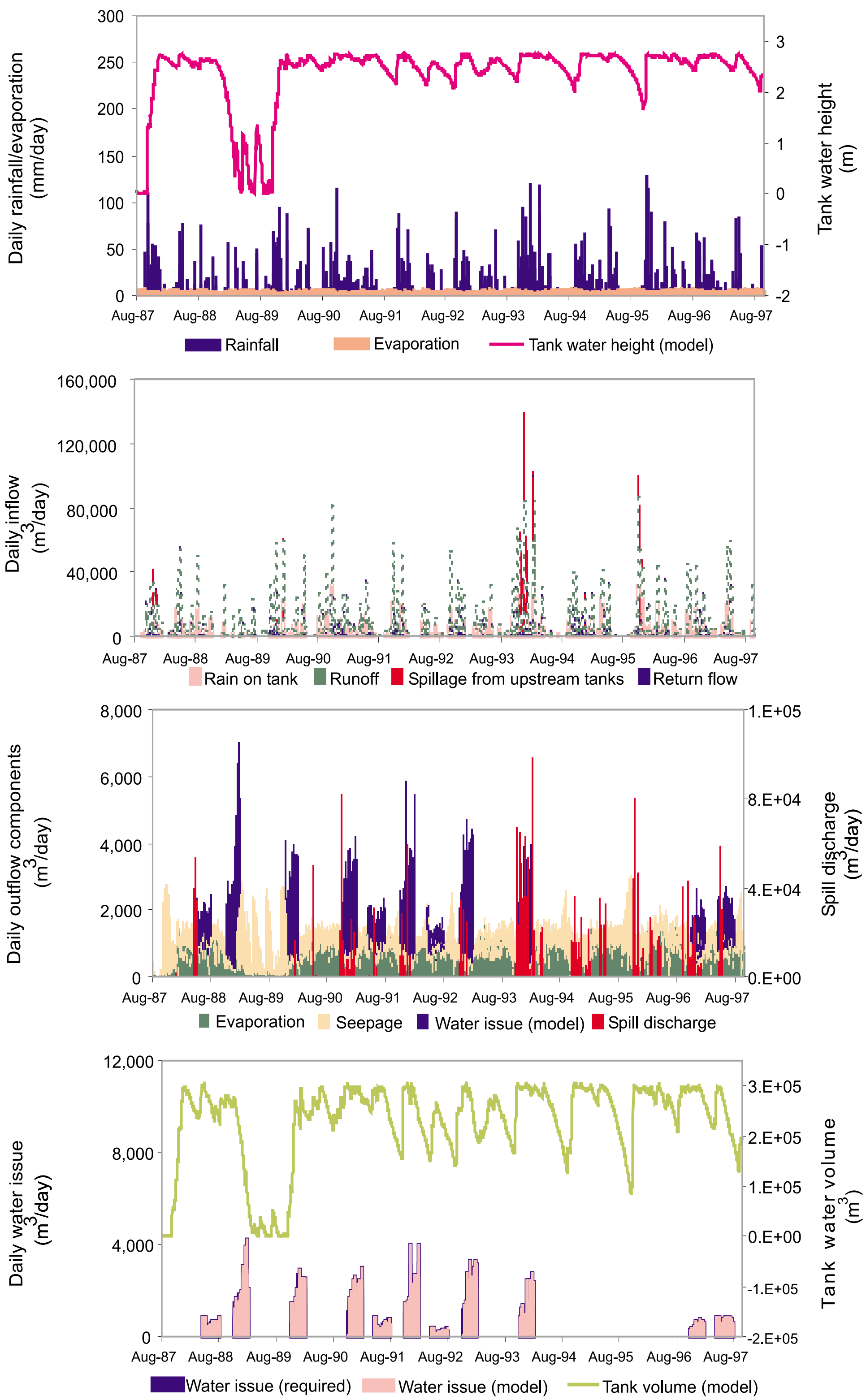
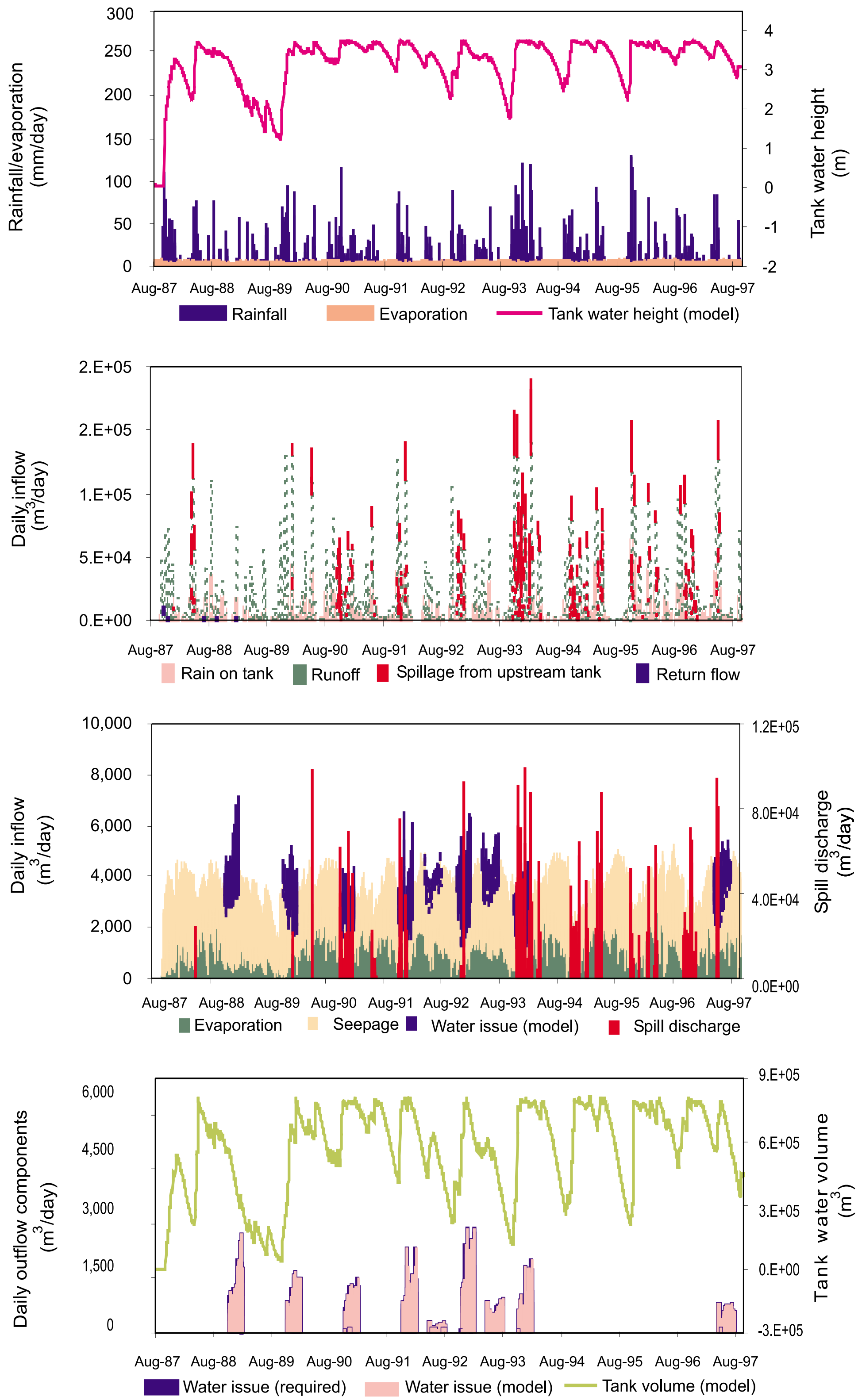


FIGURE 14.
Predicted tank water height, volume, and tank water balance components–Alisthana.



Results and Discussion

The Vendarankulama start tank was filled to its capacity several times during the time period considered, and spilling occurred a few times, most noticeably in the 93/94 maha season. The model predictions indicated low tank storage conditions over the relatively dry period 88/89. The tank storage was only sufficient to provide part of the required irrigation water release in the 88/89 maha season, and a water shortage was predicted from mid-November 1988 to mid-January 1989 in the fourth graph of figure 11. The tank storage was adequate to release the required irrigation water during other cultivation periods. The model predictions also indicated that inflow to the tank was dominated by rainfall runoff and the greater portion of the inflow was lost due to tank seepage. The irrigation water release was smaller in comparison with the other outflow components from the tank.

The predictions at the Bulankulama tank, which is the other start tank in the cascade, were similar to those at the Vendarankulama (figure 12). The Bulankulama tank was also filled to its full supply level several times and tank spilling occurred in maha 93/94 and in November 1995. The tank became empty at the end of every yala season. The model predicted a delay in the generation of runoff due to prolonged dry conditions in April 1992. The tank storage was sufficient to provide only part of the demand for irrigation water in 88/89 maha. The tank became empty during the growing stage of rice, and therefore, a water shortage was predicted from mid-November 1988 to mid-January 1989. The tank water shortage was also apparent in the 97 yala season and towards the end of the 96/97 and 92/93 maha seasons.

As a confluence tank, Meegassagama received return flow from the two upstream tanks and this helped to maintain high tank water storage during the greater part of the prediction period. Tank spilling occurred several times during the calibration period as indicated in figure 13. Low tank water and dry tank conditions were apparent during 1989. During the rest of the prediction period, this tank had considerable storage. The available tank water was sufficient to provide for the estimated irrigation water requirements. It appears that this tank had the potential to meet even greater irrigation water demand than that was estimated based on the paddy cultivation extent.

The normal Alisthana tank received return flow from the upstream Meegassagama tank in addition to the rainfall runoff from its catchment and direct rainfall on the tank. The tank storage remained high over a considerable part of the simulation period and became relatively low only a few times during the prediction period (figure 14). Spill discharge was predicted several times as indicated in figure 14. At this tank, available tank water was sufficient to meet the estimated irrigation water demand during all the cultivation seasons considered. As observed in the Meegassagama tank, this tank also showed the potential to meet even greater irrigation water demand.

In general, the application of the Cascade model illustrates how it can be used to predict water availability in the Thirappane TCS under a given cropping scenario. It was not feasible to directly compare the model predictions with field data due to insufficient field records. Although the cultivation extents were based on field data, the estimated water issue data (supplied as input to the model) may not have represented the actual water issue as this depends on various field practices. However, the model predictions indicated the feasibility of supplying the estimated irrigation water requirement at each tank, and clearly indicated the periods in which tank water shortages occurred. The results also manifested that, in comparison with the head-end tanks, the tail-end tanks in the cascade have a greater potential than indicated by the cultivation extent data to meet the irrigation water demand and irrigate larger areas. In particular, the application of the model highlighted the potential use of the model for evaluating water use scenarios that would allow the optimum use of the available tank water, minimizing water shortage during critical growth stages of the crop(s) in the command area.

Conclusions

The reasonable overall agreement between the simulated results and the measured data over the calibration period provided a degree of confidence in the calculation procedure adopted by the Cascade model for simulating water balance of the different types of tanks in the cascade system. Although it was not feasible to carry out a complete verification of the model, the calibration process that was based on two stages allowed verification of the applicability of the seepage functions over the changing field conditions at the tank cascade system. The apparent differences between the model simulations and field data can be attributed to several factors including the inadequacy of the seepage functions, the assumptions used in the model, validity of the model input, and the uncertainty of field data.

The model simulations provided valuable insights into the water balance at each tank and displayed inter-connections of the tanks within the cascade system. The application of the model for predicting availability of tank water for rice crops in the Thirappane TCS demonstrated the potential use of the model in the vital initial steps of the process aimed at optimizing the usage of the limited water resources in tank cascade systems for improved agricultural production.

The Cascade model can be further improved by using additional field observations at the Thirappane TCS and in other similar tank cascade systems. The areas of the model that need modifications or further improvement are:

1. The seepage function derived for each tank and for the general use in tank cascade systems needs to be improved involving more observed data that represent different agrometeorological conditions in the cascade.

2. An independent verification of the model should be carried out involving a new data set at the Thirappane TCS. This would allow further verification of the validity of the calibrated model parameters. Until a satisfactory independent validation of the model is completed, calibration of the model should be further extended involving more data collected at the site.

3. The model should be calibrated using data from similar cascades. This process can help eliminate the calibration requirement of the model by formulating suitable guidelines to pre-determine the values of the delay parameter and the runoff coefficient (RCF) based on the physical characteristics of the catchment.

4. The model needs to be further developed to be able to incorporate other features of tank cascade systems such as diversion weirs and feeder canals, which are not present in cascade systems such as the Thirappane TCS.

5. The model code should be further improved by incorporating the dynamic array capability available in *Lahey Fortran*.

With further improvements as suggested above, the Cascade model may provide a basis for the development of a valuable tool for evaluating different cropping scenarios and water management options in similar irrigation tank cascade systems in Sri Lanka and in other countries. The present version of the model has shown its potential use in this respect within the Thirappane tank cascade system.

Appendix A

Mathematical Representation of the Tank Water Balance Components

The mathematical expressions and assumptions used in representing the effective tank water balance components in the Cascade model are presented in this section.

Inflow Components

Runoff from rainfall on catchment

The process of runoff generation in catchments is commonly approximated by the use of simple models based on the runoff coefficient method. The runoff coefficient of most linear system models is assumed to be a constant. However, as pointed out by Xia et al. (1997), the runoff coefficient is by no means a constant, and its variability (due to the influence of factors such as evaporation, catchment wetness, and rainfall intensity) cannot be explained in terms of simple seasonal variation. The nonlinearity of the runoff generation process can be approximated through a time-varying runoff coefficient, facilitated by the use of an Antecedent Precipitation Index function indicating the degree of catchment wetness (eg., Xia et al. 1997). The Cascade model estimates runoff from rainfall on the catchment of each tank on a daily basis by adopting a modified runoff coefficient method, which allows the runoff coefficient to vary daily depending on an Antecedent Precipitation Index (API), as described by equations A.1 and A.1a. On a given day, runoff contribution to the tank denoted as node 'j', is expressed as:

$$RO_j = RCF_j R_j CA_j / API_j \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (A.1)$$

where, RO_j is runoff yield (m^3/day), RCF_j is runoff coefficient, R_j is rainfall on the catchment (m/day), CA_j is the catchment area (m^2), and API_j is Antecedent Precipitation Index. API, at node j depends on the number of days since the last day with rainfall (n). Depending on *n*, API_j can be estimated as:

$$API_j = \sum_{k=0}^{k=n} 1/(k+1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (A.1a)$$

The method adopted by the Cascade model provides a means to account for the effect of soil moisture depletion over no-rainfall periods on runoff yield. It accommodates both (1) 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 (2) 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 of 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. Therefore, when the number of days without rainfall is greater than 11 days (n > 11), API corresponding to n = 11 is used in the model.

The above process allows estimation of runoff from rainfall on the catchment on a daily basis under normal conditions. However, when there are prolonged dry spells without rainfall, soil moisture may decrease to a very low level, and runoff may not be produced in response to rainfall until the soil moisture is replenished. Particularly at the end of the yala season, during the months of July and August, such prolonged dry spells can occur and the tanks may dry up completely. This condition can cause a delay in the generation of runoff when rainfall arrives, as the soil moisture level has to rise before runoff can occur. The model accounts for the above condition by using a parameter named *delay*, which is assigned to each node (tank) to act as an indicator of the 'initial loss' of rainfall before runoff can occur in its catchment after a long dry spell. In such conditions, the model would not allow generation of runoff, until the cumulative rainfall since a prolonged dry spell exceeds the value of delay, which is also given in mm. If a simulation starts following a long dry period, which has caused tanks in the cascade to dry up, this condition is assumed at the beginning of the simulation. In addition, if the number of consecutive days (1) without rainfall, and (2) tank being dry, exceeds a set "upper limit," the model activates the condition related to long dry spells so that runoff generation will be delayed until rainfall exceeds the initial loss indicated by the delay parameter. The upper limit is assumed as 50 days, limiting the effect of the delay in generating runoff from rainfall only for periods that follow extended dry spells.

The parameters RCF and delay, which are dependent on catchment characteristics such as soil type, vegetation, land slope etc., and need to be determined through calibration, are generally expected to be in the range: delay, from 0 to 300 mm; and RCF, from 0 to 0.35. This range can be used in assigning values for the parameters at the start of a simulation.

Rain on tank water surface

Rainfall on the tank water spread area is determined as:

$$RT_j = TA_j R_j \text{......................(A.2)}$$

where, RT_j is rainfall on tank (m^3/day), R_j is the daily rainfall (m/day), TA_j is the tank waterspread area (m^2), which is updated based on the latest tank water height at the beginning of each day.

Outflow Components

Evaporation

The reduction of tank water due to evaporation is computed as:

$$EV_j = fpE_j TA_j \text{..........................(A.3)}$$

where, EV_j is evaporation (m^3/day), *fp* is pan coefficient for converting pan evaporation to tank water evaporation, E_j is pan evaporation (m/day) and TA_j is tank waterspread area (m^2).

Seepage and percolation

The seepage and percolation of tank water through the tank bed and the embankment (referred to as the tank seepage) represents a significant component of the tank water reduction. The seepage depends on the hydraulic conductivity of the tank bed and the embankment, and the difference between the tank water level and the water table in the surrounding area. The estimation of the seepage requires field measurements on the spatially varying hydraulic conductivity of the tank bed and flanks, and the time-varying tank water height and groundwater levels.

In the absence of such measurements, seepage has been assumed as a percentage of the water stored in the tank. For example, the monthly seepage from tanks has been commonly taken as 0.5 percent of the tank water volume as reported in the manual on the design of irrigation headworks for small catchment in Sri Lanka (Ponrajah 1984). Tasumi et al. (1999) pointed out that seepage of 0.5 percent of the tank volume per month is based on the seepage measurements of large tank systems constructed with modern technology and cutoff trenches, and therefore, would not be representative of the seepage in small irrigation tanks. Further, the analysis carried out by Tasumi et al. (1999) indicated that an irrigation tank completely filled with water with no inflow into the tank and outflow from sluices can loose about 75 percent of its volume due to seepage within two months of filling. This represents a seepage rate of 2.4 percent of the tank water volume per day.

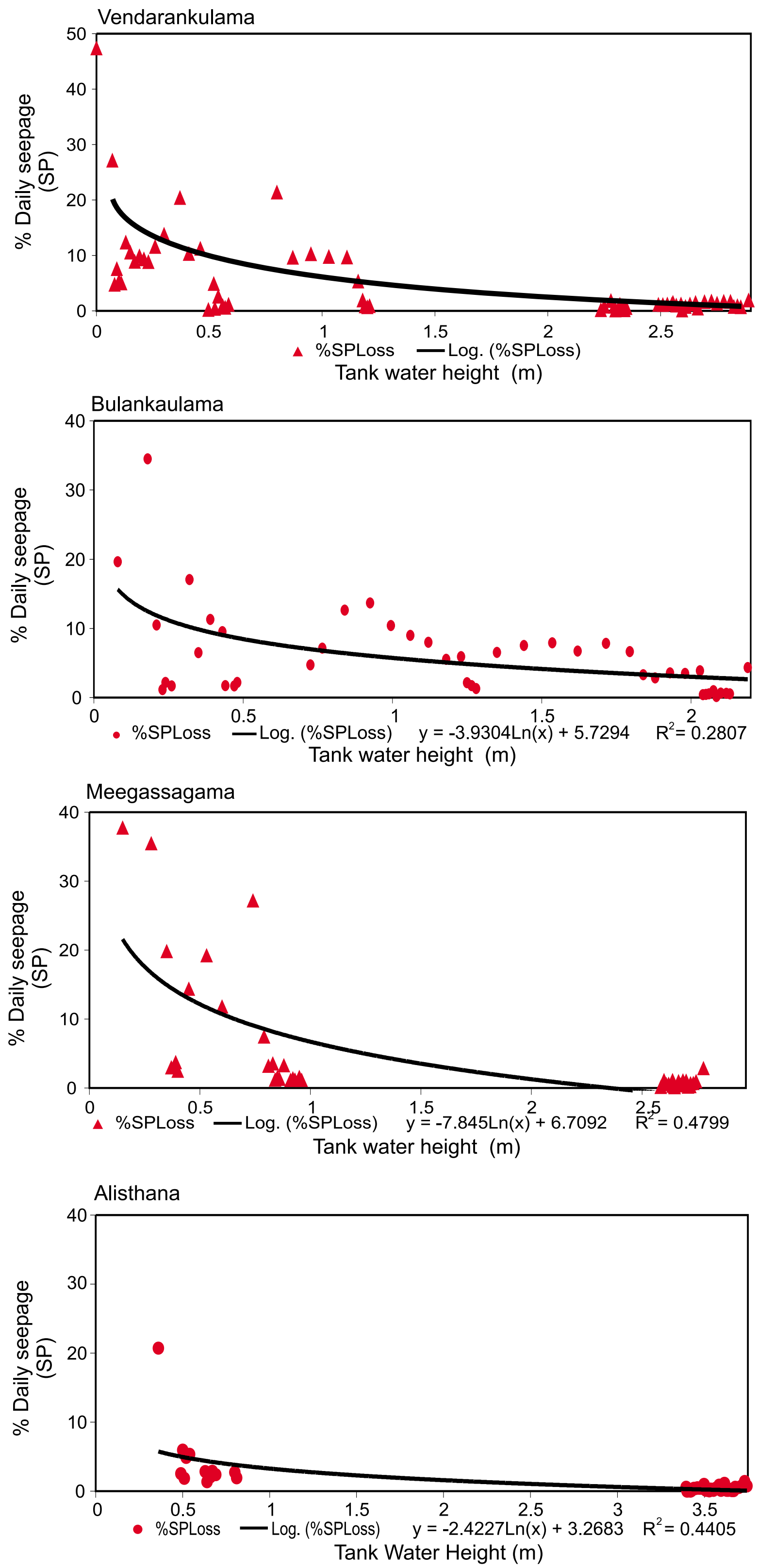
In the development of thc Cascade model, the seepage in the Thirappane TCS was estimated using the observed data from 22 July 1997 to 21 February 1998, the data set that was initially available for the study. The decrease in tank storage during time periods without rainfall occurs as a result of the tank water issue for irrigation, evaporation of tank water, and the water removal due to seepage. Therefore, the seepage during no-rainfall periods can be estimated on a daily basis from the difference between the observed tank storage decrease (which can be estimated from the tank water height measurements) and the total of evaporation and the volume of water issued for irrigation. The detailed analysis performed using the estimated seepage at each tank (Jayatilaka et al. 2000) indicated that daily seepage as a percentage of tank water volume (%SP) is relatively high when the tank water height is low when compared with the daily seepage when tank water height is high. This trend is commonly observed in all four tanks considered, and the trend line obtained for percentage SP as a logarithmic function of the tank water height for each tank is shown in figure A.1.

This analysis indicated that tank seepage rate can be even higher than 20 percent of the tank water volume when the tank water height is low, and when the tank volume is large it can decrease to a very small rate close to zero. The high daily seepage rates during periods with small volumes of tank water observed in this study is much greater than that indicated by the monthly rate used by Ponrajah (1984) and the daily rate reported by Tasumi et al. (1999). A monthly rate would not reflect the variations in the daily seepage rate under changing tank water storage conditions. Unless a study has been conducted including different tank water conditions, even the figure derived for the daily rate may not represent the possible range of variations in the seepage rate.

The daily seepage rate, 2.4 percent of the tank volume, derived by Tassumi et al. (1999) is based on an analysis on a tank cascade system in the Anuradhapura District. However, the tanks in this cascade system receive water from a feeder canal in addition to the rainfall runoff from their own catchment, and therefore, the tanks remain full most of the time. The storage under which the seepage rate has been derived was greater than 50,000 m^3. Therefore, it is not clear whether the daily seepage rate of 2.4 percent of the tank volume would be representative of the seepage under low tank water storage conditions, which commonly occur in tank cascade systems that do not receive water from other sources such as feeder canals.

The seepage rate variation observed at the Thirappane TCS agrees with the results of a water balance study at a village tank, Walagambahuwa, in the dry zone of Sri Lanka conducted by Dharmasena (1985). The seepage interpreted as a percentage of tank storage at the Walagambahuwa tank decreased as the head increased. In addition, the observed seepage rate variation in the Thirappane TCS is consistent with the effects of different field conditions on the tank water reduction due to seepage. During periods when the tank has water at or near its capacity at the full supply level, the ground water table in the surrounding area can be high. The water volume reduction due to seepage in this condition may not be a high percentage of the tank water volume. On the contrary, during dry periods when the tank storage is small, water table in the surrounding area can be low, resulting in a greater head difference between tank water and the groundwater level. This can cause a significant reduction in the volume of water due to seepage as dry conditions could prevail over a considerable area around the tank. Given that the tank water

FIGURE A.1.
Percent seepage as a function of the tank water height.



volume is low, reduction in water due to seepage can be a relatively large fraction of tank water compared with the fraction of water reduction due to seepage when the tank water volume is high.

The seepage functions derived for the tanks in the Thirappane TCS presented in figure A.1 indicate a common trend consistent with the possible variations of the seepage rate as discussed above. Although the R^2 values obtained are not very high (0.28-0.48), the logarithmic function derived for each tank was considered to represent the generally observed trend in variation in the seepage rate. Based on these functions, the tank water reduction due to seepage through the tank embankment and percolation through the tank bed, referred to as 'tank seepage' in the Cascade model, is estimated using equation (A.4):

$$SP_j = [a_j \ln(h_j) + b_j] TV_j / 100 \text{........................} (A.4)$$

where, SP_j is tank seepage (m^3/day), TV_j is tank water volume (m^3), h_j is tank water height (m), and a_j, b_j are parameters of the seepage function given in figure A.1 (in which, daily seepage as a percentage of tank volume (y) is represented as a logarithmic function of tank water height (x) in the form "y = a_j ln (x) + b_j" for tank j. At the start of the simulation, TV_j is determined using the cubic expression representing tank water volume as a function of tank height given in Jayatilaka et al. (2000a). Subsequently, TV_j is estimated at the end of each day as part of the water balance calculations.

In many field situations the required data to determine parameters of the seepage function relevant to the tank(s) may not be available. The analysis performed in this study has been extended to derive a function that can approximate the tank water reduction due to seepage in similar tank cascade systems. The seepage functions of the Thirappane TCS can be presented based on a common horizontal axis representing relative tank water height defined as *tank water height/tank water height at the full supply level* (figure A.2). Based on the average value of the SP percentage corresponding to the four expressions, a logarithmic function can be derived as presented in figure A.2. This function can provide a means to estimate seepage in irrigation tank cascades such as the Thirappane TCS, when the required information to determine the relevant parameters of the seepage function is unavailable.

Water issue for irrigation

The water released for irrigation (WQ_j) is a daily field measurement, which is part of the input required for model calibration. When the model is used for predictions, the irrigation water issue requirement needs to be estimated based on a process appropriate for the crops and field practices of the model application.

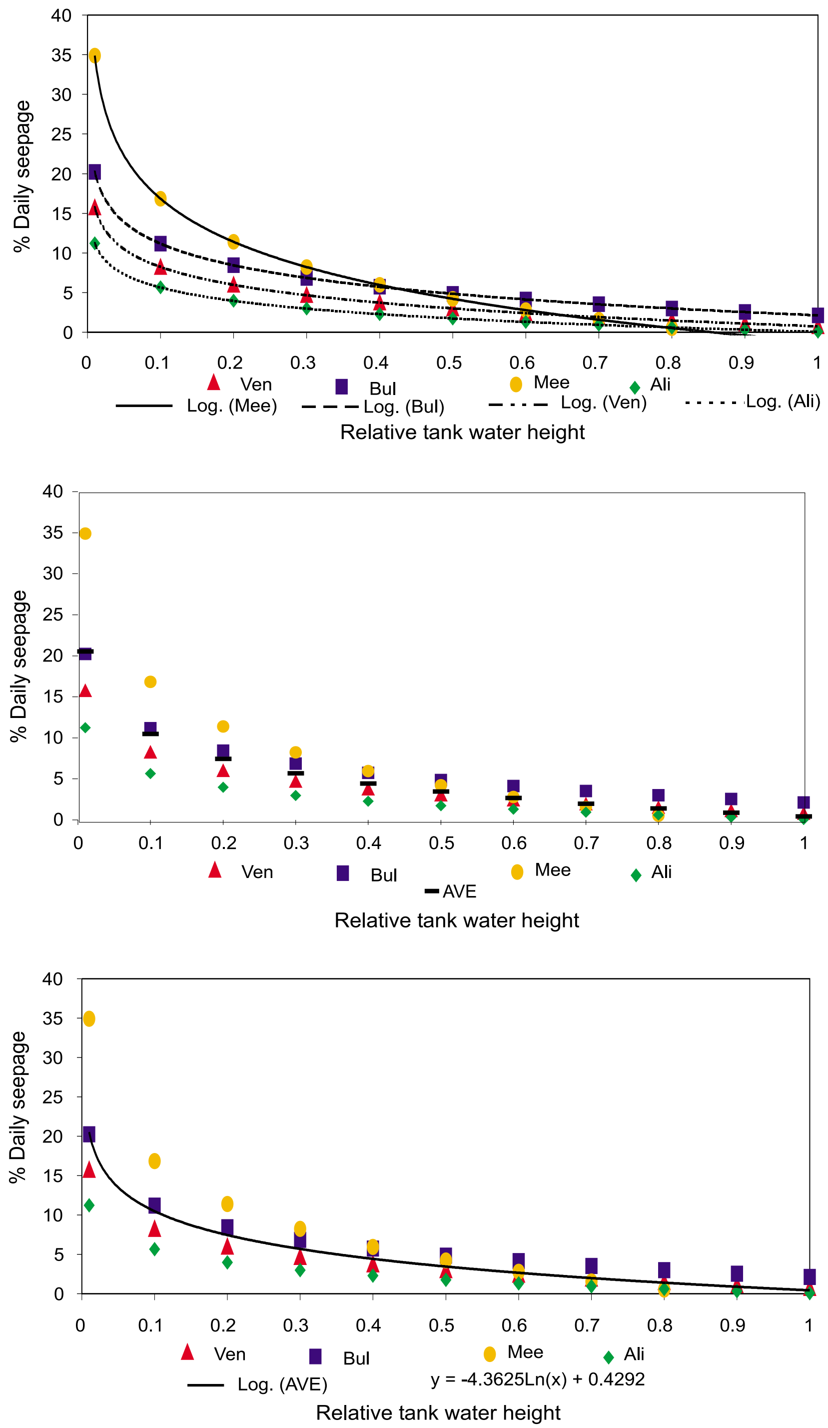
Spillway discharge

When the tank water height is greater than the weir crest level, initially, the spillway discharge is computed assuming it can be approximated with the equation A.5, which is generally applicable for broad crested weirs (French 1994).

$$SL_j = fd.L_j \left(V_j - h_j\right)^{1.5} \text{........................} (A.5)$$

where, SL_j is spillway discharge (m^3/s), L_j is the length of the spillway (m), V_j is the spill level (m), and h_j is the tank water height (m) and *fd* is the discharge coefficient taken as 1.7 $m^{1/2}$/s (French 1994). SL_j is then converted to a daily rate to obtain the upper limit of the spillway discharge allowed by the model on a given day. The actual discharge is determined by the lower of the following two quantities: (a) estimation based on the equation A.5, and (b) tank water volume in excess of the full supply level (tank capacity at the spill level).

FIGURE A.2.
Percent seepage as a function of the relative tank water height.



Additional inflow components

The return flow from upstream tanks, which forms additional inflow components to normal and confluence tanks is estimated as follows.

Return flow due to seepage and water issue

During Maha, return flow due to seepage and water issue from upstream tanks is estimated from equation A.6:

$$RF_j = \sum_{k=m}^{n} \left[fr\left(WQ_k + SP_k \right) \right] ....(A.6)$$

where, RF_j is return flow at tank j (m^3/day), k is the contributing upstream node number, m is the first contributing upstream node, n is the last contributing upstream node, WQ_k is water issue at the upstream node k (m^3/day), SP_k is the seepage at upstream node k (m^3/day), *fr* is a user-defined coefficient ($0 \le fr \le 1$).

It is assumed that the water released for irrigation during the yala season would be just adequate to provide for the requirements in the command area, and as such, part of the irrigation release would not arrive as return flow at the downstream tank. The return flow component in yala is therefore, estimated from equation A.6 with WQ set to zero. *fr* denotes the fraction of the seepage and water issue in the upstream tank that would become available as inflow at the downstream tank. Ponrajah (1984) noted that 20 percent of the irrigation release for cultivation in the immediately upstream tank is available as drainage for reuse in the downstream tank.

It is difficult to assign a return flow fraction that would be applicable for both flow components (seepage and irrigation release) in each tank, under the spatially and temporally varying conditions in a cascade system. On the other hand it is not feasible to determine different return flow fractions for the two components (seepage and irrigation release) at each tank in the cascade. The coefficient *fr* in the Cascade model is expected to provide a simple means to provide a reasonable estimate of the return flow fraction, which would be generally applicable to the tank cascade. Initially *fr* can be set to be in the range 0.1–0.4, and this can be refined through calibration of the model.

Return flow due to spillway discharge

The return flow due to spillway discharge at upstream tanks is estimated as:

$$SI_j = \sum_{k=m}^{n} \left(fs.SO_k . \right) ....(A.7)$$

where, k is the contributing upstream node number, m is the first contributing upstream node, n is the last contributing upstream node, SI_j is inflow at tank j due to spillage at upstream tank (m^3/day), SO_k is spill discharge at upstream node k (m^3/day), and *fs* is a user-defined coefficient that determines the fraction of spill discharge that arrives at the downstream tank. In the study conducted by Shinogi et al. (1998), this fraction was taken as 0.57 and 0.67 for the Vendarankulama and Bulankulama tanks, respectively. Although in general, *fs* could vary from tank to tank, in the Cascade model it is assumed to be a common coefficient and can be set to a value in the range, $0 \le fs \le 1$. In the absence of field measurements to determine *fs,* it is assumed that 0.5 would be a reasonable value.

It should be noted that the above computations of return flow are based on the assumption that part of the water released for irrigation, tank seepage, and spillway discharge from the upstream tank can arrive at the downstream tank within the same day. As the model was designed for cascades with small irrigation tanks with relatively small command areas this assumption is considered to be reasonable.

Processing Procedure

The daily water balance for tank 'j' in the cascade can be written in the form of equation A.8.

$I_j - O_j = DS_j$...(A.8)

where, I_j is total inflow and is O_j outflow and DS_j is the change in storage determined from the difference between tank storage at the beginning and the end of the day. Tank storage at the end of the day is taken as the storage at the beginning of the next day. Inflow components and outflow components of the tank water balance are substituted in equation A.8 in the order explained in the processing procedure illustrated by the flowchart presented in figure 5. It provided the basis for the Cascade-model code, which is written as a *Lahey Fortran* program.

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