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Working Paper No. 37

WATER BALANCE MODEL FOR PLANNING REHABILITATION OF A TANK CASCADE IRRIGATION SYSTEM IN SRI LANKA

Jun Itakura

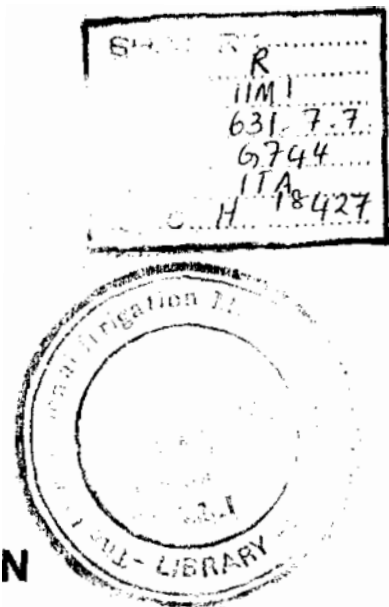
In May 1992, Jun Itakura started his work with IIMI as an Irrigation Specialist to carry out research studies on the improvement of water management in inter-connected tanks in the dry zone of Sri Lanka. Mr. Itakura was seconded to IIMI for three years by the Government of Japan under the JICA-IIMI Collaborative Program. He has since returned to work with the Agriculture Improvement Bureau of the Ministry of Agriculture, Forestry and Fisheries in Japan.



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Foreword

Since time immemorial, people in South Asia have collected rainfall runoff in small storage reservoirs (called tanks) for later use in agricultural production, for domestic use and watering of livestock. A unique feature of the tanks in Sri Lanka is that often several of the tanks are linked together through a canal. The resulting cascade of tanks should then be managed as one system. The Thirappane cascade, which is the topic of this study, falls within the catchment area of a much bigger reservoir, Nachchaduwa. The latter was built around 900 AD, and restored in 1906, when many of the tanks still in use now were surveyed and restored to use. Cascade management, however, was not always carried out properly and restoration work not done, that the skills to do so were lost. The management of these interconnected tanks presents many interesting questions, the answers to which hitherto have not been fully explored. The effectiveness of storage-based irrigation systems was such that over time more and more people were attracted to the command areas of the tanks and many of the systems became unsustainable due to overcrowding.

The objective of this study was a limited one, i.e., to explore through simple water balance modelling several improved management options for a particular set of tanks in the Thirappane Cascade and to examine how the tank cascade can be stabilized through structural modifications. The water balance model developed for this purpose has deliberately been kept simple, requiring only data that can be easily collected in the field. As a result, the major constraint of the model is in the assumed static runoff coefficients, which are known to be deficient as runoff depends—among other things—on the soil moisture content when rainfall and runoff occur. Notwithstanding the limitations in the assumed nature of the coefficients employed in the water balance model, it was found that the model was effective in illustrating mean system response characteristics.

The model was used to examine the effect of raising the crest level, and hence enhancing the storage capacity, of two of the larger tanks in the system in terms of irrigated area. The model was also used to predict what would happen if the storage of two of the tanks was combined into one. The results of the analyses indicated that all three of the interventions would pay off in wet years. It also showed that it is important to consider the water management of all tanks in the cascade together when considering changes in the structural arrangement or water management of the tanks.

The significance of the study as described in the paper is not so much in the outcome of these particular modelling exercises but in that it points the way forwards a sound approach to Improving the management of these valuable but threatened irrigation facilities.

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Water Balance Model for Planning Rehabilitation of a Tank Cascade Irrigation System in Sri Lanka

INTRODUCTION

The two seasons of Sri Lanka are strongly influenced by the monsoon circulation (Figure 1). The *maha* season, from September to March, during the northeast monsoon, brings considerable rainfall over the whole of the island. The southeast monsoon brings reliable rainfall only over the southwest of the country from April through August, during the so-called *ya/a* season. Based on such a noticeable difference in the rainfall pattern, the country is divided into two zones. The wet zone is in the southwest one fourth of Sri Lanka, and the remaining three fourths of the country make up the dry zone (Figure 2).

Cultivation of rice is important in both zones; other crops that are grown include tea, rubber and coconut (Table 1). In the wet zone, two rice crops can be grown per year. In the dry zone, rainfall is less reliable but yet the dry zone has been of major importance for rice production since time immemorial and continues to be so to this day. Tank (the subcontinental term for reservoir) based irrigation has been developed over the centuries to overcome the unreliability of rainfall. As a storage system, the tank could store catchment runoff and regulate the flow according to the crop requirements. As a result, the tank systems have increased the available water for irrigation of rice fields in the dry zone. An aerial picture of the dry zone reveals that there are hundreds of tanks of various sizes, many of which are interconnected.

Some ancient tanks were linked through long canals to form large dam-networks stretching over several river basins. More commonly, a large number of interlinked tank irrigation systems were built in small watersheds, the so-called "tank cascade system" (TCS) (Figure 3). In the small watersheds, interlinking tanks facilitated re-use of return flow from an upstream command area in the command area of the next lower tank. This practice increased the consumable fraction of water collected in the watershed.

OBJECTIVES

The effectiveness of storage-based irrigation systems was found to be such that more and more people were attracted to the command areas of the tanks and many of the systems became unsustainable over time because of overcrowding. For that reason, this study attempts to assess the resilience of an existing TCS. To cope with the functional deterioration of TCS, a simple water balance model has been developed to examine how a TCS can be stabilized through structural modifications.

METHODOLOGY

The system of the Thirappane Cascade (Figure 4) has been selected for this study for its typical and simple features. The system is situated in a series of small watersheds within the huge catchment of the Nachchaduwa Dam, which was constructed in ancient times. The sample TCS is only 8 km long from the most upstream to the most downstream tank, and there is a total of 6 small inter-linked tanks in the system. Nowadays, each tank has its own command area and no regulating tanks remain in the TCS. Tail-end parts of a command area often overlap the upstream parts of the next tank area (Figure 5). Tanks now store insufficient water during dry years, because of segmentation of the watershed and the decrease in catchment area of each tank in the system.

The methodology consists of three steps:

- Develop the water balance model for the TCS through calculation of the components of water balance.
- * Simulate fluctuations of tank storage with the water balance model to compare the simulated and the actual water levels for validation of the model.
- * Apply the model to some hypothetical cases in which the original structure of the TCS is changed to enhance the stability of the system.

BASIC STRUCTURE OF THE WATER BALANCE

The general structure of the water balance of a TCS is given in Figure 6. The water balance of tank (i) in period (t) is equal to the inflow minus the outflow plus the change in storage in the tank. Equation 1 shows the linkage between tanks through the return flow term:

$$QA_{i,t} + QB_{i,t} + QC_{i-1,t} = QD_{i,t} + QE_{i,t} + QF_{i,t} + dS_{i,t} \quad \text{----- (1)}$$

$$S_{i,t} = S_{i,t-1} + dS_{i,t} \quad \text{----- (2)}$$

where

QA is runoff flowing into the tank

QB is rainfall onto the tank surface

QC is return flow from the upstream tank

QD is evaporation from the water in the tank

QE is seepage and percolation losses from the tank

QF is discharge from the tank

S is tank storage volume, and dS the change in volume during period t

i(subscript) is the tank serial number (1-6)

t is the time period.

The tanks do not spill water often during the maha rainy season, but if they do, the quantity spilled needs to be added to the water balance equation. In that case, equation 1 is changed into:

$$QA_{i,t} + QB_{i,t} + QC_{i-1,t} = QD_{i,t} + QE_{i,t} + QF_{i,t} + \underline{QG_{i,t}} + dSi_{i,t} \text{ ----- (1)}$$

COMPONENTS OF THE WATER BALANCE

In sophisticated water balance models, a runoff component is included to estimate the runoff from the catchment area (QA). However, in the case of small watersheds, it was difficult to find sufficiently large watercourses where flow measurements could be made. The runoff model component cannot be developed without actual flow measurements and, therefore, as a stop-gap measure, the average seasonal runoff percentage (computed from flow data estimated by analyzing the water balance) was adopted. Hence:

$$QA = R_{i,t} * CA_i * f_{xi} \text{ ----- (3)}$$

where R is precipitation, CA, the size of the catchment and f_x the average seasonal runoff percentage.

Because most of the TCS were developed in small watersheds and they consist of many small tanks, the catchment area of each tank is rather small. Moreover, the areas of the TCS are flat and the tanks are shallow. The tank area is therefore not negligible compared with the catchment area, as is shown in Table 2. Thus, for this study, rainfall on the tank surface (QB) is separated from runoff flow into the tank (QA).

$$QB = R_{i,t} * WA_{i,t} \text{ ----- (4)}$$

where WA is the surface area of the tank.

The return flow from the upstream tank is important in the water balance of a TCS. but its dependence on topography, soil moisture, daily water management of the upstream tank, etc. is too complicated to model. It was therefore assumed that the return flow flows only into the next tank downstream in a constant ratio. f_z . QC was also taken as a linear function of QE + QF.

$$QC_{i,t} = (QE_{i,t} + QF_{i,t}) * f_{zi} \text{ ----- (5)}$$

where f_z is the average return flow ratio

The evaporation loss from the tank surface area, QD, is given by the following equation:

$$QD_{i,t} = Ep_{i,t} * WA_{i,t} * dt \text{ ----- (6)}$$

where Ep is evaporation from the tank, and dt the time period.

The losses, QE, refer to seepage through the tank embankment and percolation through the bed. Seepage and percolation depend on the water level in the tank, but here it is assumed that the loss ratio, f_y , is a linear function of the tank surface area, as these tanks are quite shallow.

$$QE = f_y \cdot WA_{i,t} \cdot dt \quad \text{----- (7)}$$

where f_y is the seepage and percolation ratio.

QF is the water supply released through the tank outlets within a specified time period.

CALCULATION OF THE TERMS OF THE WATER BALANCE

The water balance for the sample TCS required data on precipitation (R), pan evaporation (**Ep**), tank discharge (QF), and tank storage (**S**). These data were collected during two years. Values of QB, QD, QF, and dS were calculated. The tank water surface area, WA, was obtained from the water level through a rating curve relating surface area and water level.

The terms QA, QC, QE, and the coefficients f_x , f_y , and f_z were arrived at through an iterative process. The first step involved the calculation of QE for the uppermost tank for which QC is nil. The calculation was done for a prolonged dry period for which also QA was equal to zero. The coefficient f_y was then evaluated from equation 7. The same value of f_y was used for the other tanks, and their QC values were then calculated. This, in turn, made it possible to compute QE and hence f_z for each tank from equation 5. These QA values were calculated for rainy periods and the average f_x for each maha season and yala season was found from equation 3.

When the tank was filled to the brim and spilling occurred, two unknowns, QA and QG, remain to be solved. In the case of spilling, the f_x value of the preceding period was used for the calculation of QA. Once QA is known, QG could be calculated. The effect of spilling due to large amounts of runoff in a particular period was sometimes observed to carry over into the next period although no further rainfall had occurred. For the occurrence of spilling, equation 5 had to be modified as follows:

$$QC_{i,t} = (QE_{i,t} + QF_{i,t}) \cdot f_{zi} + QG_{i,t} \quad \text{----- (5)}$$

The length of the period was taken as 5 or 6 days. Shorter periods were not justified considering the measurement error in reading the staff gauges.

DESCRIPTION OF THE STUDY AREA

The six tanks in the Thirappane Cascade do not form a single cascade, but there are four tanks on the main branch of the cascade and two more on a tributary branch. The main cascade, as shown in Figure 4, consists of the Vendarankulama, Meegassagama, Aisthana, and Thirappane tanks. The two on the tributary branch, Badugama and Bulankulama, are much smaller than the other four. The main land use types in the catchment of this TCS are shown in Figure 5. The command areas of Vendarankulama and Bulankulama are joined, creating opportunities for water transfer between them. Drainage water from the Vendarankulama command area can be used by Bulankulama farmers.

Surveys of the command areas were carried out in 1992 (Figures 7-12). A command area varies from one season to another (Table 7). As mentioned before, the lower part of the command area of one

tank runs into the surface area of the next tank because of pressure on the land (Figure 5). The fields are generally quite small, less than 0.05 hectare (ha).

Aerial photographs of the catchment areas were taken in **1982**. The command areas are given in Table 8. Part of the catchment is covered by forest, but the forested area has been decreasing due to slash and burn cultivation. To arrest deforestation, tree planting projects have been introduced in the area. Rating curves of the tanks were based on tank bed surveys carried out in **1992**. In the main cascade, tank size increases downstream (Table 9).

With respect to irrigation construction and management, the area is under the jurisdiction of the Department of Agrarian Services (DAS), which is responsible for minor irrigation works in systems with command areas of less than 80 ha. The total irrigated area of each tank is planned at the beginning of each season during farmers' meetings in the presence of officers of DAS. Each tank community conducts its own meeting. Otherwise, the systems of this TCS are owned and managed by the farmers. Formerly DAS was a central government department but, in recent years, its functions have been transferred to the provincial government and, more recently, to the Divisional Secretariat in Thirappane.

Rice is the dominant crop during maha with some other field crops, such as chili and soybean, on upland fields. During yala, the proportion of field crops is higher than in maha because of water shortage. The proportion of cash crops has been increasing recently with an increase of privately owned wells. The rice cultivation calendar is given in Figure 13. Direct seeding of rice is widely practiced although DAS favors transplanting to intensify cultivation.

Figure 14 presents a simplified picture of the water delivery system. There are two types of outlets from the tank, "tower outlet" and sluice gate. The tower outlet is used in the smallest tanks and allows water to flow from a hollow tower consisting of rings: as the water level rises or falls, the operator can add or remove rings to keep the tower top close to the water level, but no other control is possible. On the larger tanks, various sluice gates are used.

Rotational delivery of water to several blocks is often intended but it is poorly implemented because of inadequate infrastructure. In some cases, main canals are provided with cross-regulators. As shown in Figure 14, plot-to-plot irrigation takes place through temporary watercourses. The drainage arrangements are often not clear. Farmers *sometimes* obstruct the drainage flows to irrigate fields not reached by the irrigation water.

Small tractors are used for land preparation, which nevertheless usually takes over 30 days to complete in maha contrary to the official standard of **15** days. Farmers are anxious to ~~finish~~ the work as early as possible to make it possible to complete harvesting before the April rains. The main soil type in the area is low-humic grey soil, which is of low permeability. The standard irrigation interval is 7 days and the average application is 75 mm.

DATA COLLECTION

The schedule of data collection in the sample area is shown in Figure 15. Data were collected from the middle of November **1991**. Staff gauges were installed in all tanks to monitor changes in water level. Five rain gauges were installed in the sample area. Thirteen Parshall flumes were installed at the outlets to the command areas. One evaporation pan (**120** cm in diameter) was located near the right bank of Meegassagama. The evaporation value obtained here was used for the tank evaporation in equation 6.

DATA ANALYSIS

The storage, rainfall and tank discharge for five tanks are presented in Figures 16-20. Spilling from all tanks occurred on 30 December 1991. In mid-January, the rains suddenly stopped and a long dry spell continued until mid-April. During this period, runoff into the tanks almost stopped while tank discharge rose to compensate for the lack of rain. Tank storage dropped sharply as outflow exceeded inflow. In mid-March, the maha irrigation season was virtually over. Tank discharge declined, and the rate of decline in water storage slowed considerably.

Rainfall returned in mid-April and water volumes in the tanks rose again. However, it did not reach a sufficient level as runoff had decreased markedly during the long dry spell. Consequently, in most command areas, farmers were obliged to sharply reduce the areas under irrigation (Table 7). The rate of decline in water storage was much less than during the dry spell of maha as a result of the smaller irrigated areas. With the start of the rainy season in October, most of the rain infiltrated to increase soil water content and hence runoff remained small. The volumes of water stored in the tanks rose only slowly until early November. Spilling did not occur during this second maha season as the rainy season was shorter and rainfall intensity less than the year before. Discharges from the tanks are given in Table 1D. Because of the lower discharges, the cultivated areas in four of the command areas were also less than those for the year before (Table 7). Farmers tried to cope with the situation by planting short-term varieties of rice, and as some circumstantial evidence shows, by paying more attention to daily water management. As in the previous maha, rains ceased in January. Although there continued to be a few showers, tank storage showed the same trend as before but the dead storage volume was reached nearly one month earlier than in the first year of observations.

Precipitation during the initial stage of yala was also less than that in the previous yala season (Table 12). Water storage in most of the tanks hardly responded to the rains due to the markedly lower runoff. Because of the low water levels at the end of April, rice cultivation in 1993 yala was abandoned in all the command areas.

COMPUTATION OF THE COEFFICIENTS

As indicated before, the average f_y value was obtained from the water balance of the Vendarankulama tank. The values were 4.7 mm/day in the 1991/92 maha and 4.8 mm/day in the 1992/93 maha. Considering that the dry spell was longer and not interrupted by any showers, 4.7 mm/day has been used for f_y throughout the model. The f_z value of yala was taken as zero because both QE and QF were small during this season. The f_z values for maha for the other tanks are given in Table 13. The f_z of Bulankulama could not be determined because it was not possible to measure QF for this tank.

The values of f_x are given in Table 14. The values show a consistent difference between maha and yala and between the two years of observations.

SIMULATIONS OF THE WATER BALANCE

Simulations of the water balance were carried out according to the format of Table 15. Although the time span of the water balance analyses was five or six days, simulations were run with a one-day time

period. The tank rating curves (relating volume of storage with water level height) are presented in Figure 21.

First, tank storage was simulated for the existing conditions. Comparison between actual and simulated storage assesses the validity of the model (Figures 22 and 23). As can be seen from the graphs, the difference between simulated storage and actual storage was greater during rainy periods than during dry spells, and greater during the first year than the second year. This is due to the inherent weakness of the simple runoff model used in the water balance model. However, the agreement was obviously sufficient to use the model for the assessment of management changes. (See Annex 2 for a more detailed analysis of the simulation model.)

Three simulations are reported here. The first deals with the possibility of raising the crest level of the Meegassagama tank in order to enhance its storage capacity. Spilling of water occurred in all tanks during the 1991/92 maha season, which indicates that there could be scope for increasing tank storage capacities. The simulation was carried out with the first year's data, subject to the following conditions:

- * Raising the crest level of the Meegassagama tank should not diminish the storage achieved in the other tanks.
- * Discharge QF should increase at the same rate as extension of the command area.
- Extension of the command area is limited only during maha.
- Simulated storage should not decrease below actual storage at the end of March.

The results of the simulation are shown in Figure 24. It is shown that the crest level could be raised by about 60 cm without adversely affecting storage in the other tanks of the cascade. The concurrent increase in command area of Meegassagama tank is 39 ha.

The second simulation involved the possibility of enhancing storage in the Alisthana tank, also based on the first year's data and subject to the same set of conditions as in the first simulation. The results are shown in Figure 25. It was found that the crest level could be raised by about 30 cm, increasing the command area by 16 ha, without affecting storage in the other tanks of the cascade.

The third simulation examines the possibility of combining the Vendarankulama and the Meegassagama tanks, based on the second year's data. Peak storage in all tanks was extremely low during the second maha season, but especially in small tanks such as Vendarankulama and Bulankulama. In these two tanks, storage was reduced to the dead storage before the end of February. Subsuming the storage of Vendarankulama in Meegassagama could result in slowing the rate of decrease in storage and hence of abandoning farm land for lack of water in late yala. Costs of operation and maintenance would also be reduced. The simulation was carried out subject to the following conditions.

- * Simulated tank storage should not decrease below actual storage at the end of March
- * Discharge from the tank should increase at the same rate as extension in command area

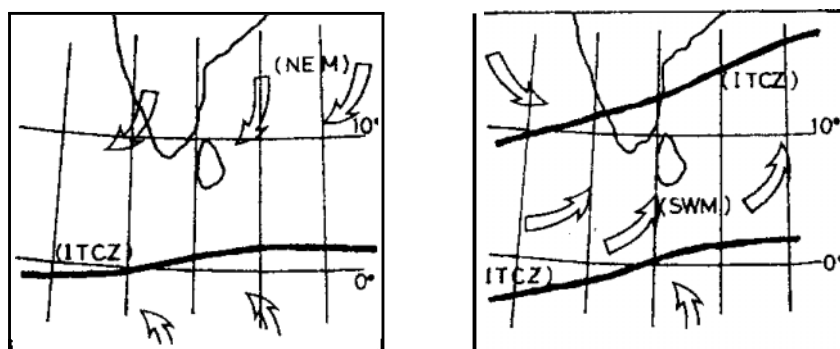
The results are presented in Figure 26. Only 4 ha of the combined command areas of the two tanks was lost although the reuse of return flow was markedly reduced.

CONCLUSIONS

It was shown in the paper that the simple water balance model applied to the sample tank cascade can help to assess possible improvements in managing water that aim to enhance the usable fraction of rainfall in the catchment area. It was found to be important to consider **the** water management of all tanks of a cascade together in an integrated manner.

The water balance model, certainly if a more satisfactory rainfall-runoff model is incorporated, is a useful decision support tool **to be** used in operating tank cascades optimally. The type of analysis described in **the** paper would also help in identifying which tanks should be rehabilitated in a rehabilitation program, and what kind of changes to make.

Figure 1. Monsoon circulation.



ITCZ = Inter-Tropical Convergence Zone

NEM = Northeast Monsoon (October - February; corresponds to the maha season)

SWM = Southwest Monsoon (May - September corresponds to the yala season)

Figure 2. Dry and wet zones of Sri Lanka.

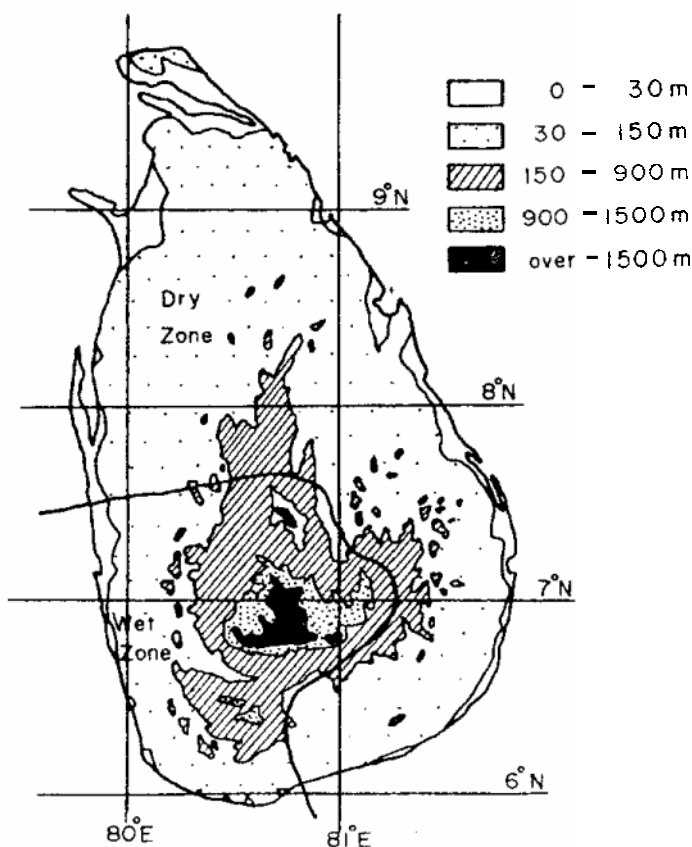


Figure 3. Tank cascade irrigation system.

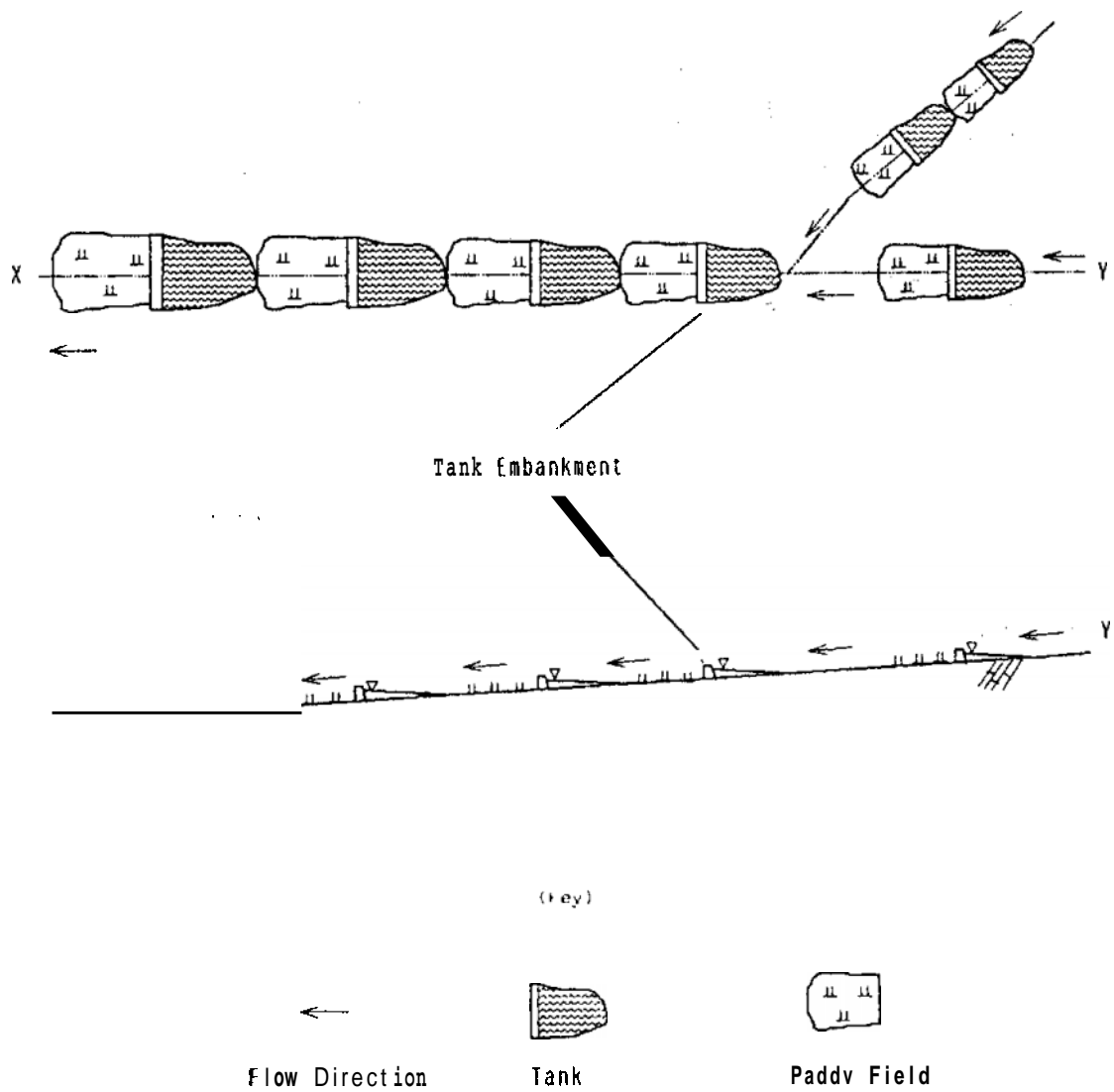


Figure 4. Nachchaduwa Dam and neighbouring tank cascade systems.

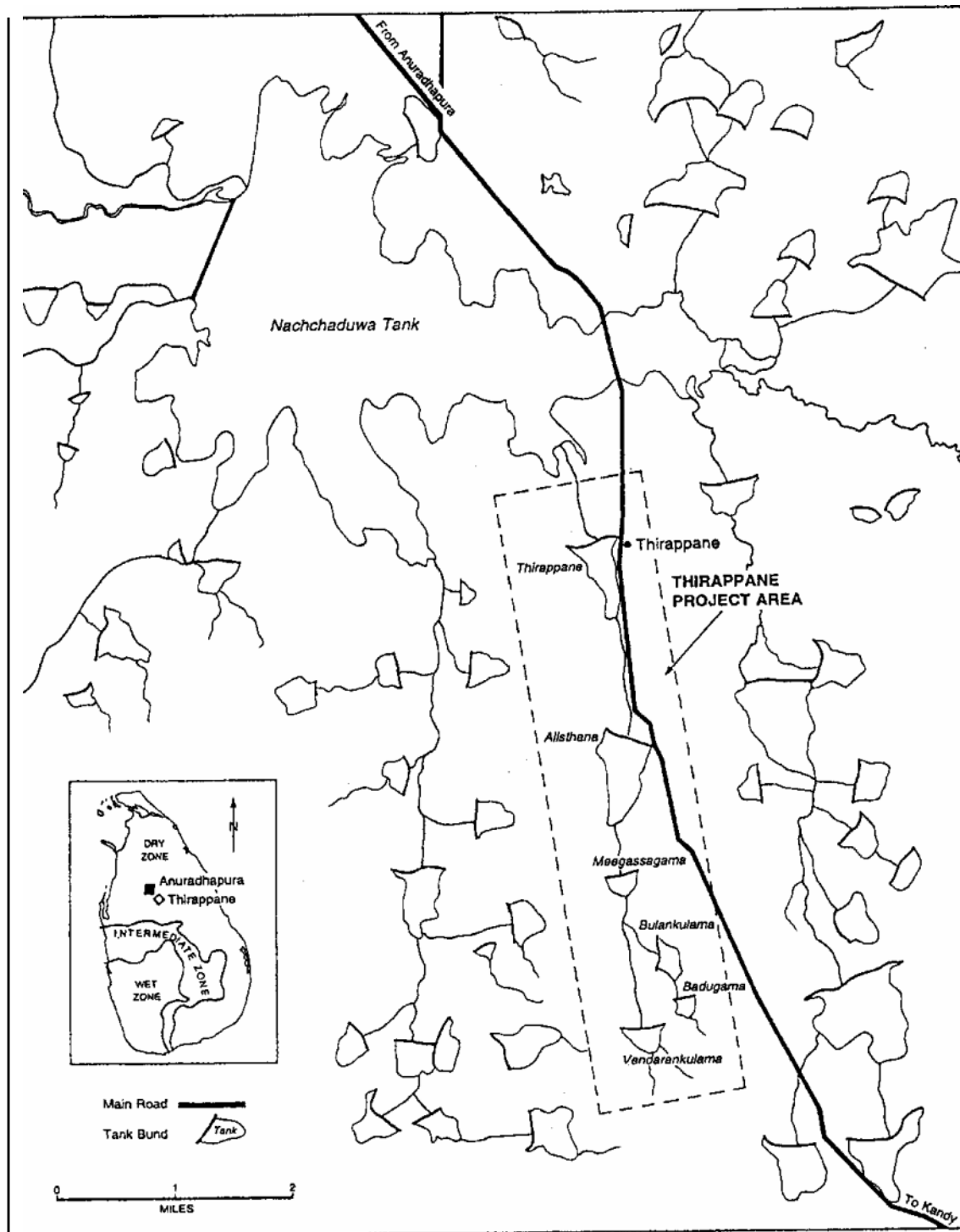


Figure 5. Land use in catchment of Thirappane Cascade.

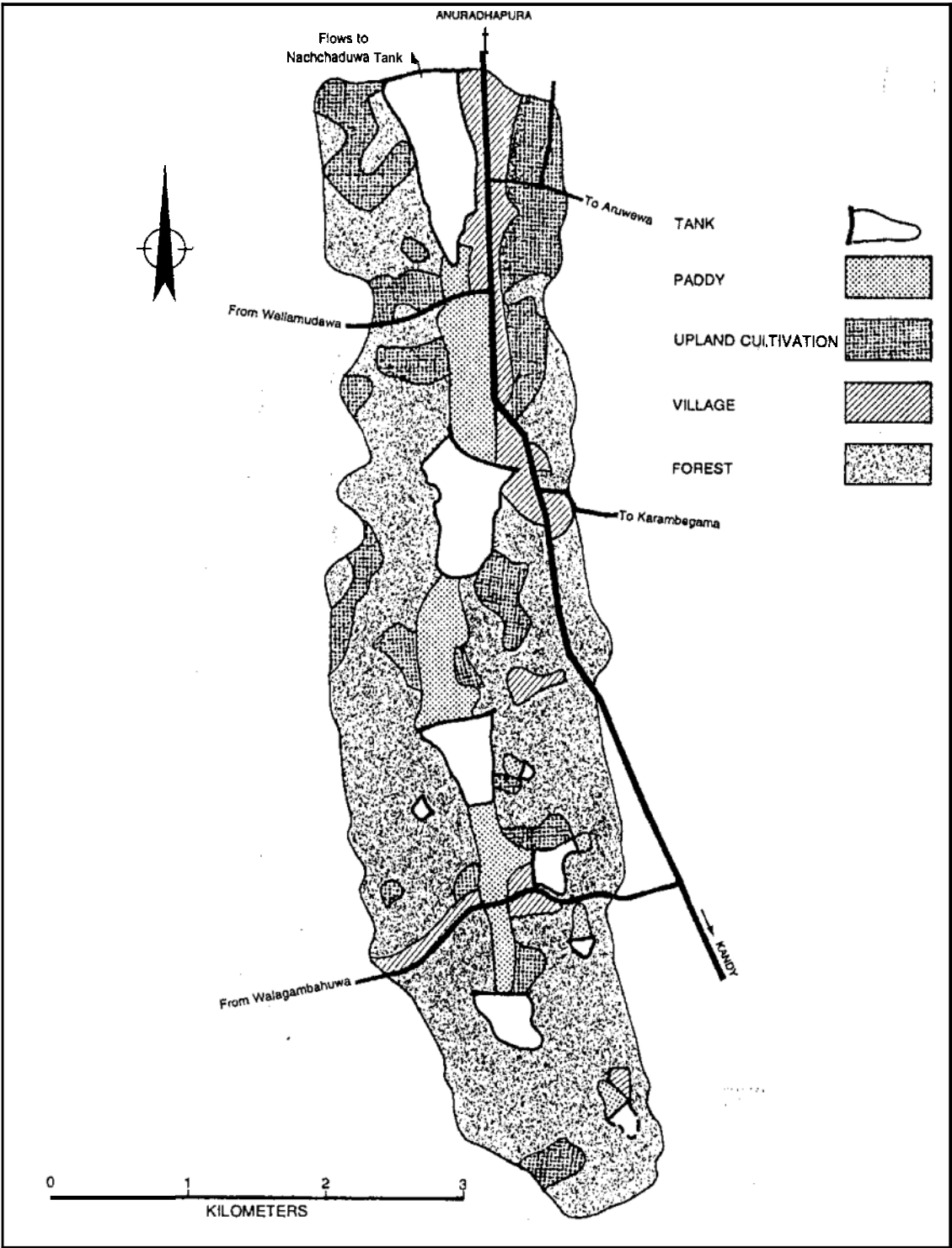


Figure 6. Structure of water balance model.

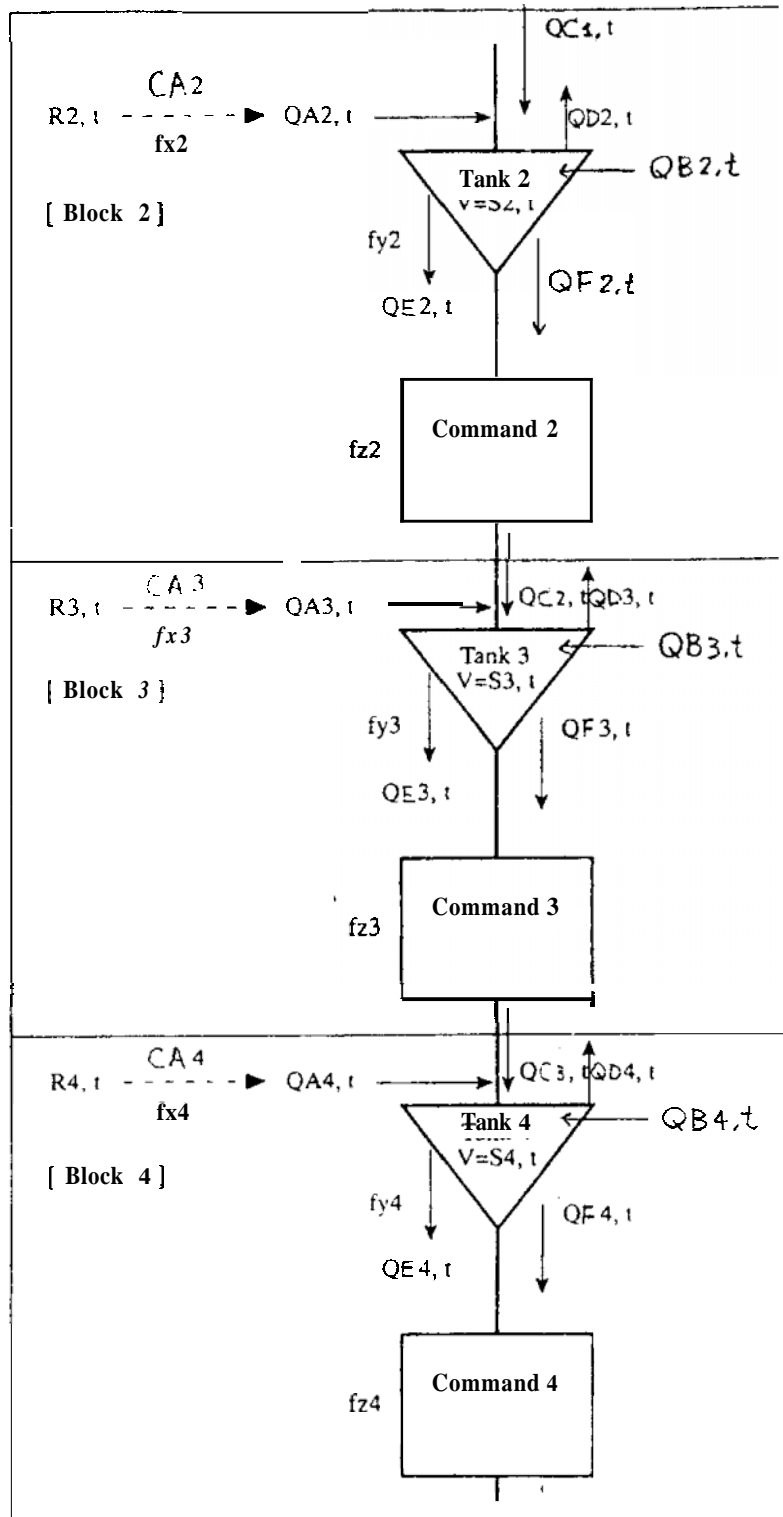


Figure 7. Command area of Vendarankulama Tank.

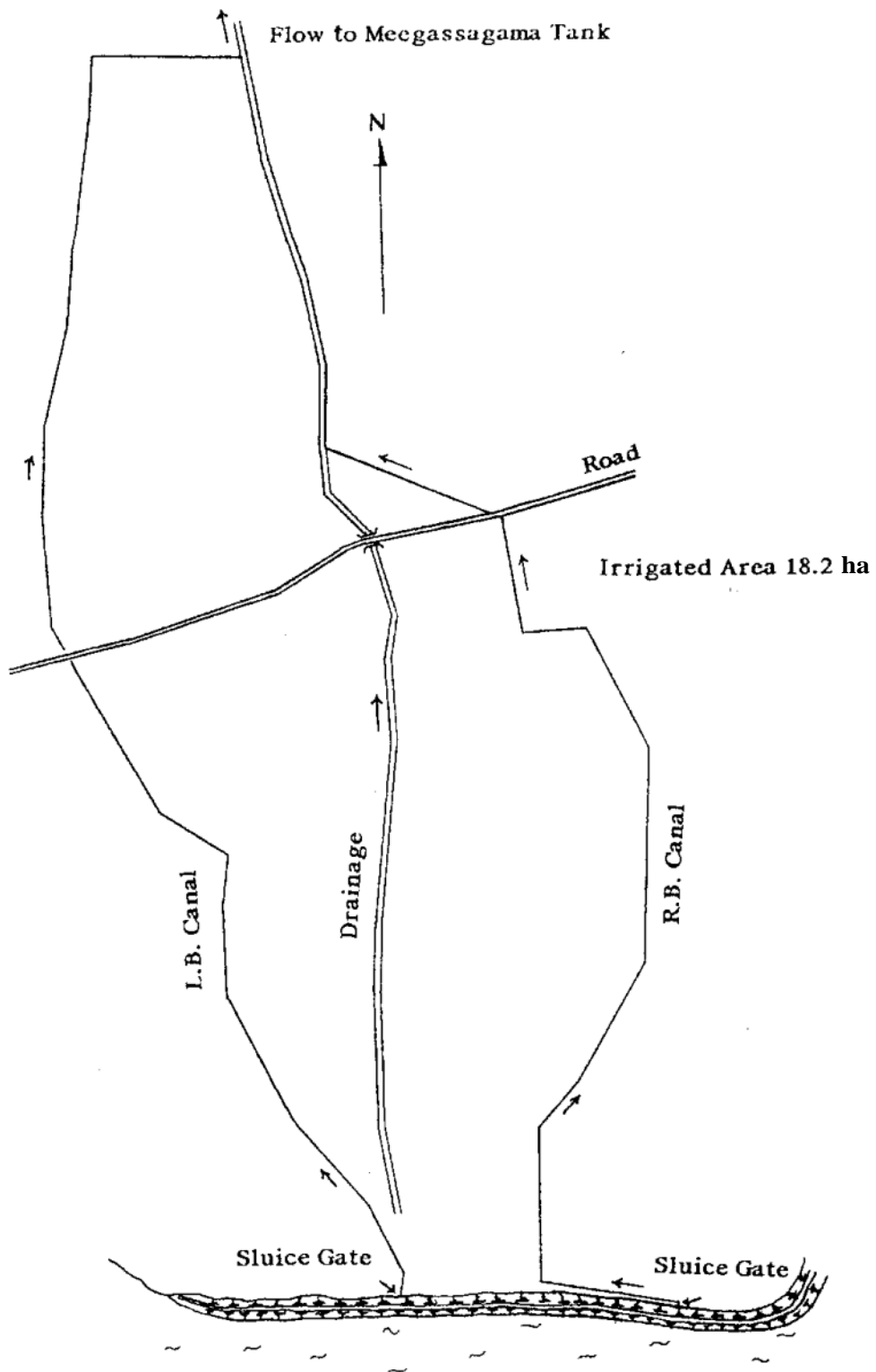


Figure 8. Command area of Meegassagama Tank.

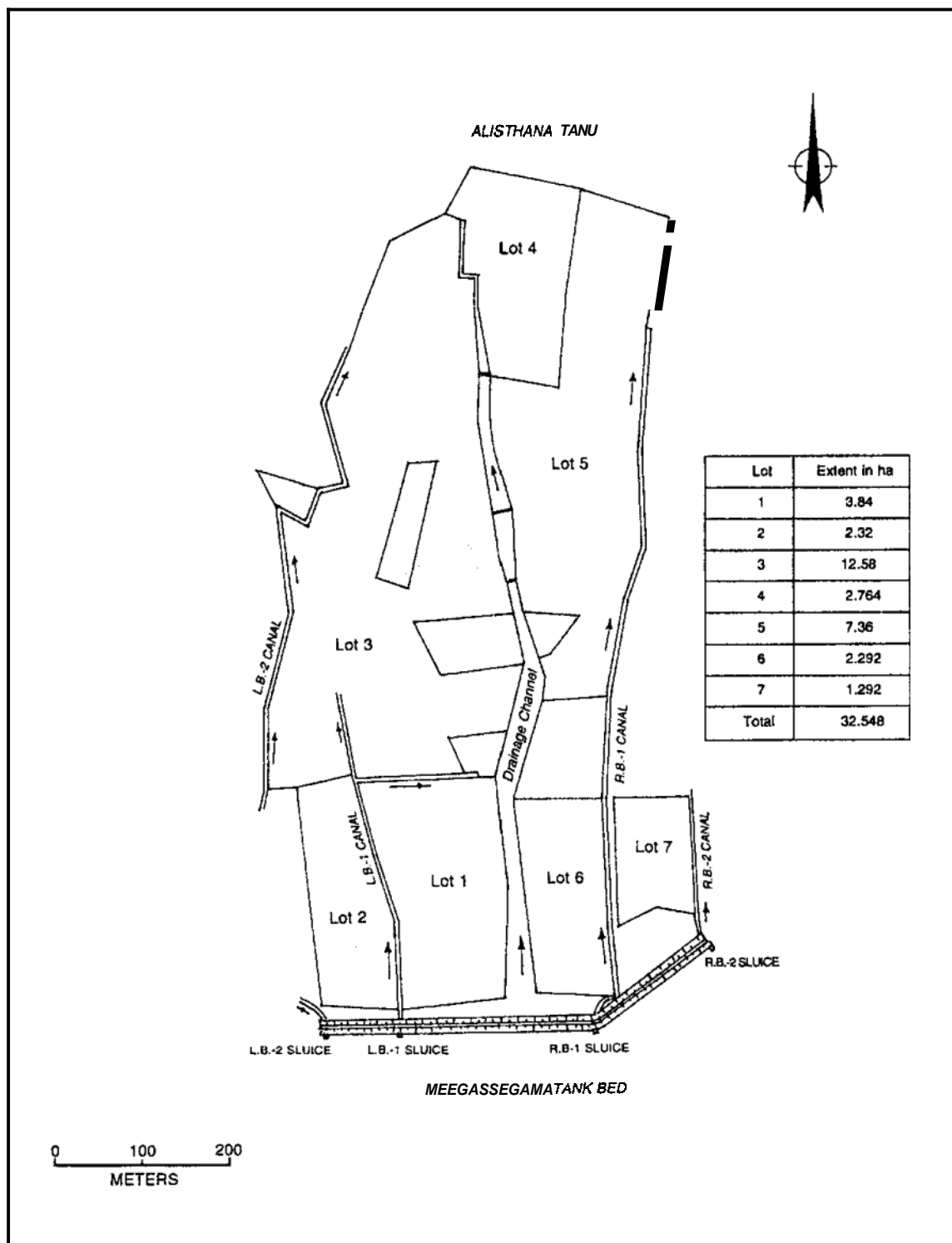


Figure 9. Command area of Alisthana Tank.

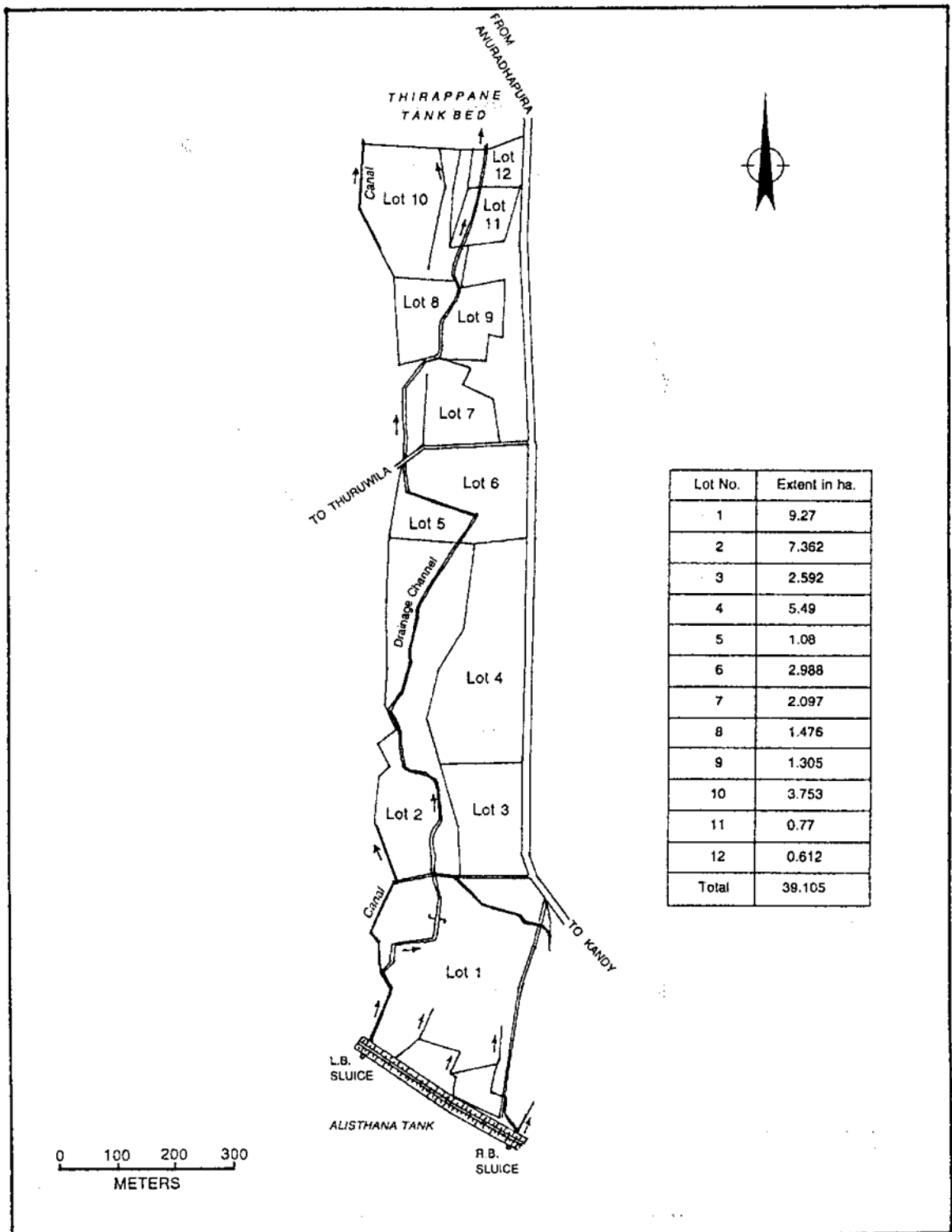


Figure 10. Command area of Thirappane Tank.

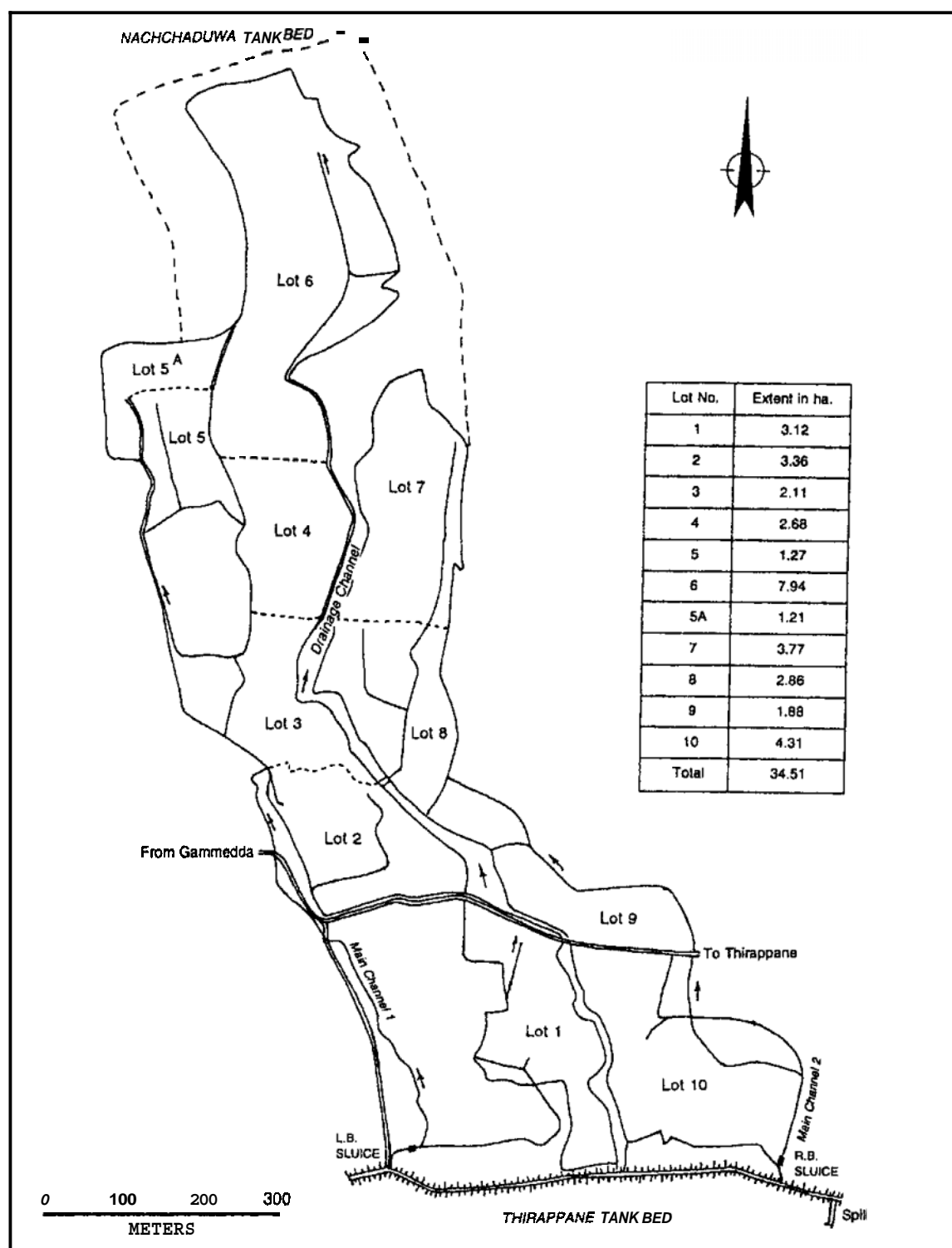


Figure 11. Command area of Badugama Tank.

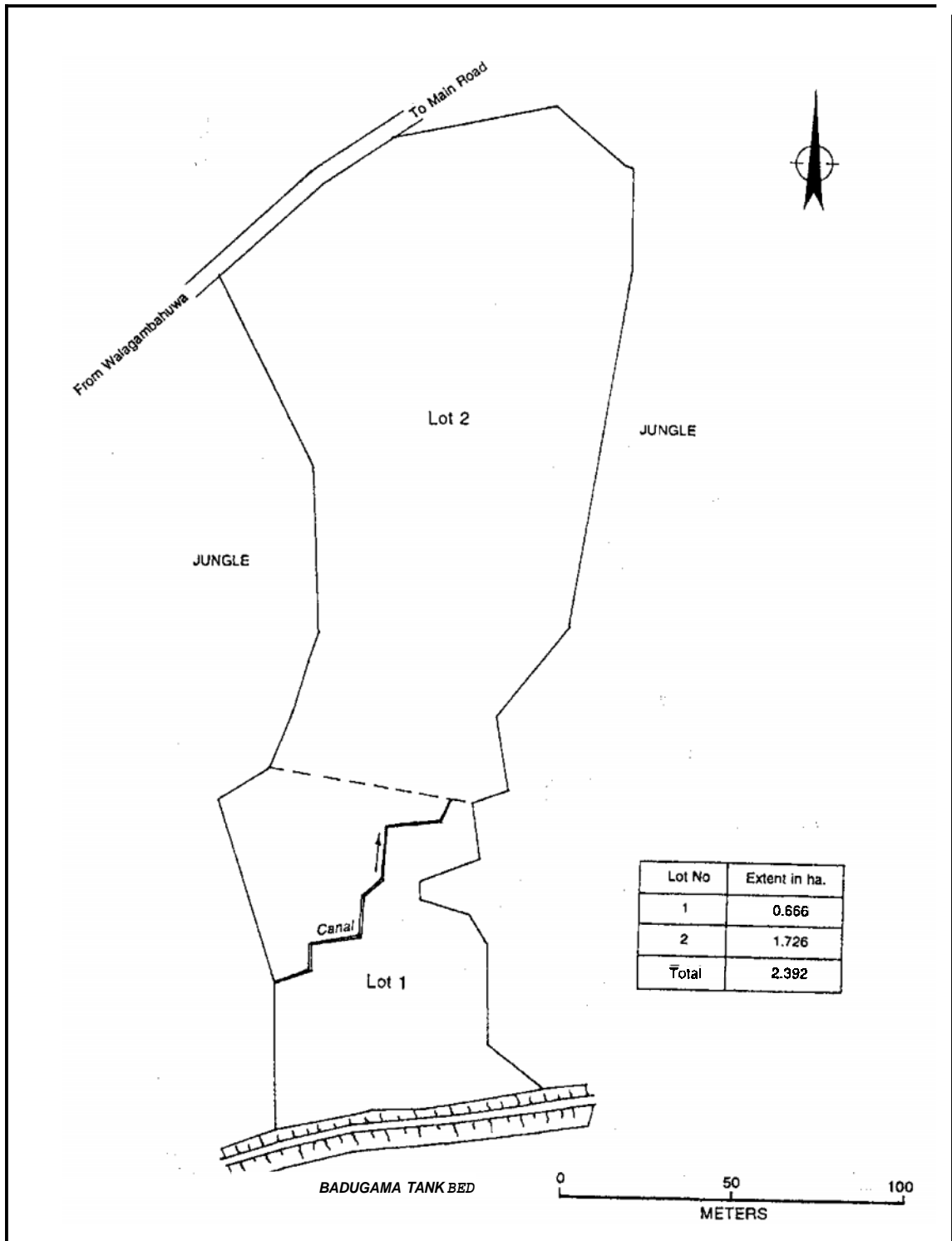
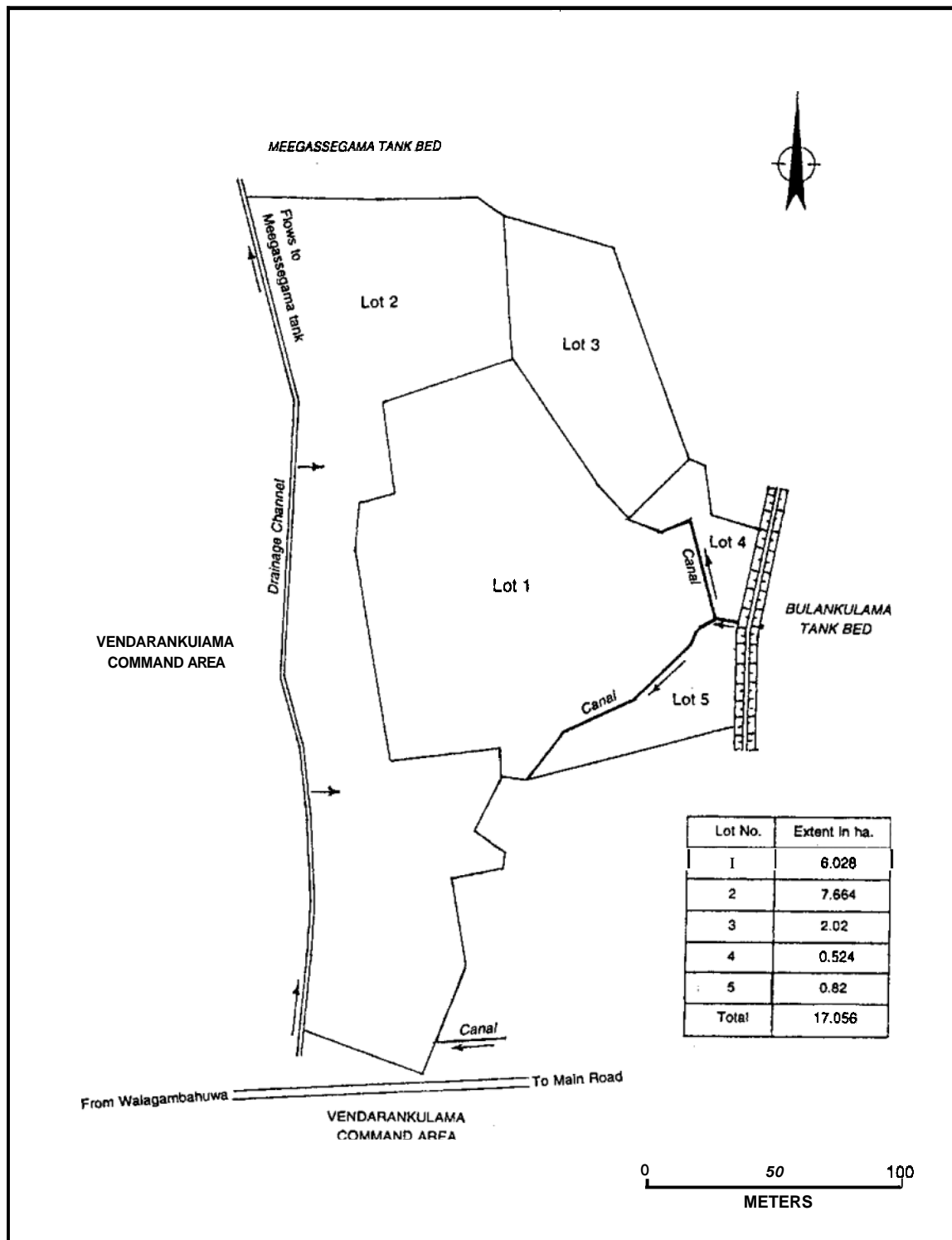


Figure 12. Command area of Bulankulama Tank.



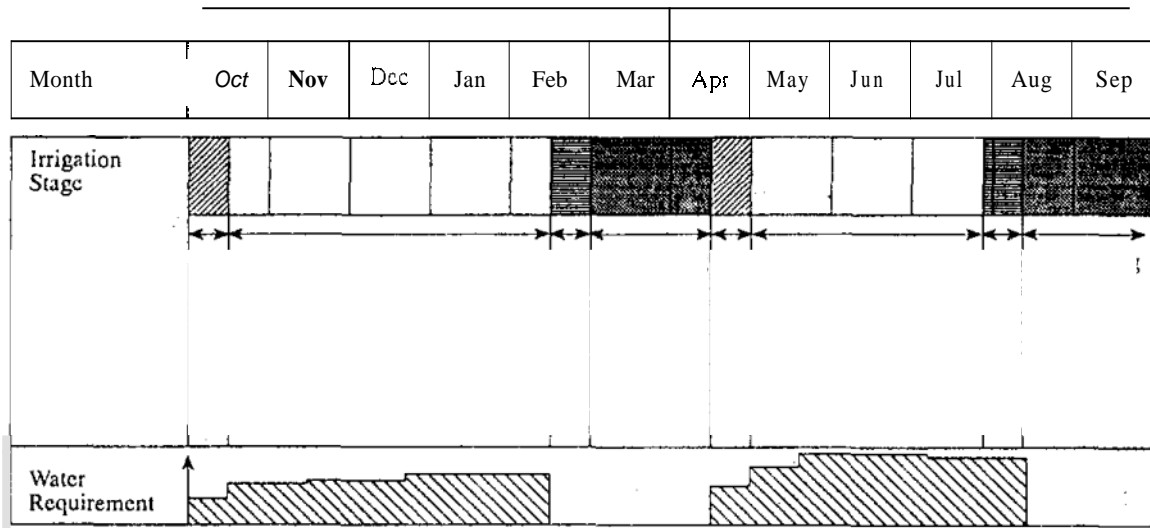


Figure 14. Water delivery system.

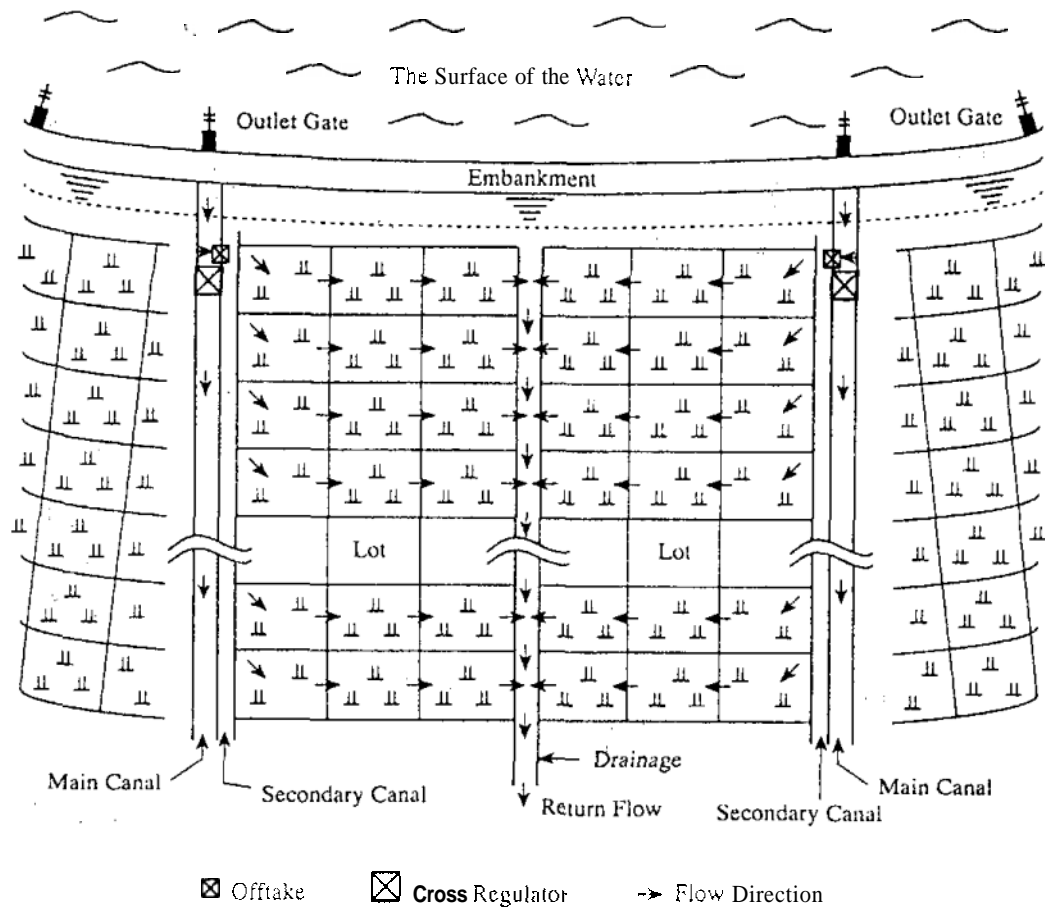


Figure 15. Data collecting system.

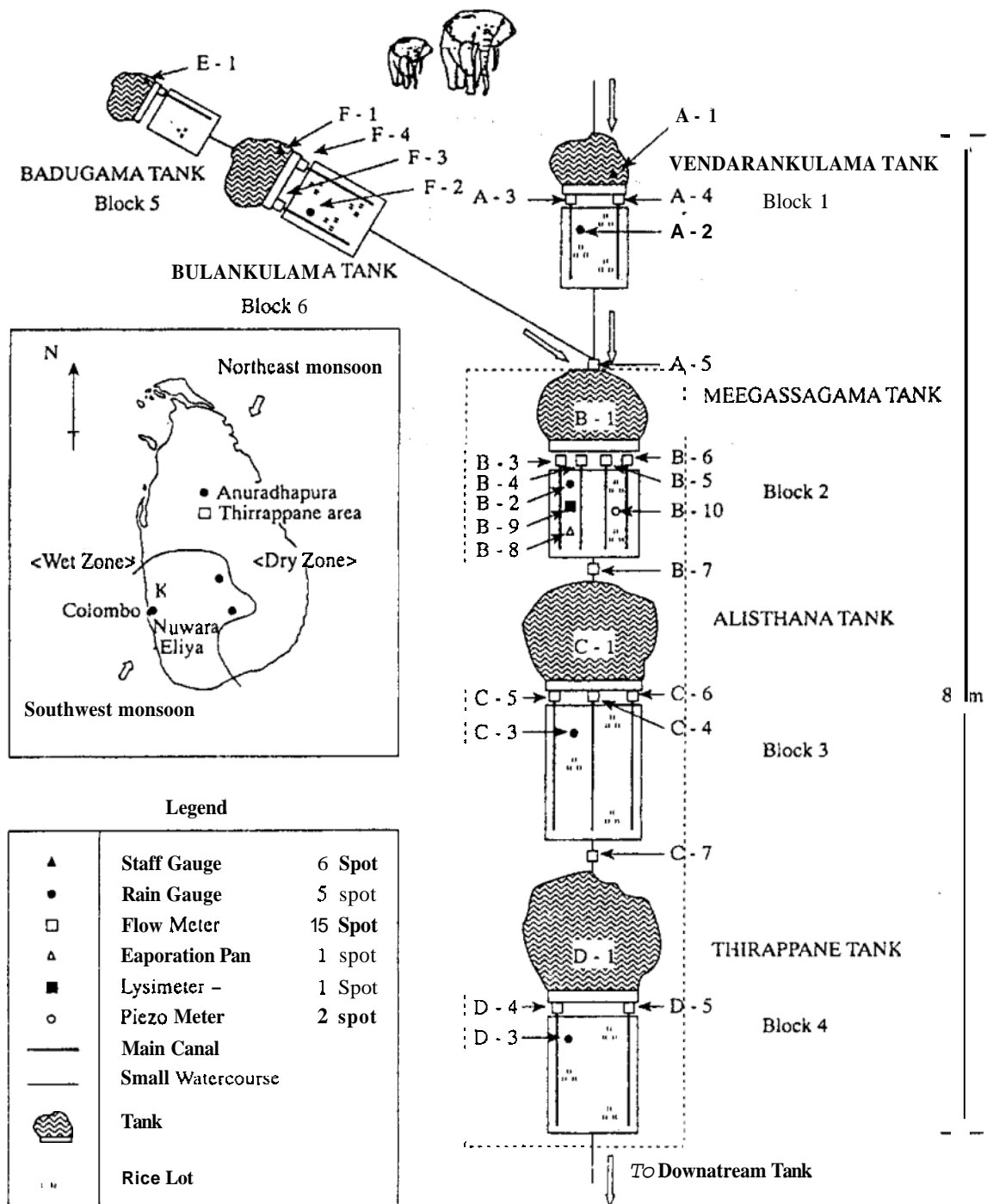


Figure 16. The linkage among S , R , and QF at Vendarankulama.

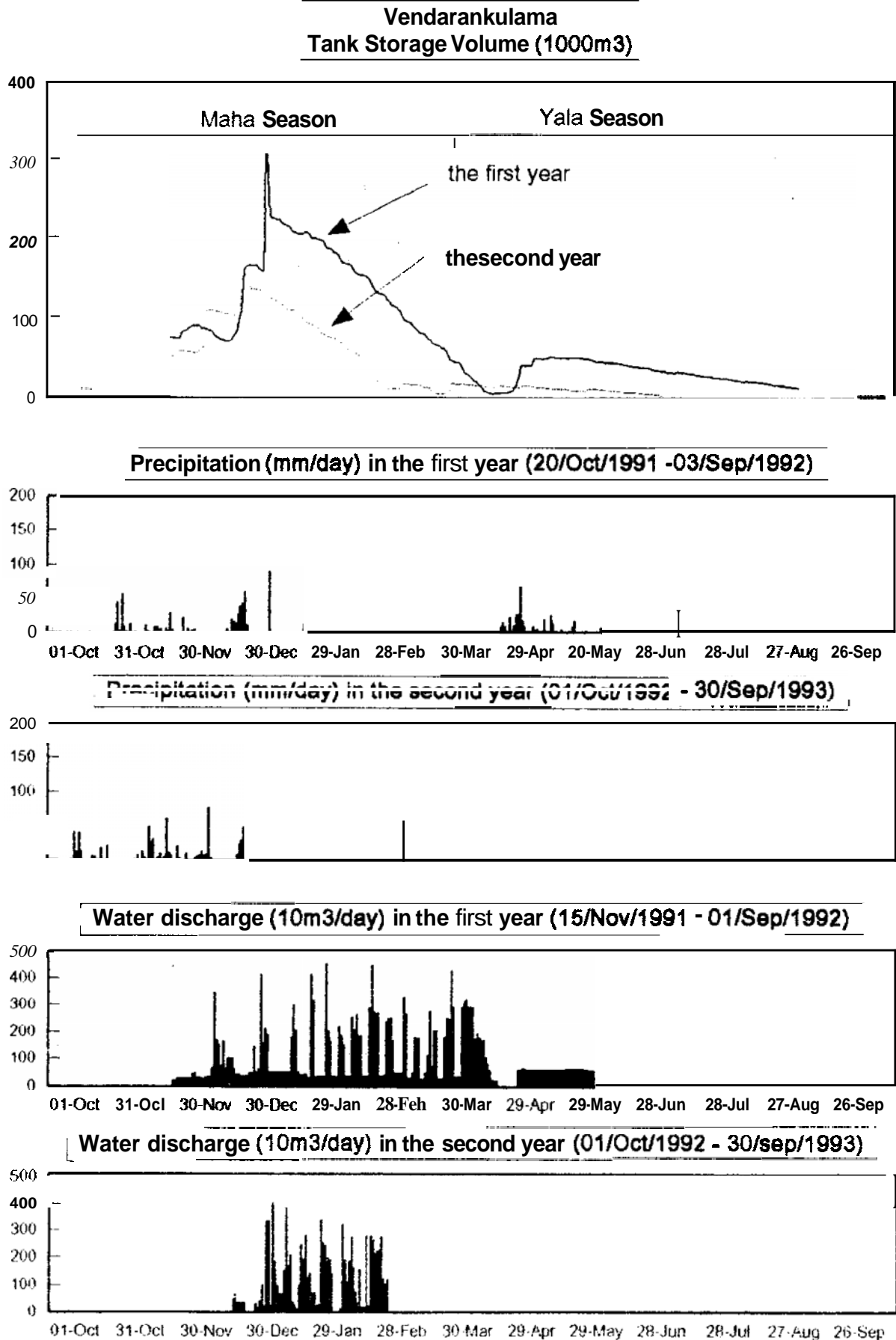


Figure 17. The linkage among S , R , and QF at Bulankulama.

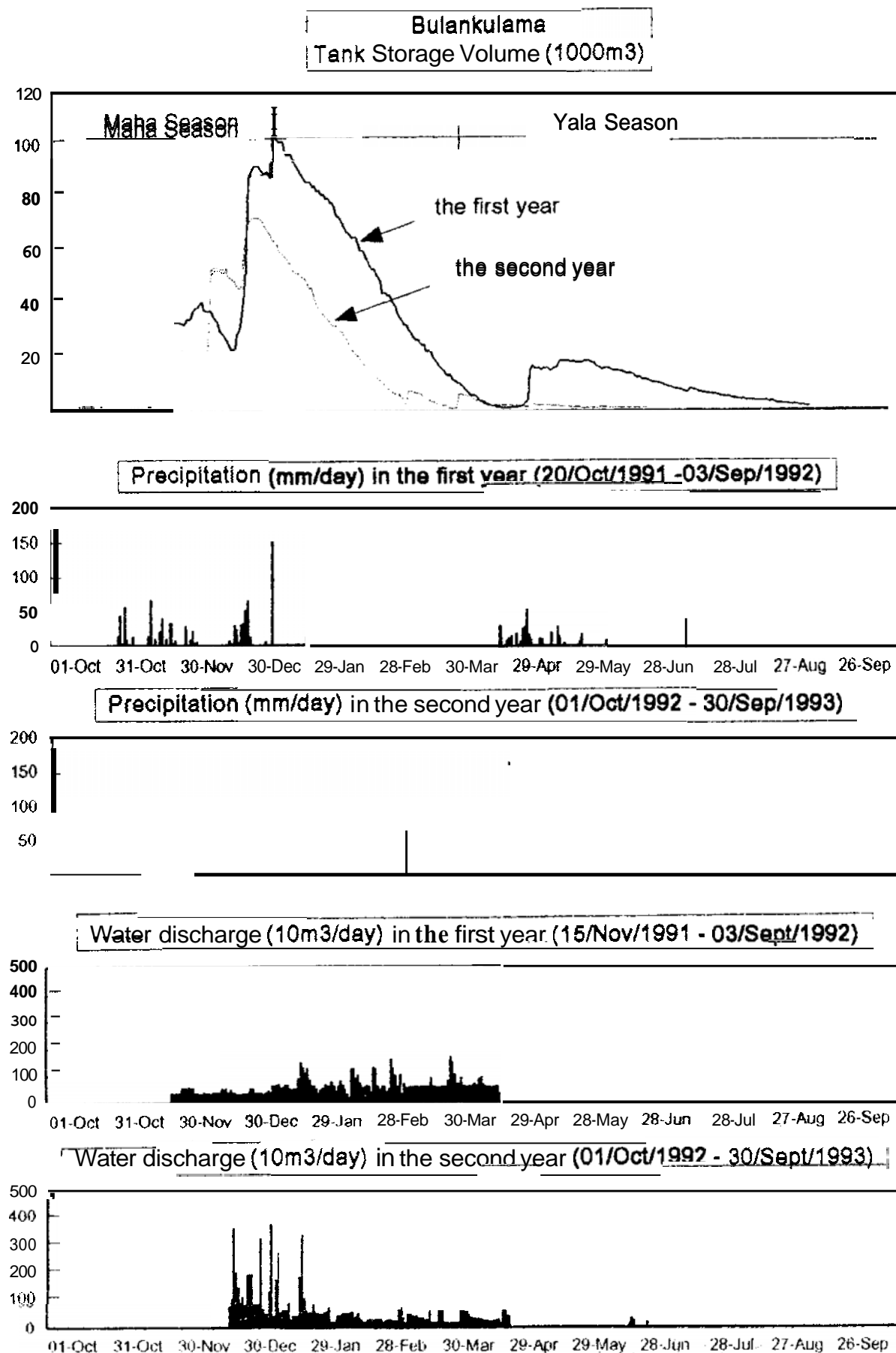


Figure 18. The linkage among S,R, and QF at Meegassagama.

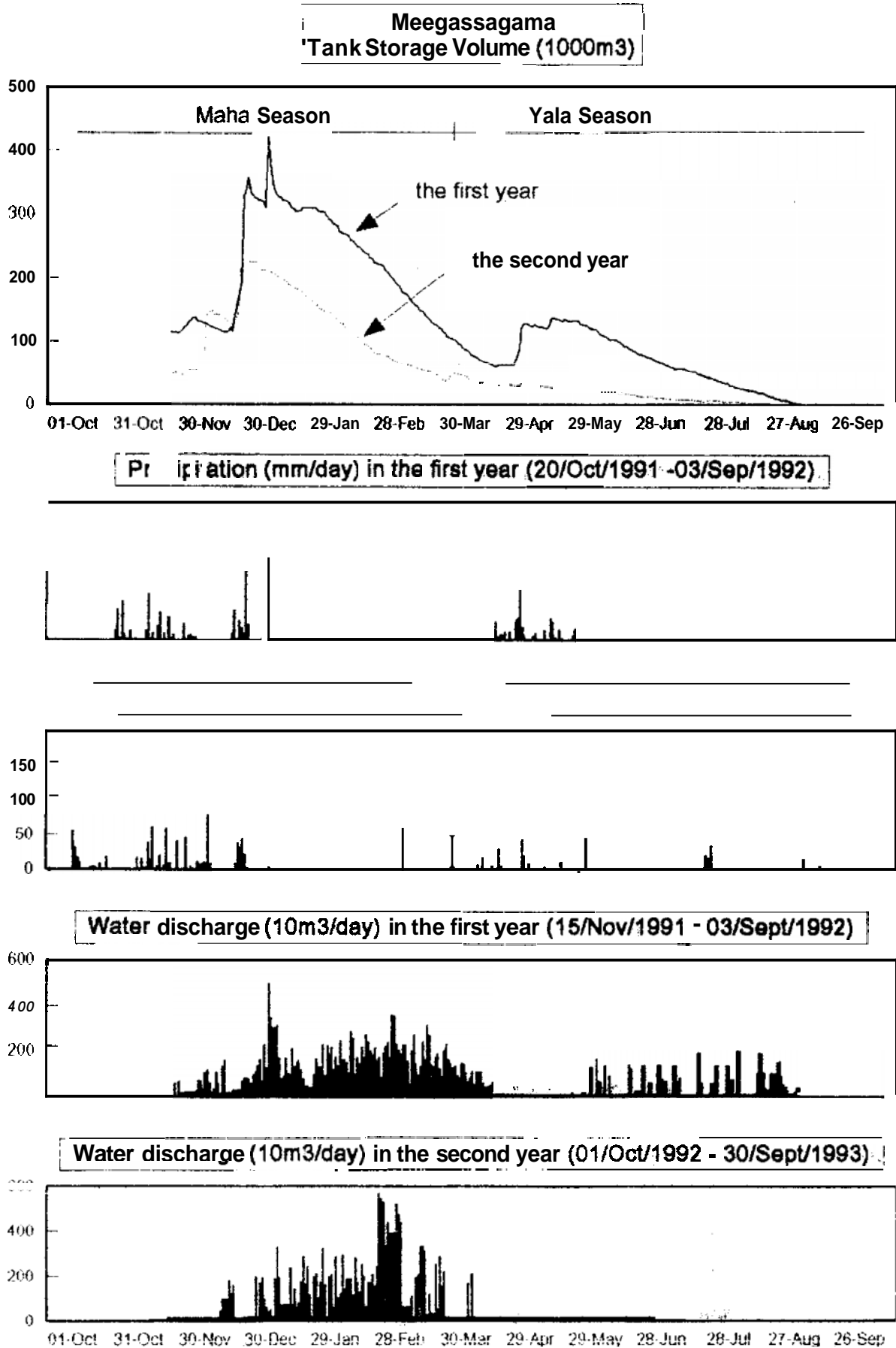


Figure 19. The linkage among S,R, and QF at Alisthana.

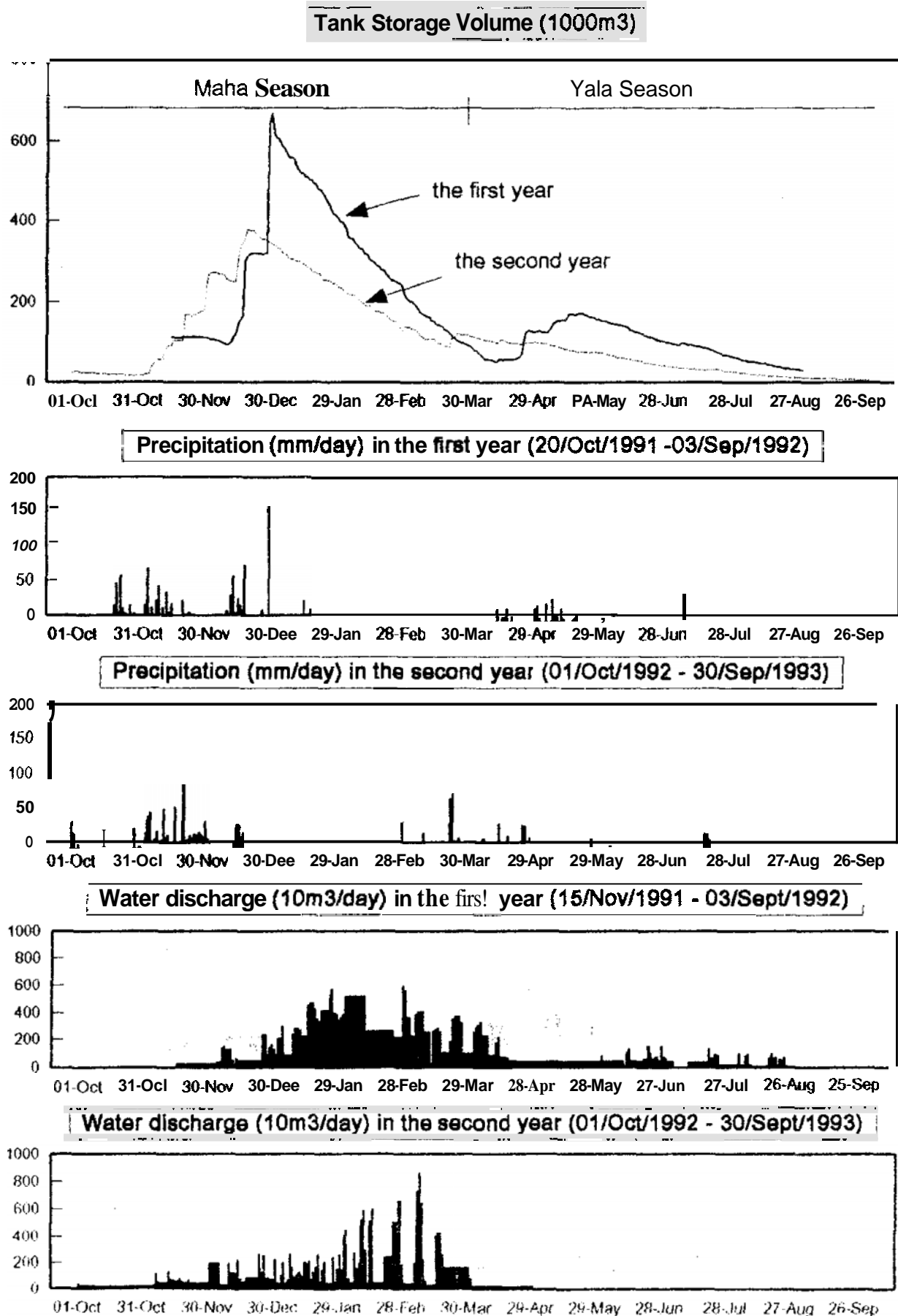


Figure 20. The linkage among S, R, and QF at Thirappane.

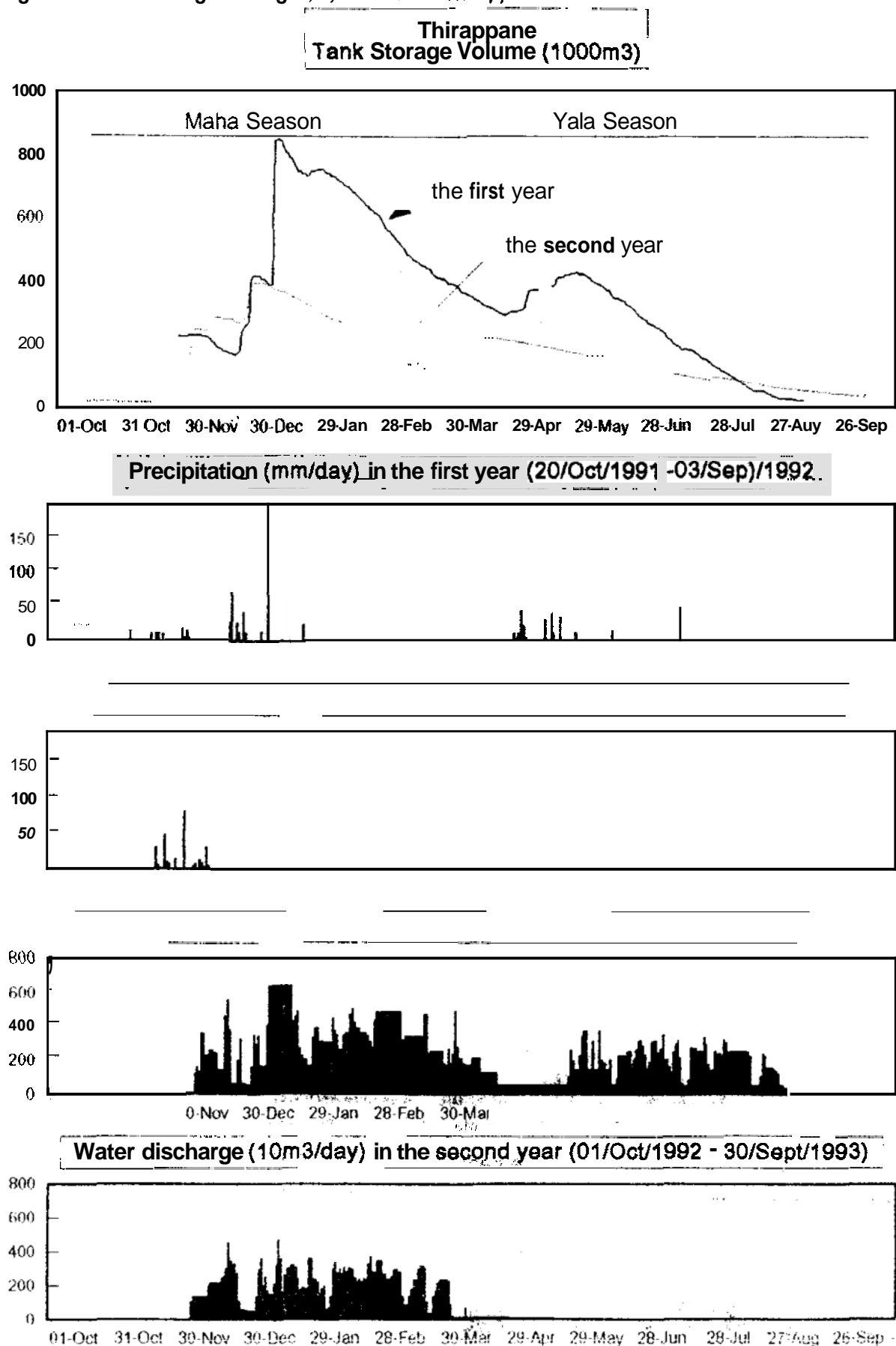
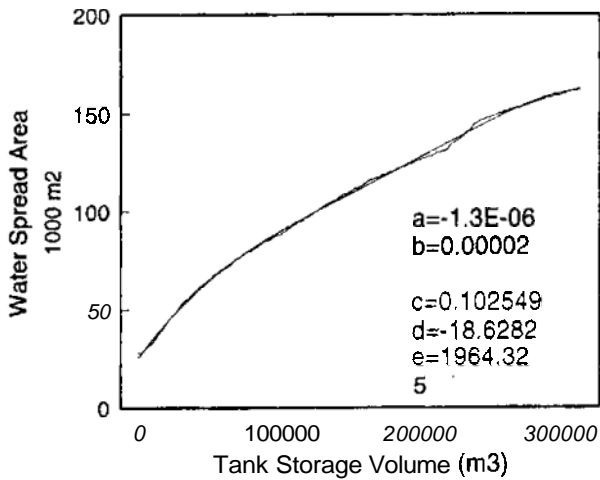
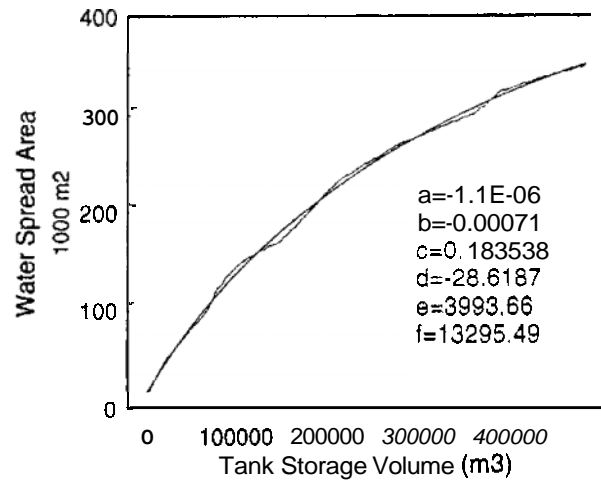
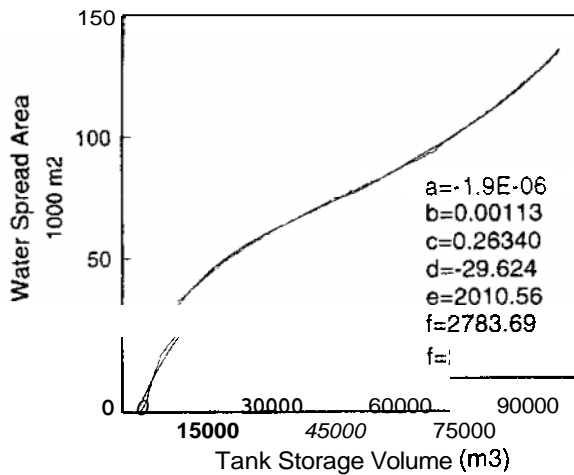
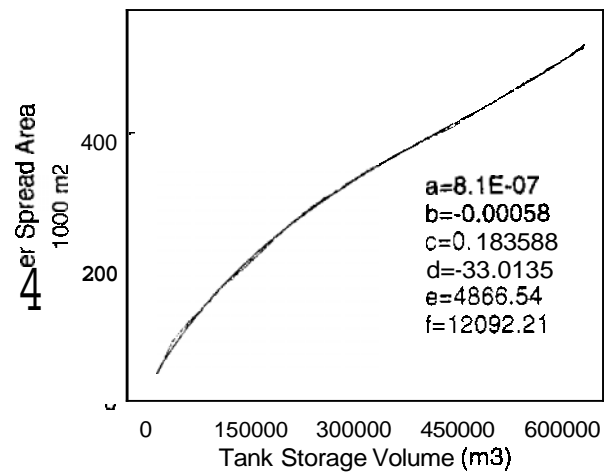
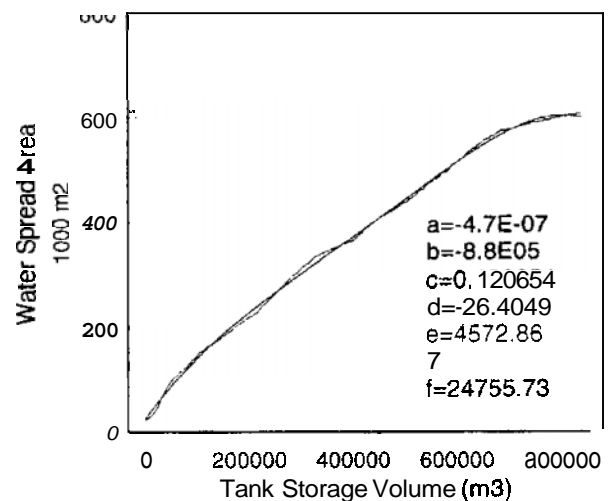


Figure 21. V-A Regression curves.

Vendarankulama**Meegassagama****Bulankulama****Alisthana****Thirappane**

— Actual curve

— Regression curve

$$y = ax^5 + bx^4 + cx^3 + dx^2 + ex + f$$

Figure 22. Simulation in the existing condition (the first year)

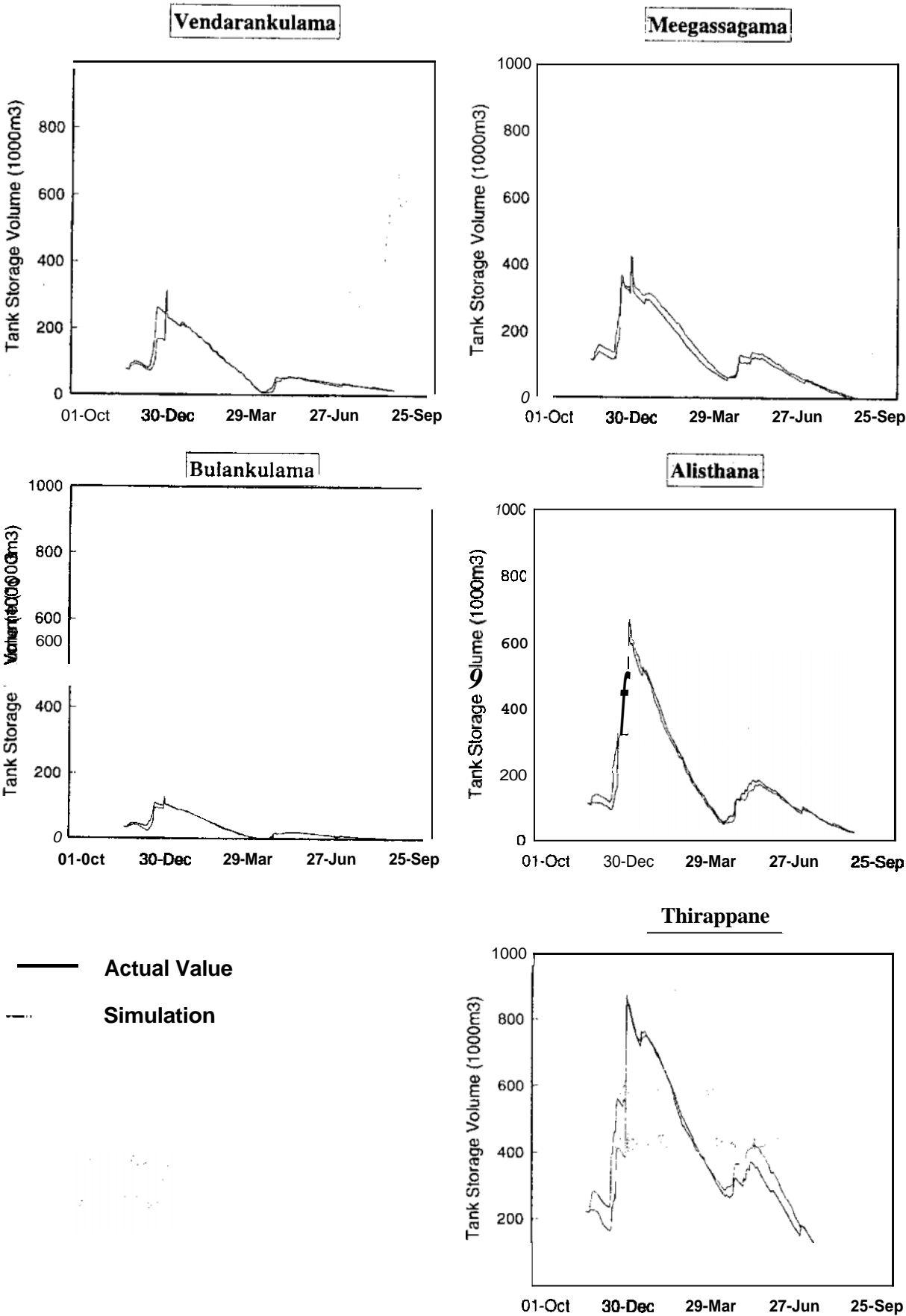


Figure 23. Simulation in the exiting condition (the second year).

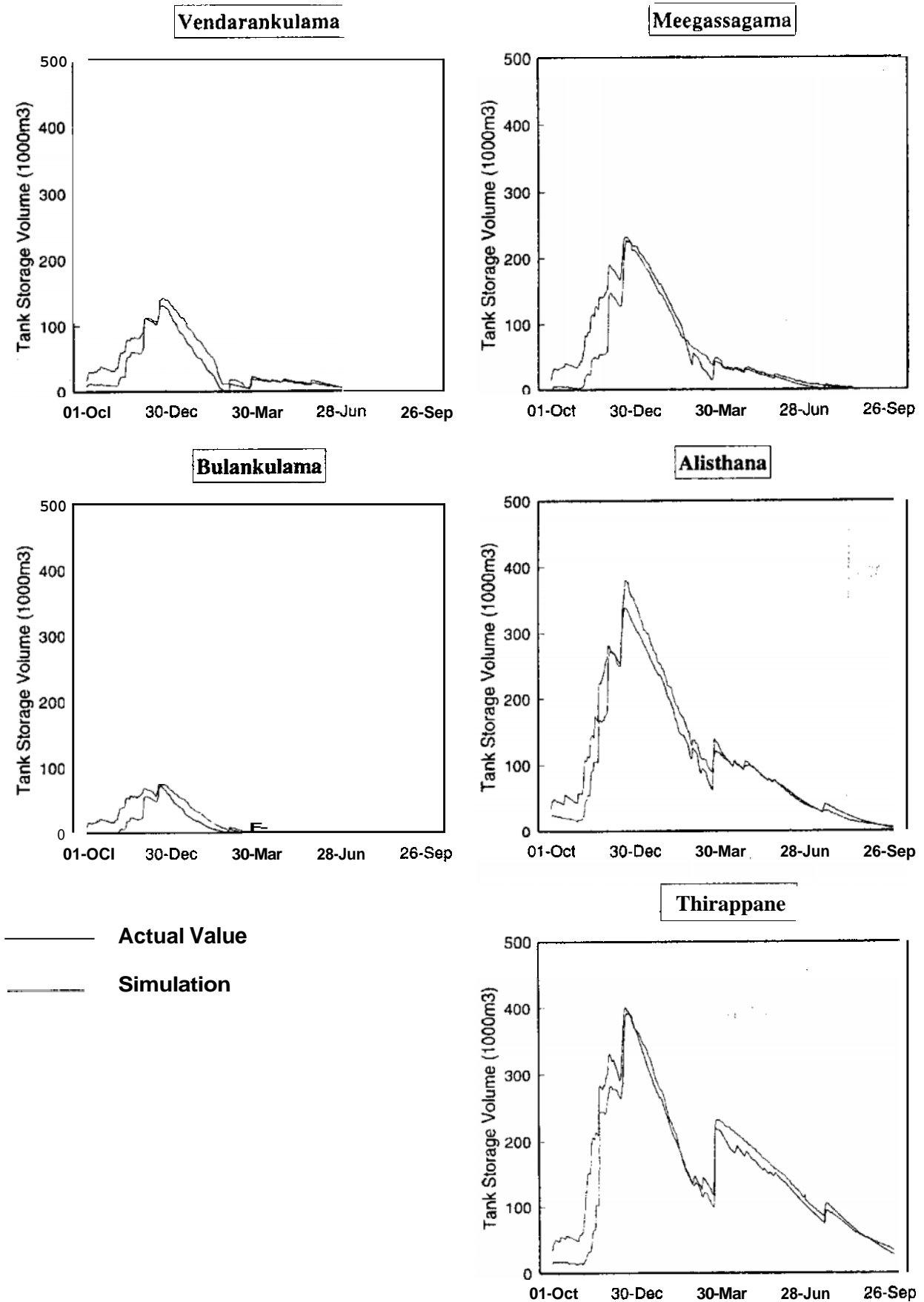


Figure 24. Planning simulation Case 1: Raising crest level in Meegassagama tank.

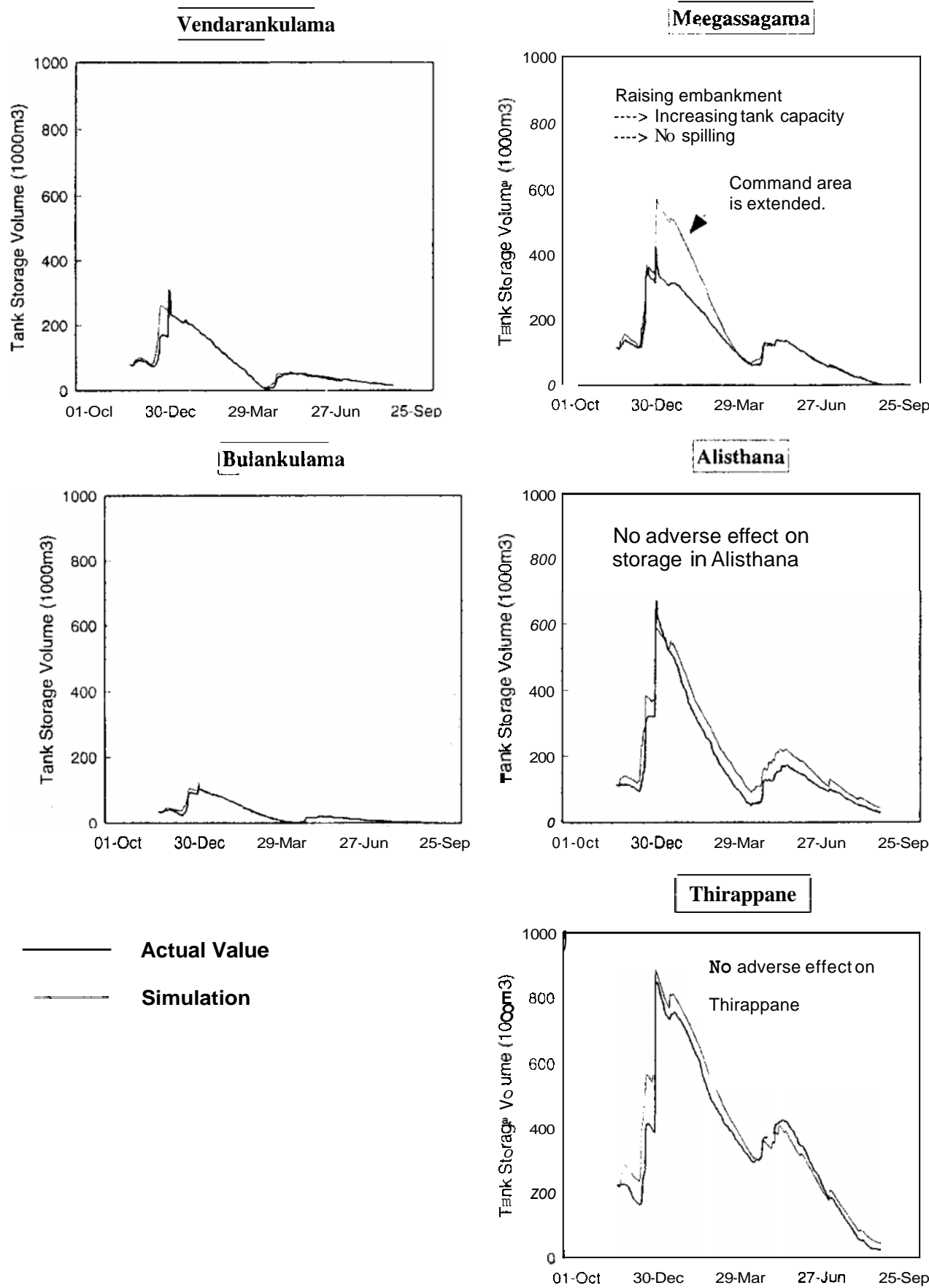


Figure 25. Planning simulation Case 2: Raising Alisthana.

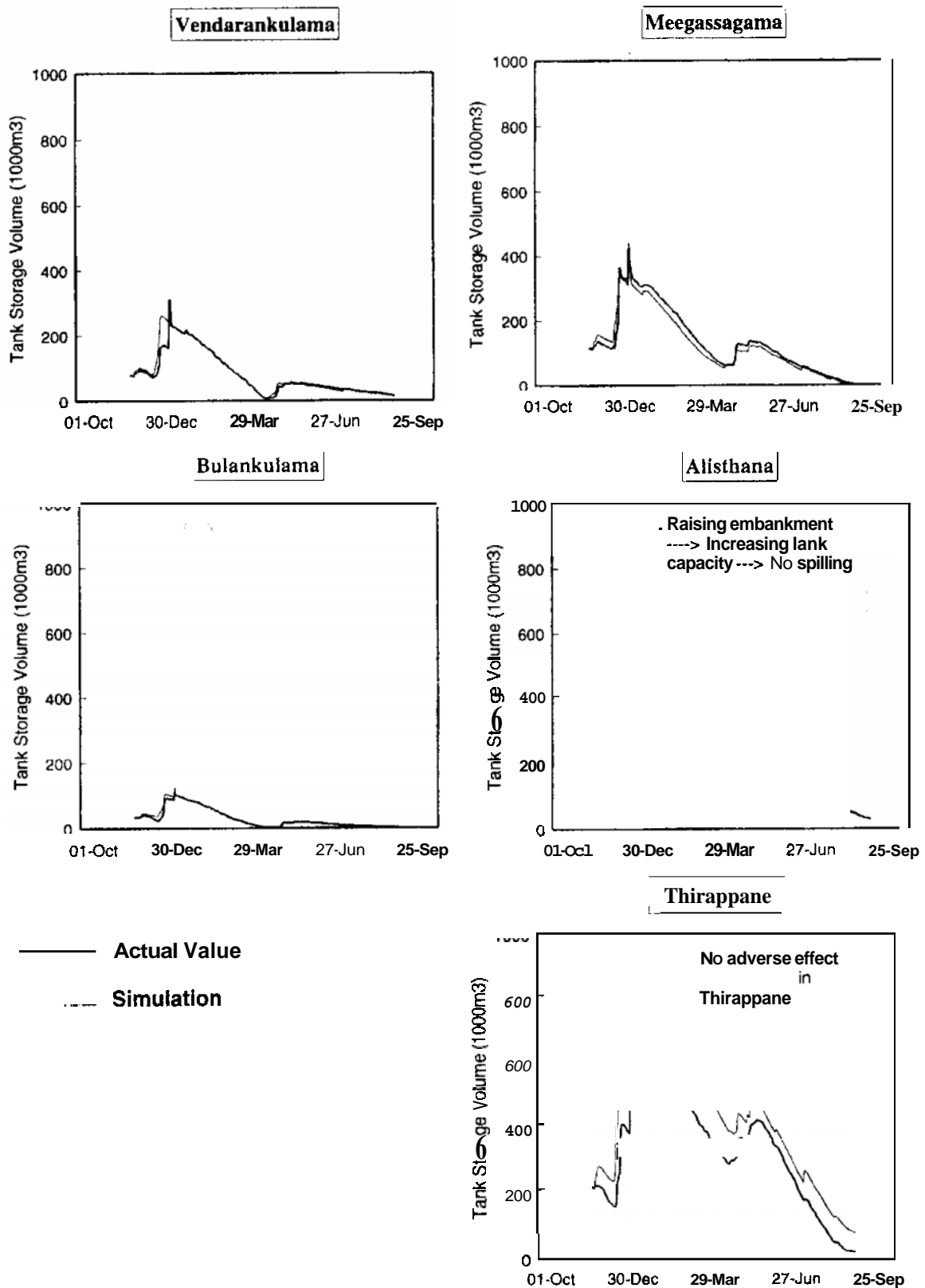


Figure 26. Planning simulation Case 3: Subsuming Vendarankulama into Meegassagama tank.

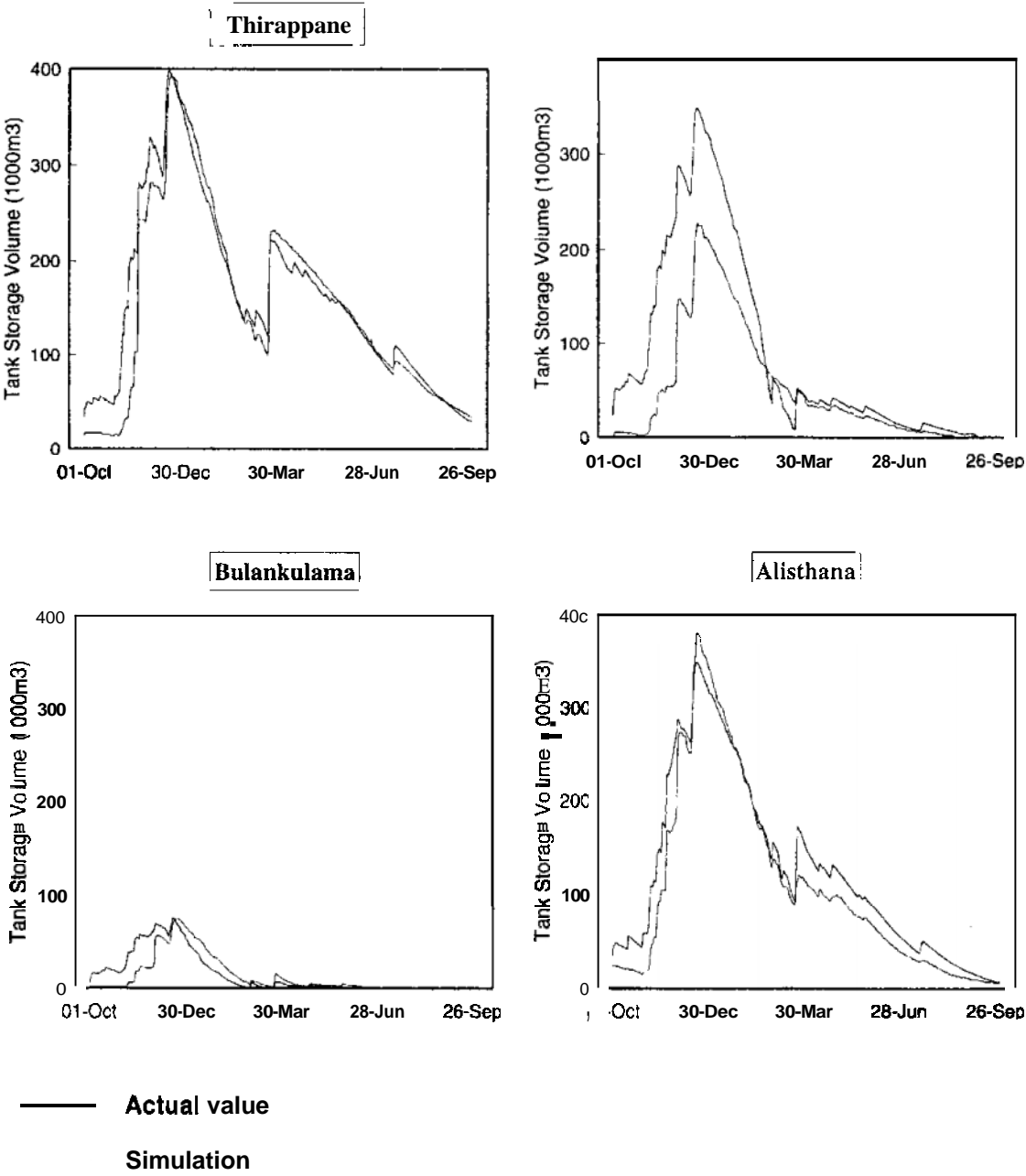


Figure 27-1. Linkage among QD, QE, Ep, WA (second-year data).

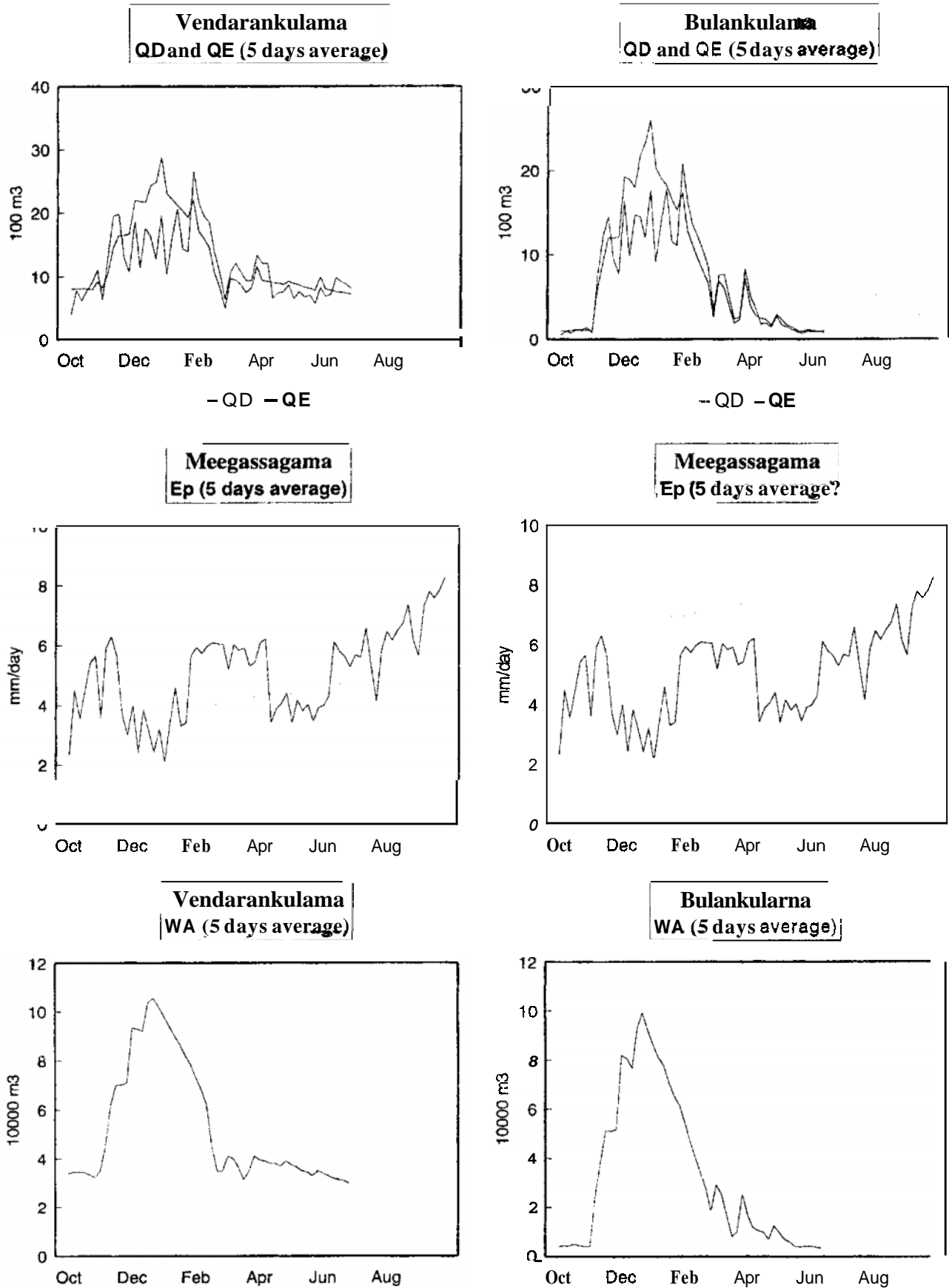


Figure 27-2. Linkage among QD, QE, Ep, WA (second-year data)

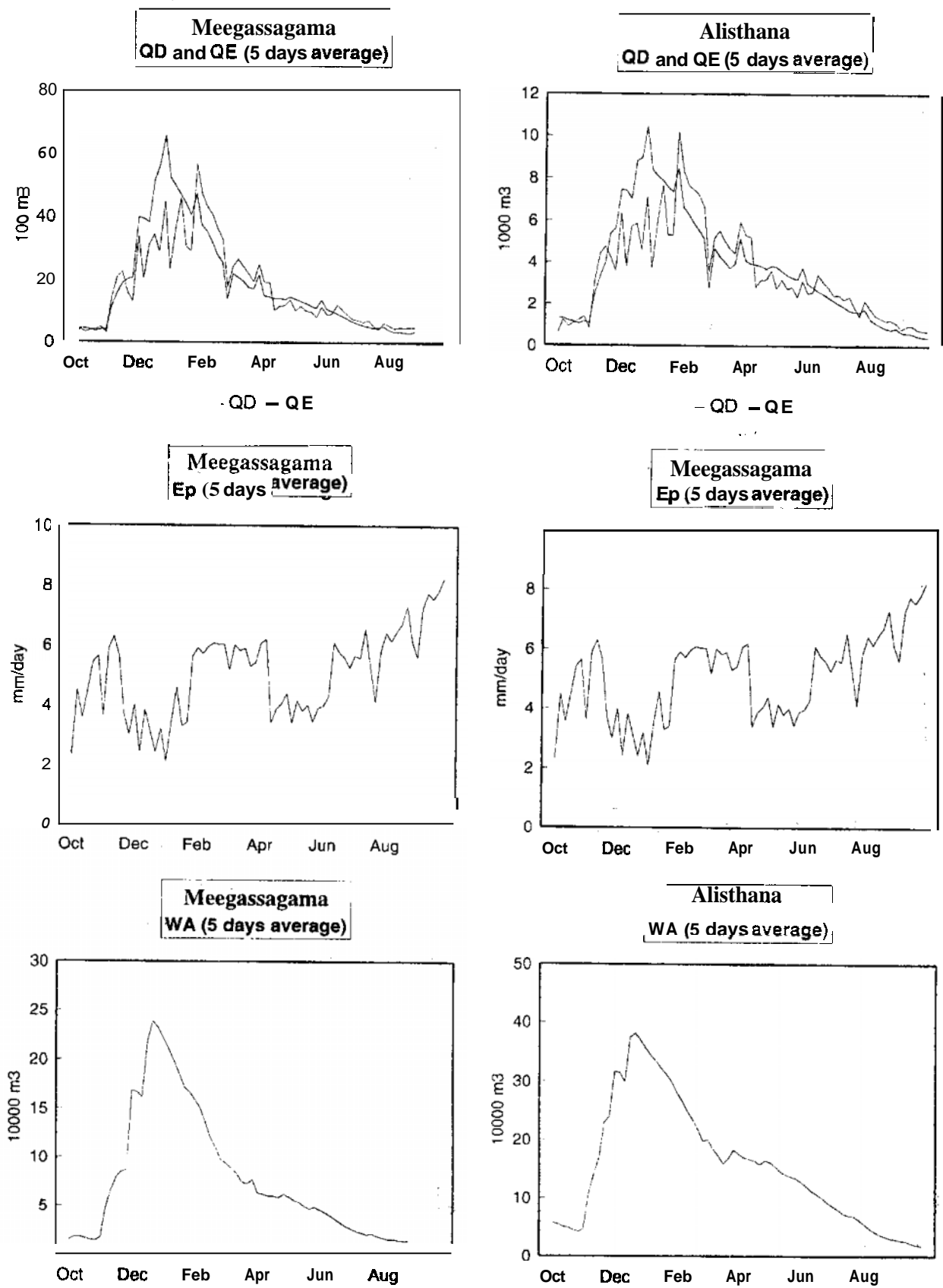


Figure 27-3. Linkage among QD, QE, Ep, WA (second-year data).

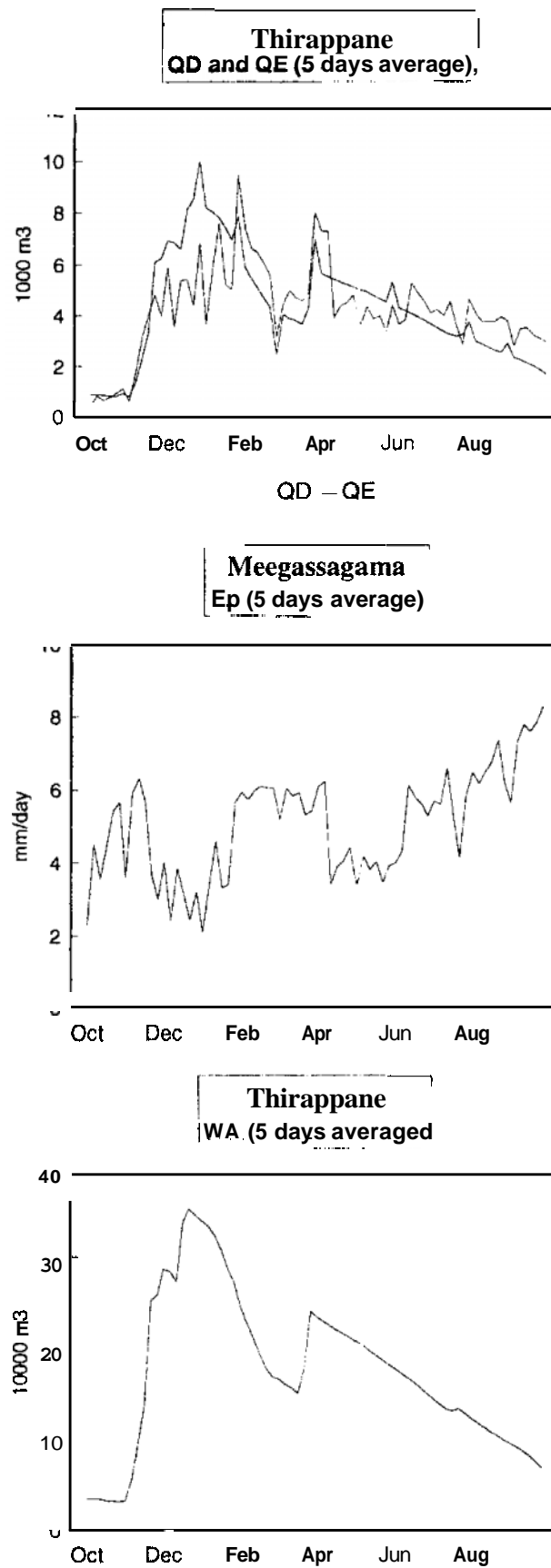


Figure 28. Fluctuation of the tank water storage volume.

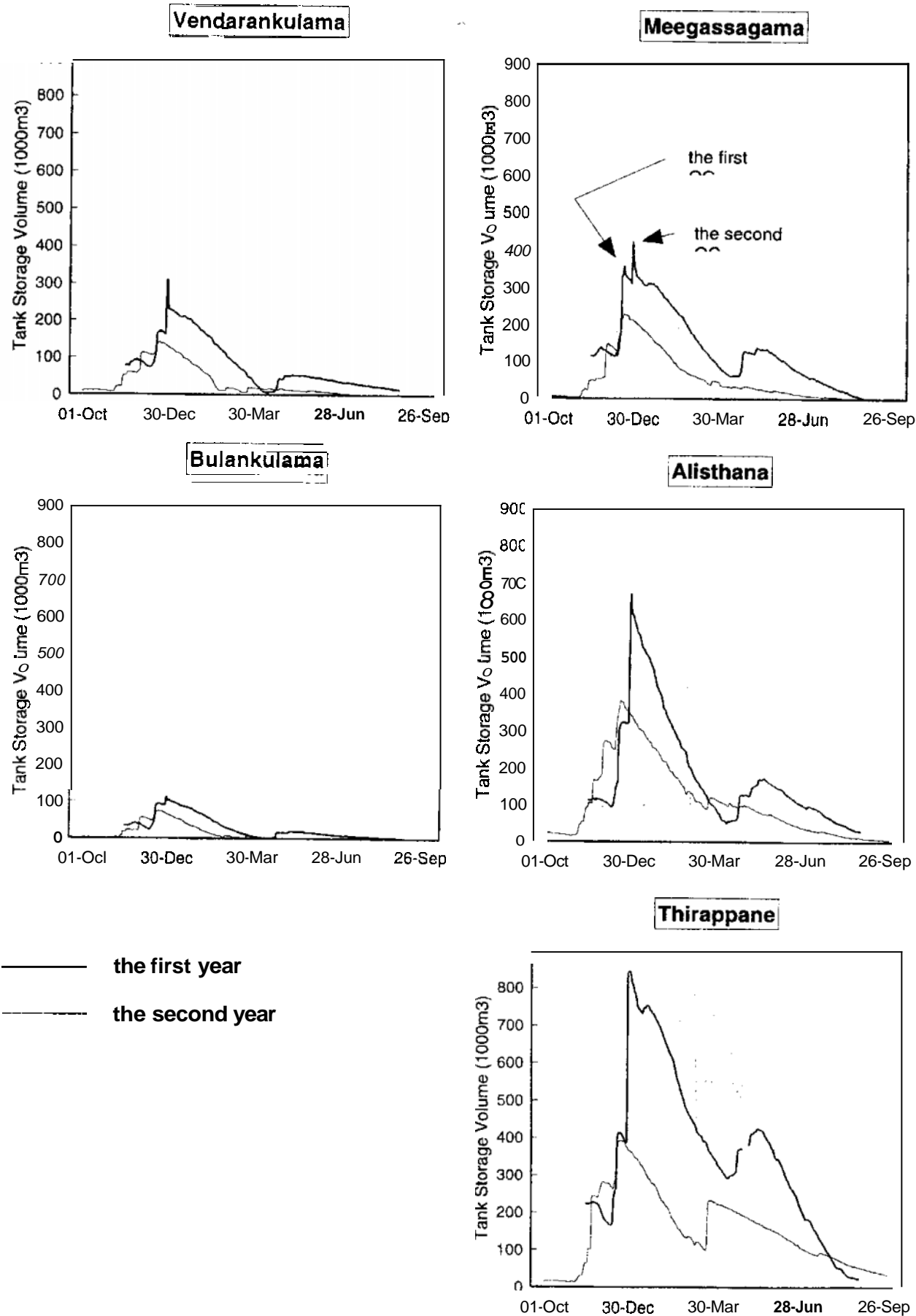


Figure 29. Fluctuation in composition of outflow (firstyear, excluding spill water).

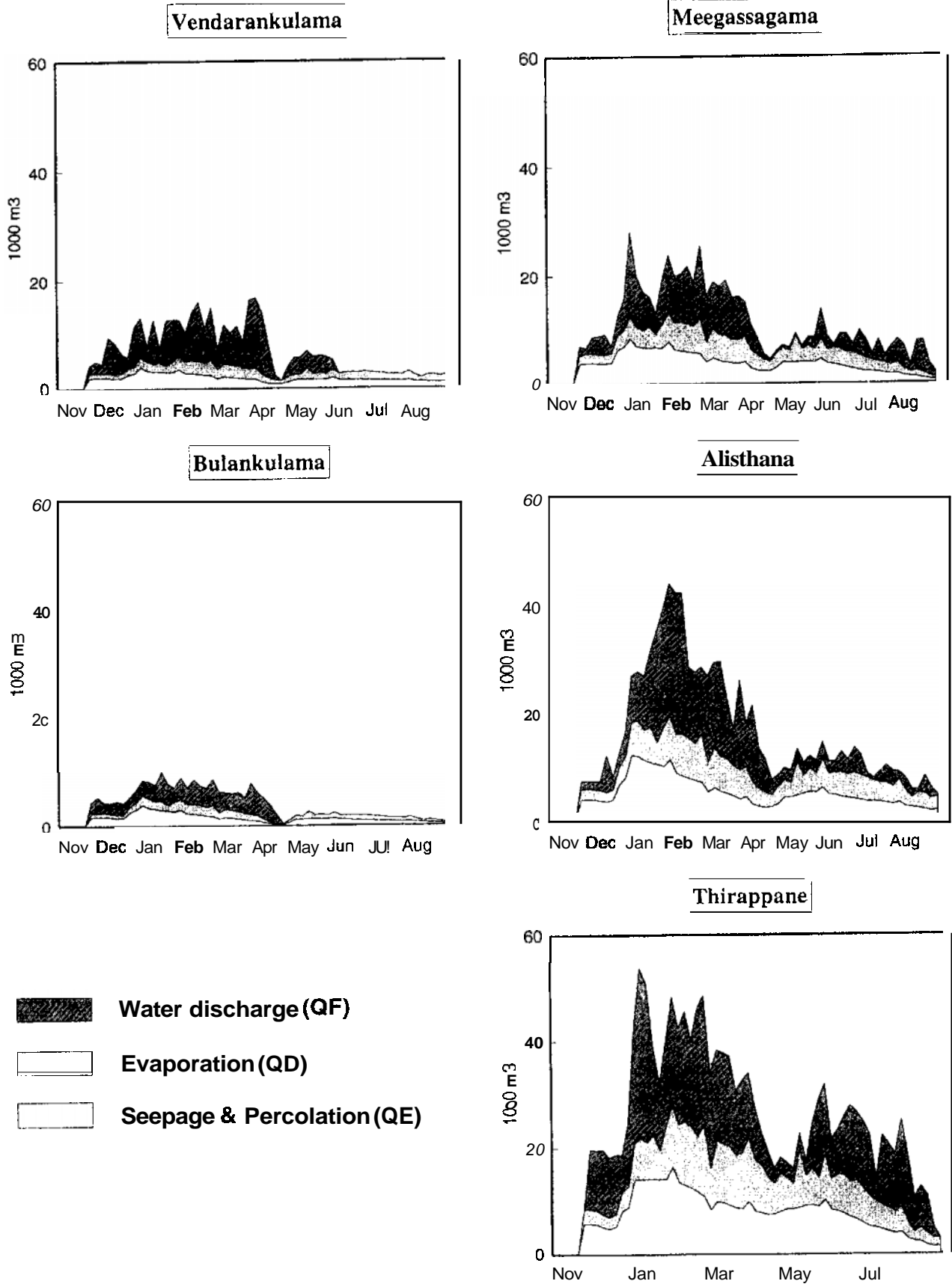


Figure 30. Fluctuation in composition of outflow (second year).

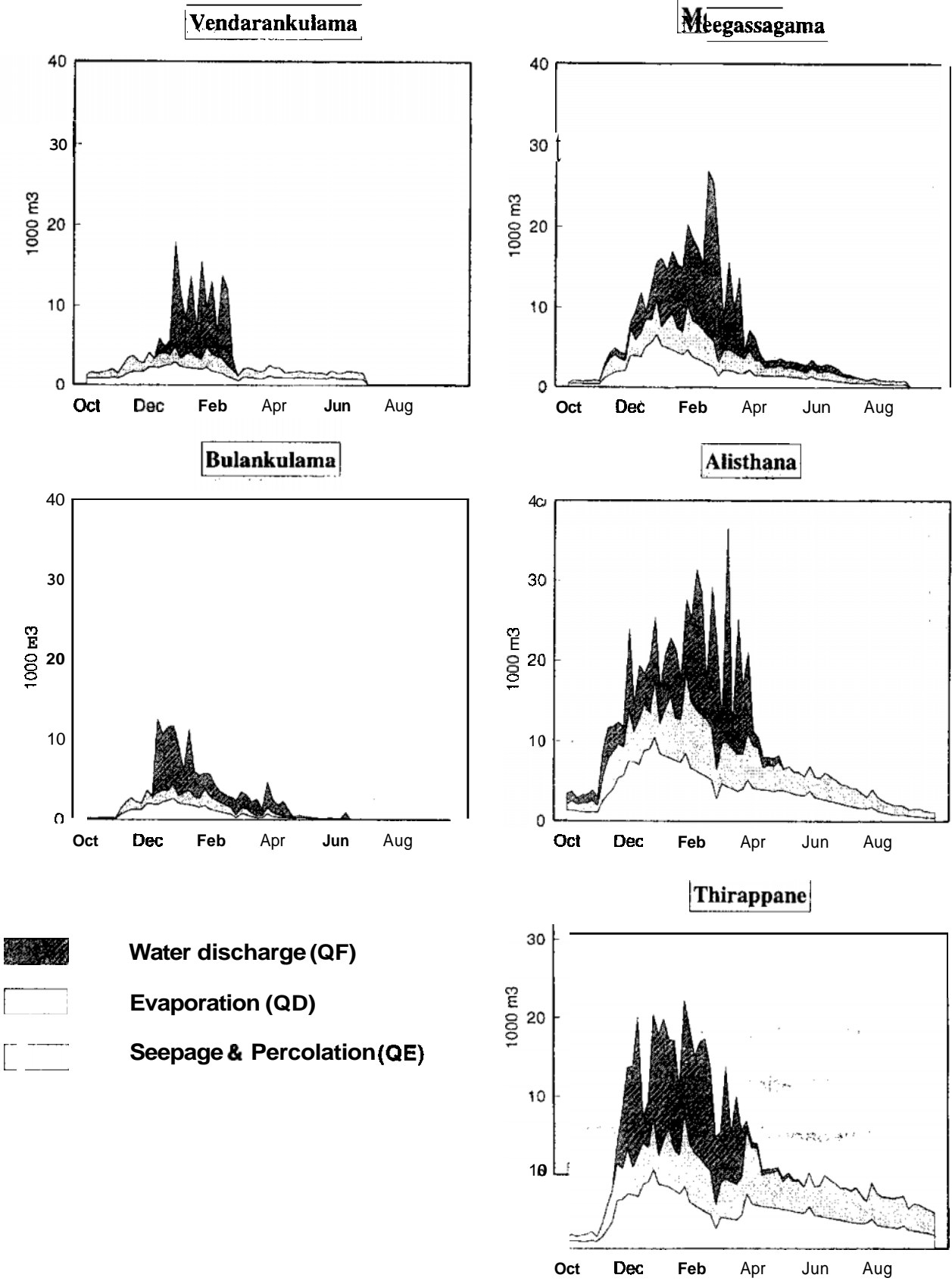


Figure 31. Composition of the total outflow (first maha season, including spill water).

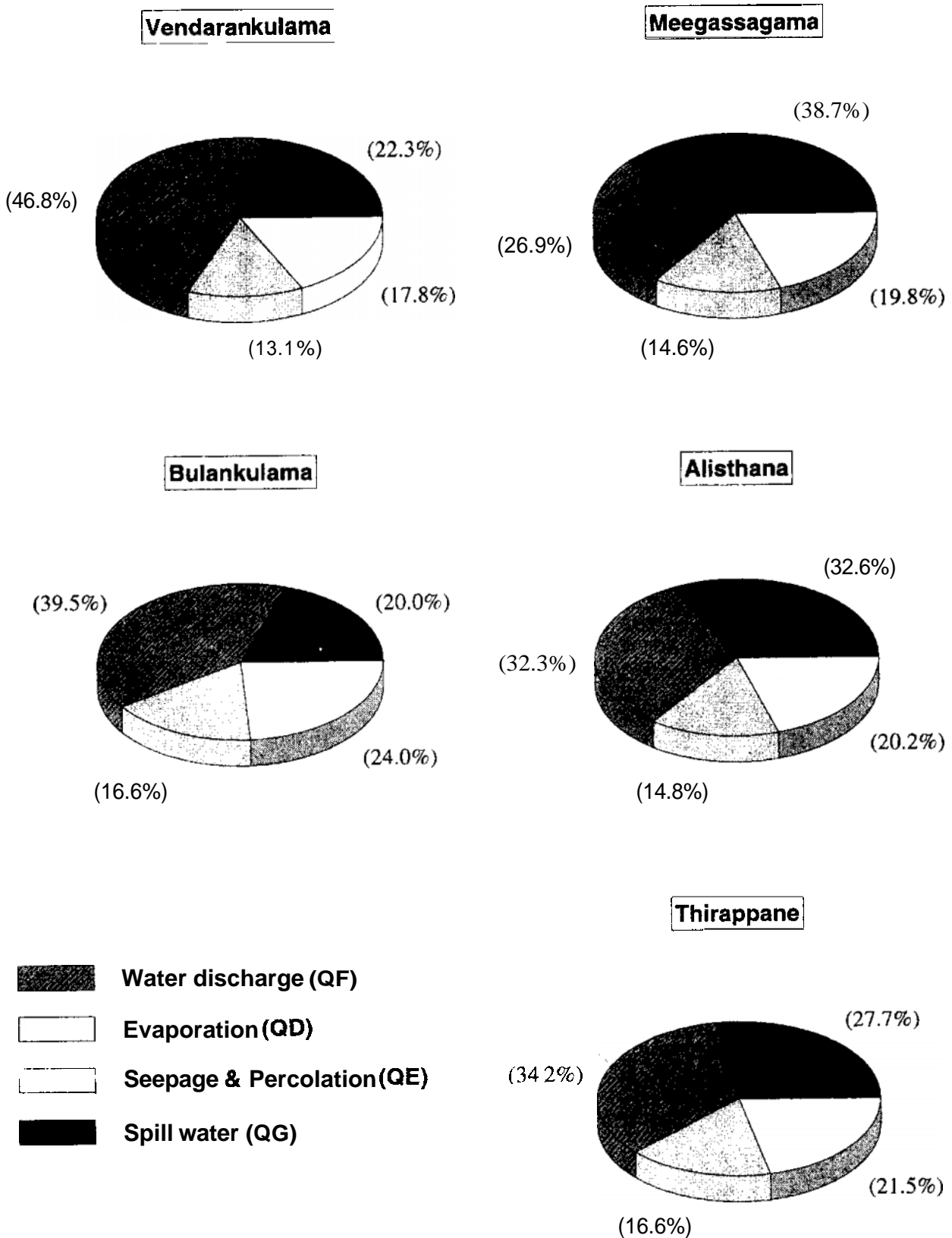


Figure 32. Composition of the total outflow (second maha season)

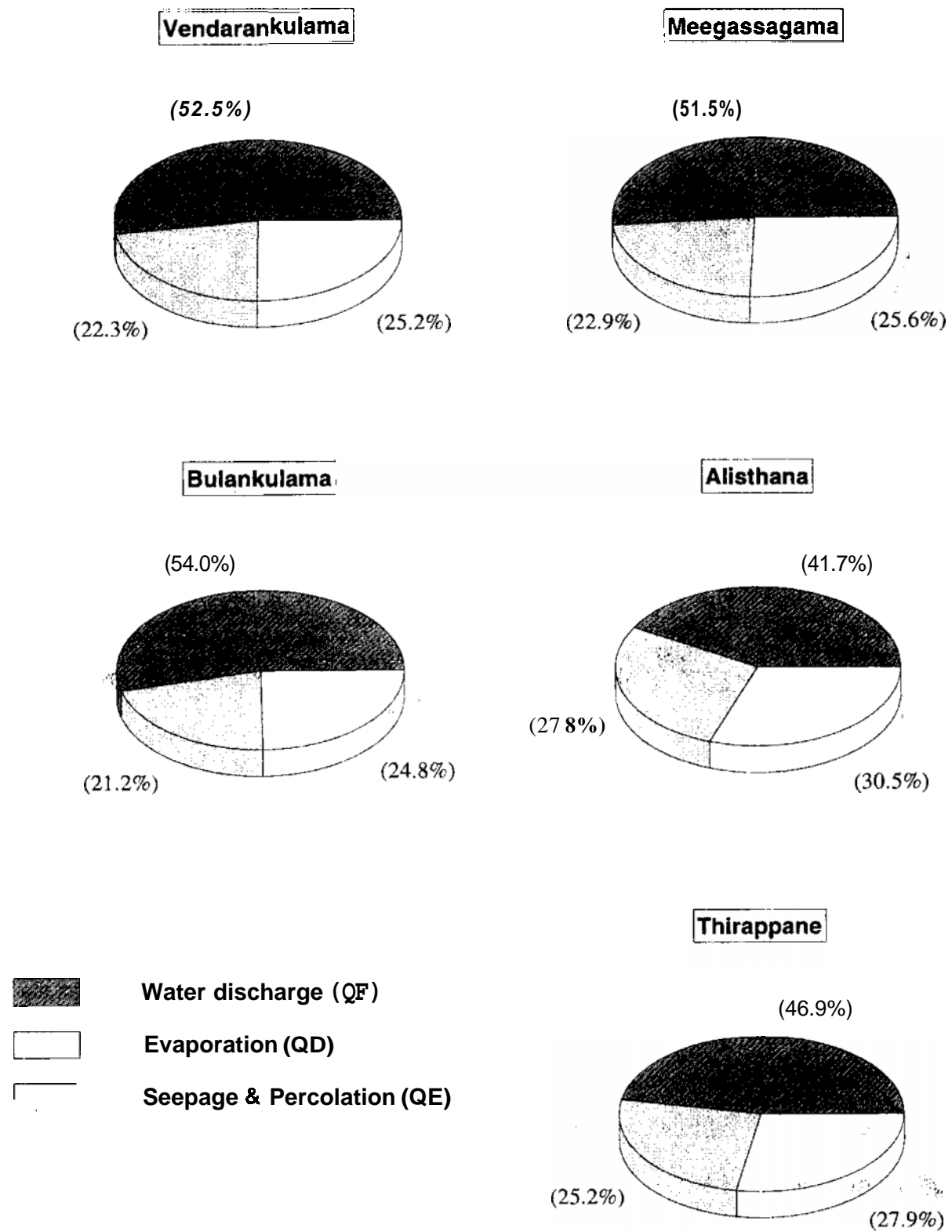


Figure 33. Precipitation and estimated runoff (first year, 5-day average).

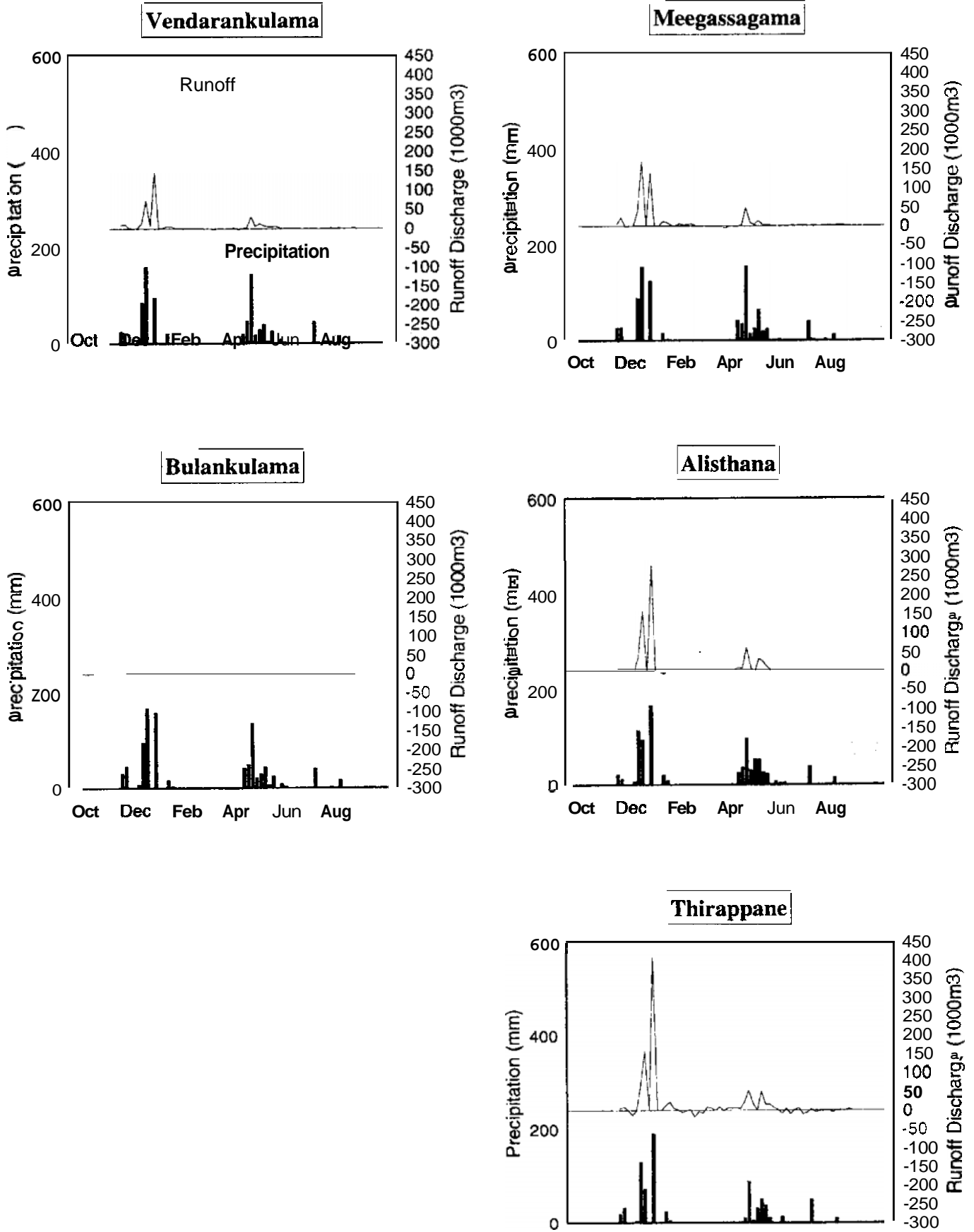


Figure 34. Precipitation and estimated runoff(second year, 5-day average).

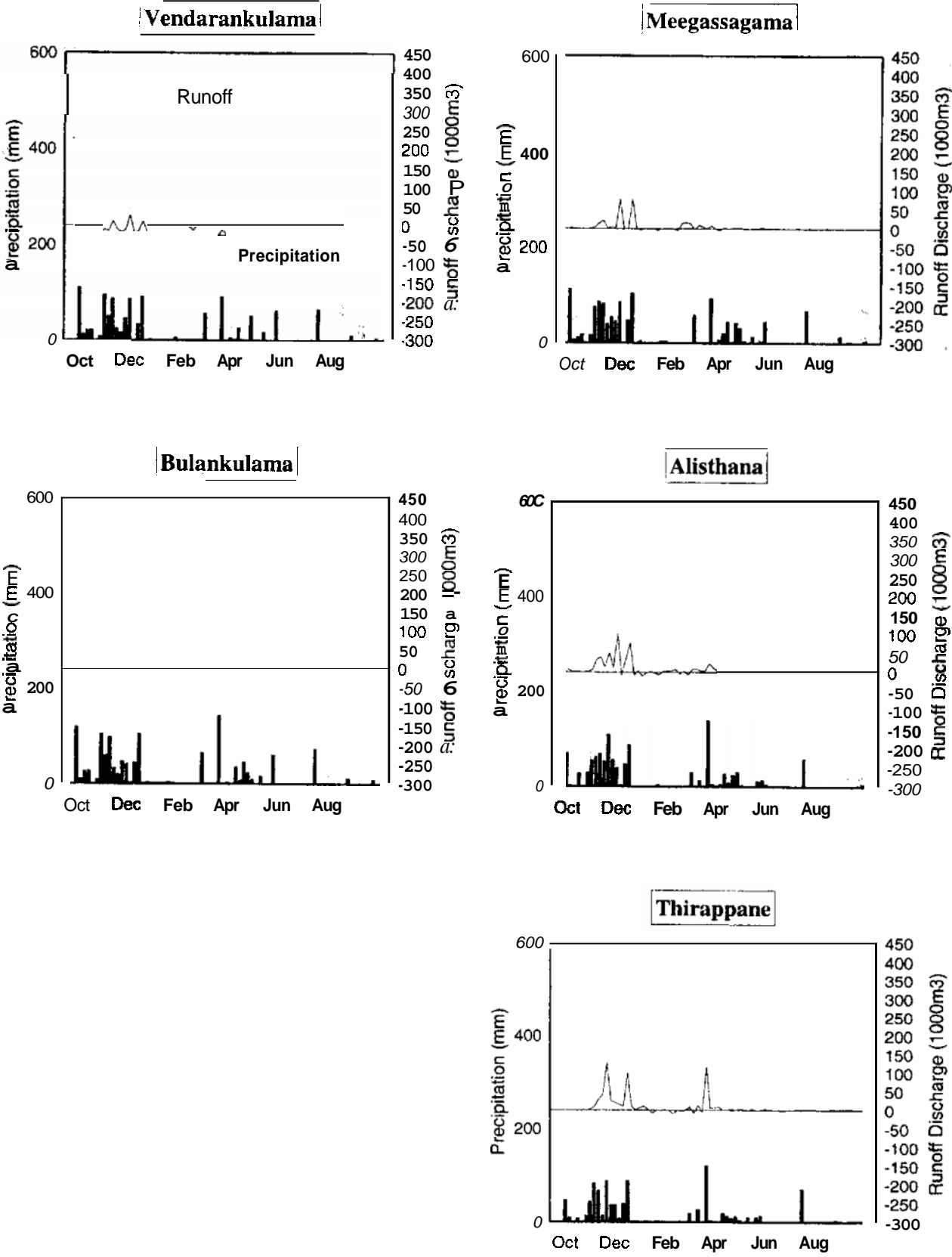


Figure 35. Fluctuation of composition of inflow (first year, QC excludes the spill water coming from upstream tank).

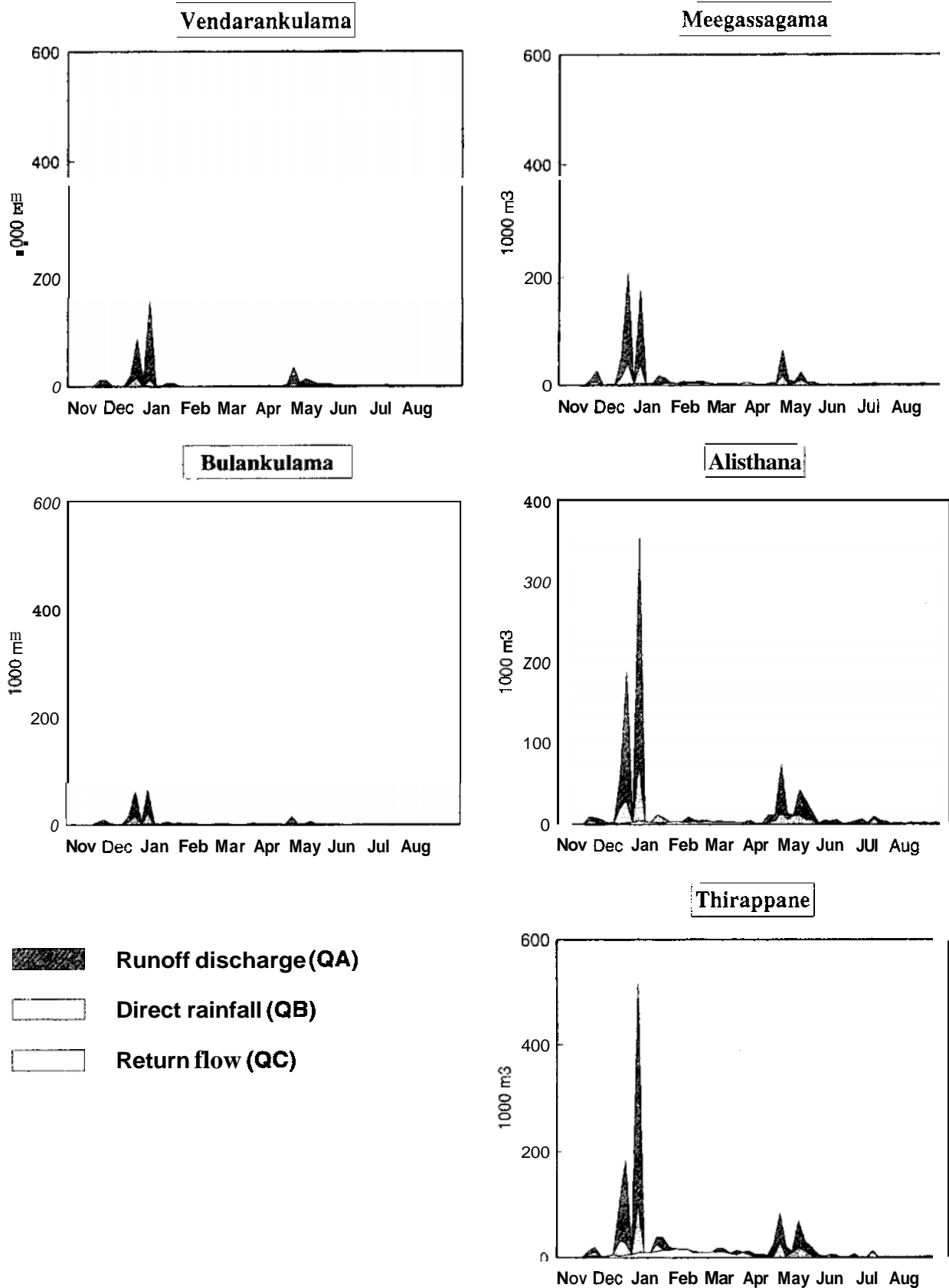


Figure 36. Fluctuation of composition of inflow (second year).

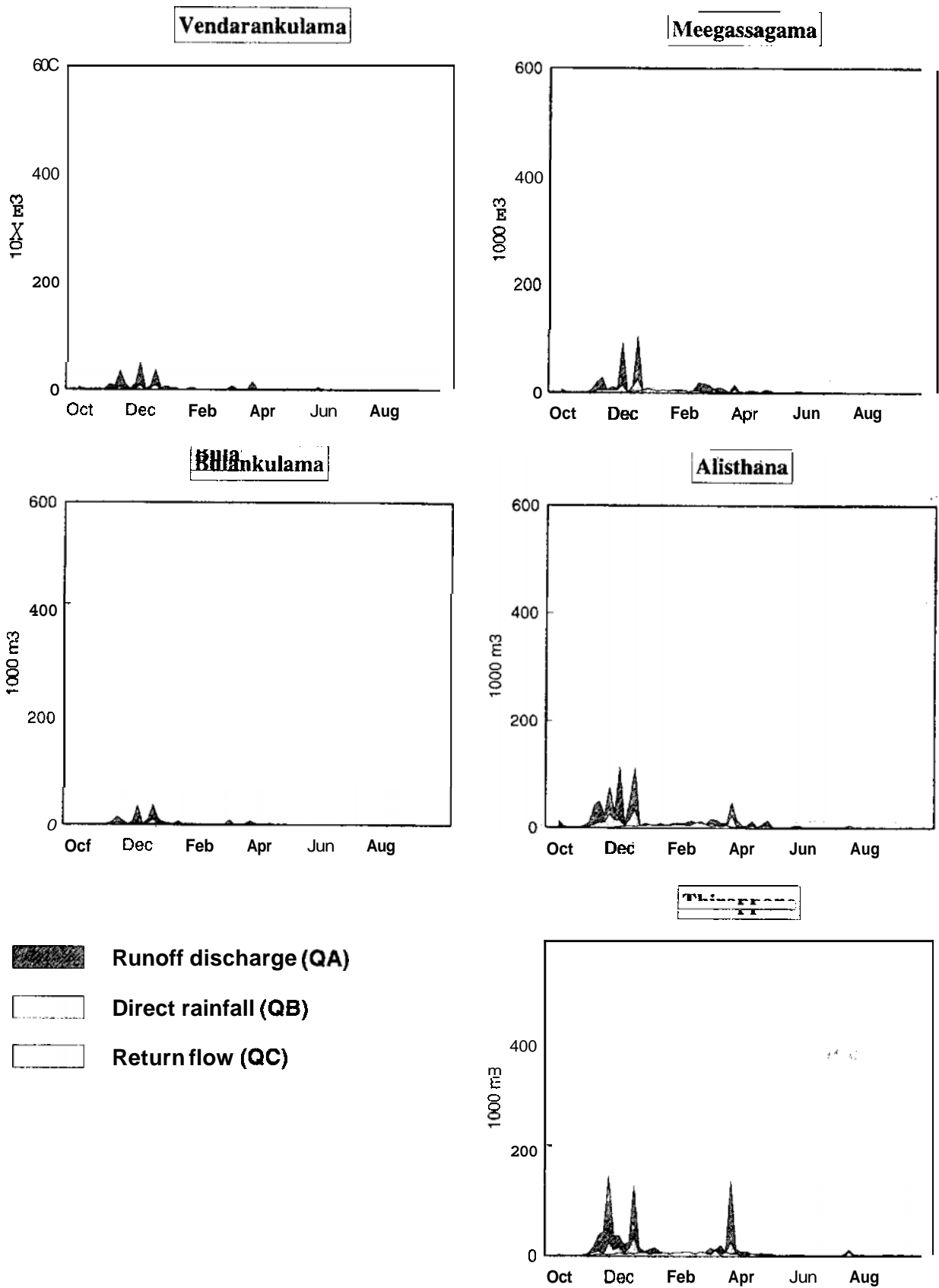
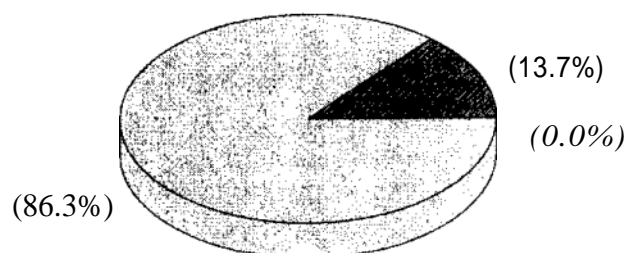
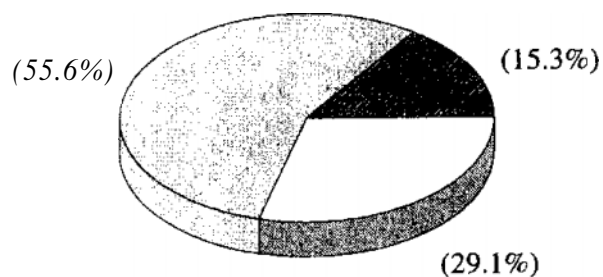


Figure 37. Composition of total inflow (first maha, 16 November - 31 March, QC includes spill water from upstream tank).

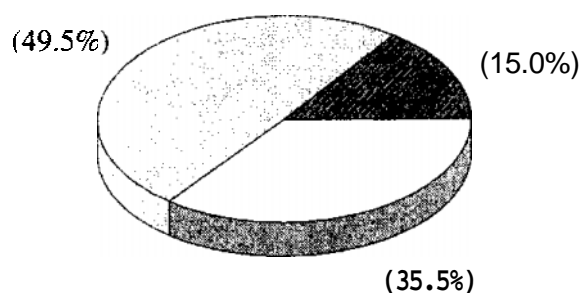
Vendarankulama



Meegassagama



Alisthana



Thirappane

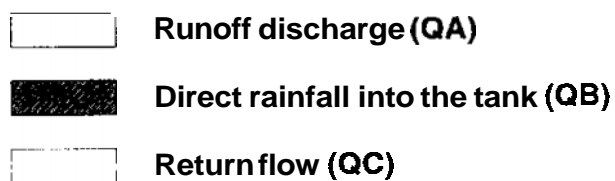
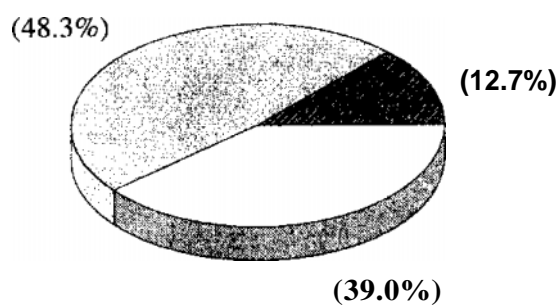
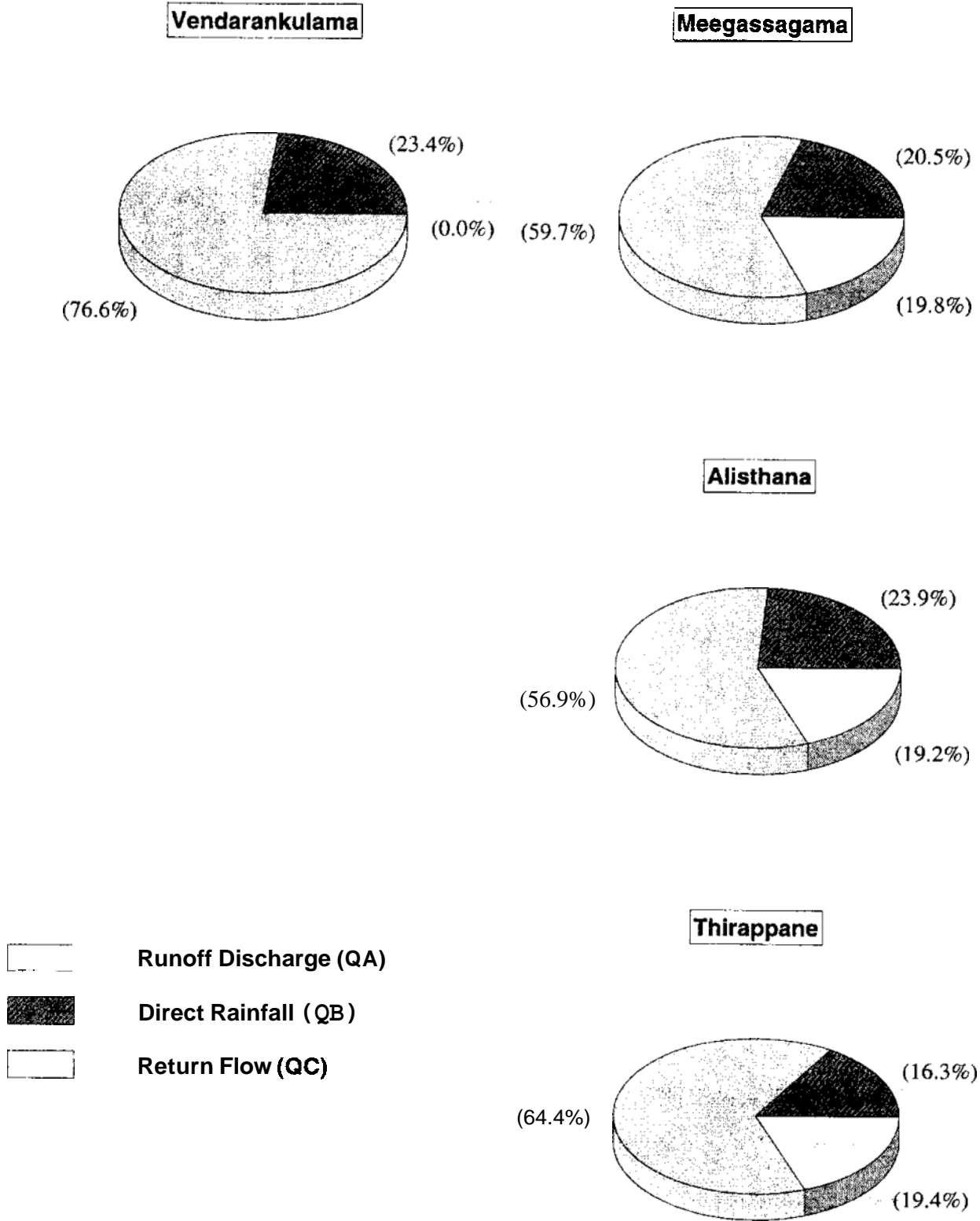


Figure 38. Composition of total inflow (second maha season, 76 November - 31 March).



	Rice	Tea	Rubber	Coconut	Others	Total
Land use(1000 ha) Share (%)	740 39	222 12	199 10	416 22	323 17	1900 100
GDP (100,000 Rs) Share (%)	6378 24.6	3004 11.7	718 2.8	3261 12.7	12366 48.1	25729 100

Source: Kikuchi, Sano, 1993, Agriculture of Sri Lanka 1993, Association for International Cooperation of Agriculture & Forestry. Japan

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
Tank Catchment Area (CA) km ²	1.95	0.64	3.56	3.70	4.48
Full Tank Water Surface Area (FWA) km ²	0.13	0.10	0.30	0.51	0.60
FWA / CA (%)	6.7	15.6	8.4	13.8	13.4

Table 3. Calculation of QE and fy for first tank (for the uppermost tank, assessing no rain during March)

Month	Period	No. t	QA _{i,t}	QB _{i,t}	QC _{i-1,t}	QD _{i,t}	QE _{i,t}	QF _{i,t}	dS _{i,t}
October	01 - 05	1	<u>QA_{1,1}</u>	QB _{1,1}	0.00	QD _{1,1}	<u>QE_{1,1}</u>	QF _{1,1}	dS _{1,1}
	06 - 10	2	<u>QA_{1,2}</u>	QB _{1,2}	0.00	QD _{1,2}	<u>QE_{1,2}</u>	QF _{1,2}	dS _{1,2}
	11 - 15	3	<u>QA_{1,3}</u>	QB _{1,3}	0.00	QD _{1,3}	<u>QE_{1,3}</u>	QF _{1,3}	dS _{1,3}
	16 - 20	4	<u>QA_{1,4}</u>	QB _{1,4}	0.00	QD _{1,4}	<u>QE_{1,4}</u>	QF _{1,4}	dS _{1,4}
	21 - 25	5	<u>QA_{1,5}</u>	QB _{1,5}	0.00	QD _{1,5}	<u>QE_{1,5}</u>	QF _{1,5}	dS _{1,5}
	26 - 31	6	<u>QA_{1,6}</u>	QB _{1,6}	0.00	QD _{1,6}	<u>QE_{1,6}</u>	QF _{1,6}	dS _{1,6}
	:	:	:	:	:	:	:	:	:
March	01 - 05	31	0.00	0.00	0.00	QD _{1,31}	<u>QE_{1,31}</u>	QF _{1,31}	dS _{1,31}
	06 - 10	32	0.00	0.00	0.00	QD _{1,32}	<u>QE_{1,32}</u>	QF _{1,32}	dS _{1,32}
	11 - 15	33	0.00	0.00	0.00	QD _{1,33}	<u>QE_{1,33}</u>	QF _{1,33}	dS _{1,33}
	16 - 20	34	0.00	0.00	0.00	QD _{1,34}	<u>QE_{1,34}</u>	QF _{1,34}	dS _{1,34}
	21 - 25	35	0.00	0.00	0.00	QD _{1,35}	<u>QE_{1,35}</u>	QF _{1,35}	dS _{1,35}
	26 - 31	36	0.00	0.00	0.00	QD _{1,36}	<u>QE_{1,36}</u>	QF _{1,36}	dS _{1,36}
			<u>fx</u>		<u>fz</u>		<u>fy</u>		

*1. Underlined values: unknown values.

*2. Double underlined values: unknown values, which are calculated in this table

Table 4. Calculation of QE for the second tank.

Month	Period	No. t	QA _{i,t}	QB _{i,t}	QC _{i-1,t}	QD _{i,t}	QE _{i,t}	QF _{i,t}	dS _{i,t}	
October	01 - 05	1	<u>QA1,1</u>	QB1,1	<u>QC1,1</u>	QD1,1	<u>QE1,1</u>	QF1,1	dS1,1	
	06 - 10	2	<u>QA1,2</u>	QB1,2	<u>QC1,2</u>	QD1,2	<u>QE1,2</u>	QF1,2	dS1,2	
	11 - 15	3	<u>QA1,3</u>	QB1,3	<u>QC1,3</u>	QD1,3	<u>QE1,3</u>	QF1,3	dS1,3	
	16 - 20	4	<u>QA1,4</u>	QB1,4	<u>QC1,4</u>	QD1,4	<u>QE1,4</u>	QF1,4	dS1,4	
	21 - 25	5	<u>QA1,5</u>	QB1,5	<u>QC1,5</u>	QD1,5	<u>QE1,5</u>	QF1,5	dS1,5	
	26 - 31	6	<u>QA1,6</u>	QB1,6	<u>QC1,6</u>	QD1,6	<u>QE1,6</u>	QF1,6	dS1,6	
:	:		:		:	:	:	:		
March	01 - 05	31	0.00	0.00	<u>QC1,3</u> <u>1</u>	QD1,31	<u>QE1,31</u>	QF1,31	dS1,31	
	06 - 10	32	0.00	0.00	<u>QC1,3</u> <u>2</u>	QD1,32	<u>QE1,32</u>	QF1,32	dS1,32	
	11 - 15	33	0.00	0.00	<u>QC1,3</u> <u>3</u>	QD1,33	<u>QE1,33</u>	QF1,33	dS1,33	
	16 - 20	34	0.00	0.00	<u>QC1,3</u> <u>4</u>	QD1,34	<u>QE1,34</u>	QF1,34	dS1,34	
	21 - 25	35	0.00	0.00	<u>QC1,3</u> <u>5</u>	QD1,35	<u>QE1,35</u>	QF1,35	dS1,35	
	26 - 31	36	0.00	0.00	<u>QC1,3</u> <u>6</u>	QD1,36	<u>QE1,36</u>	QF1,36	dS1,36	
			<u>fx</u>		<u>fz</u>		<u>fy</u>			

*1. Underlined values: unknown values,

*2. Double underlined values: unknown values, which are calculated in this table.

Table 5. Calculation of QC and fZ for the second tank.

Month	Period	No. t	QA _{i,t}	QB _{i,t}	QC _{i-1,t}	QD _{i,t}	QE _{i,t}	QF _{i,t}	dS _{i,t}	
October	01 - 05	1	<u>QA1,1</u>	QB1,1	<u>QC1,1</u>	QD1,1	QE1,1	QF1,1	dS1,1	
	06 - 10	2	<u>QA1,2</u>	QB1,2	<u>QC1,2</u>	QD1,2	QE1,2 QE1,2	QF1,2 QF1,2	dS1,2	
	11 - 15	3	<u>QA1,3</u>	QB1,3	<u>QC1,3</u>	QD1,3	QE1,3 QE1,3	QF1,3 QF1,3	dS1,3	
	16 - 20	4	<u>QA1,4</u>	QB1,4	<u>QC1,4</u>	QD1,4	QE1,4	QF1,4	dS1,4	
	21 - 25	5	<u>QA1,5</u>	QB1,5	<u>QC1,5</u>	QD1,5	QE1,5	QF1,5	dS1,5	
	26 - 31	6	<u>QA1,6</u>	QB1,6	<u>QC1,6</u>	QD1,6	QE1,6	QF1,6	dS1,6	
		:	:		:		QE1,31	QF1,31	:	
March	01 - 05	31	0.00	0.00	<u>QC1,3</u> <u>1</u>	QD1,31	QE1,31	QF1,31	dS1,31	
	06 - 10	32	0.00	0.00	<u>QC1,3</u> <u>2</u>	QD1,32	QE1,32	QF1,32	dS1,32	
	11 - 15	33	0.00	0.00	<u>QC1,3</u> <u>3</u>	QD1,33	QE1,33	QF1,33	dS1,33	
	16 - 20	34	0.00	0.00	<u>QC1,3</u> <u>4</u>	QD1,34	QE1,34	QF1,34	dS1,34	
	21 - 25	35	0.00	0.00	<u>QC1,3</u> <u>5</u>	QD1,35	QE1,35	QF1,35	dS1,35	
	26 - 31	36	0.00	0.00	<u>QC1,3</u> <u>6</u>	QD1,36	QE1,36	QF1,36	dS1,36	
			<u>fx</u>		<u>fz</u>		<u>fy</u>			

*1 Underlined values unknown values

*2 Double underlined values unknown values, which are calculated in this table

Table 6. Calculation of QA and fx for the second tank.

Month	Period	No. t	QA _{i,t}	QB _{i,t}	QC _{i-1,t}	QD _{i,t}	QE _{i,t}	QF _{i,t}	dS _{i,t}	
October	01 - 05	1	<u>QA1,1</u>	QB1,1	QC1,1	QD1,1	QE1,1	QF1,1	dS1,1	
	06 - 10	2	<u>QA1,2</u>	QB1,2	QC1,2	QD1,2	QE1,2	QF1,2	dS1,2	
	11 - 15	3	<u>QA1,3</u>	QB1,3	QC1,3	QD1,3	QE1,3	QF1,3	dS1,3	
	16 - 20	4	<u>QA1,4</u>	QB1,4	QC1,4	QD1,4	QE1,4	QF1,4	dS1,4	
	21 - 25	5	<u>QA1,5</u>	QB1,5	QC1,5	QD1,5	QE1,5	QF1,5	dS1,5	
	26 - 31	6	<u>QA1,6</u>	QB1,6	QC1,6	QD1,6	QE1,6	QF1,6	dS1,6	
March	01 - 05	31	0.00	0.00	QC1,3 ₁	QD1,31	QE1,31	QF1,31	dS1,31	
	06 - 10	32	0.00	0.00	QC1,3 ₂	QD1,32	QE1,32	QF1,32	dS1,32	
	11 - 15	33	0.00	0.00	QC1,3 ₃	QD1,33	QE1,33	QF1,33	dS1,33	
	16 - 20	34	0.00	0.00	QC1,3 ₄	QD1,34	QE1,34	QF1,34	dS1,34	
	21 - 25	35	0.00	0.00	QC1,3 ₅	QD1,35	QE1,35	QF1,35	dS1,35	
	26 - 31	36	0.00	0.00	QC1,3 ₆	QD1,36	QE1,36	QF1,36	dS1,36	
			<u>fx</u>		<u>fz</u>		<u>fy</u>			

*1. Double underlined values: unknown values, which are calculated in this table.

Table 7. Irrigated areas.

Name of tank	Nominal command area ha	Irrigated area 1991/1992 maha ha	Irrigated area 1992 yala ha	Irrigated area 1992/1993 maha ha	Irrigated area 1993 yala ha	Number of families irrigating	Average sue of family irrigated area ha
Vendarankulama	182	182	0 0	182	0 0	17	1 07
Meegassagama	32 5	32 5	6 1	32 5	0 0	34	0.96
Alisthana	39.1	32.4	2.0	25.2	0.0	35	0.93
Thirappane	34.5	26.2	32.3	29.7	0.0	56	0.47
Badugama	2.4	1.1	0.0	1.7	0.0	2	0.55
Bulankulama	17.1	17.1	0.0	13.0	0.0	41	0.42

Table 8. Catchment areas.

Name of Tank	Catchment area (km ²)
Vendarankularna	1.95
Meegassagama	3.56
Alisthana	3.70
Thirappane	4.40
Badugama	0.26
Bulankulama	0.64

Table 9. Dimensions of tanks.

Name of tank	Height (m)	Effective capacity (1,000 m ³)	Full water spread area (km ²)
Vendarankulama	2.9	220	0.13
Meegassagama	3.0	360	0.30
Alisthana	2.8	580	0.51
Thirappane	3.2	790	0.60
Badugarna	2.2	80	0.07
Bulankulama	2.1	100	0.10

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
1991/1992 maha	over 100%	over 100%	over 100%	over 100%	over 100%
1992/1993 maha	64%	73%	63%	66%	50%

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
1991/1992 maha	170119	85938	192083	312375	436441
1992/1993 maha	93393	76072	184867	233945	274904

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
1992 yala	325	353	375	348	237
1993 yala	201	283	265	243	194

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
1991/1992 maha	0		20	18	45
1992/1993 maha	0		28	40	36

*

Table 14. Seasonal runoff percentage (fx).

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
1991/1992 maha	34	31	25	28	32
1992 yala	10	12	5	12	13
1992/1993 maha	9	18	7	13	15
1993 yala	3	5	1	5	8

Table 15. Water balance model (for one year simulation, from 01 October to 30 September).

Date	$R_{i,t}$	$Q_{Ai,t}$	$Q_{Bi,t}$	$Q_{Ci-1,t}$	$E_{pi,t}$	$Q_{Di,t}$	$Q_{Ei,t}$	$Q_{Fi,t}$	$dS_{i,t}$	$S_{i,t}$	$Q_{Ei-1,t} + Q_{Fi-1,t}$	$W_{Ai,t-1}$
	A	B	C	D	E	F	G	H	I	J	K	L
		$A * CA_i * f_{xi}$	$A * L$	$K * f_{zi}$		$E * L$	$f_{yi} * L$		$B+C+D-F-G-H$	$J+I$		
October 01												
October 02												
:	:	:	:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:	:	:	:
September 29												
September 30												

(WA tank water surface area, CA catchment area of the tank, Ep pan-evaporatton (daily) in Meegassagama)

Table 16. Total water balance in the first observation year

Top value: 199111992 maha (from 16 November 1991 to 31 March 1992)

Bottom value: 1992 yala (from 01 April 1992 to 30 September 1992)

Tank	R_i	Q_{Ai}	Q_{Bi}	Q_{Ci-1}	Q_{Di}	Q_{Ei}	Q_{Fi}	Q_{Gi}	dS_i
Vendaran kulama	408 398	273026 79511	43425 19797	0 0	47460 36755	64872 37593	170119 40960	81000 0	-47000 -16000
Bulan kulama	520 428	102160 32326	50849 11187	36464 0	36006 19342	52129 20425	85938 8245	43400 0	-28000 -4500
Meegassagama	436 438	380122 80794	104842 54241	198670 0	104116 69125	141301 73400	192083 75011	27613 5 0	-30000 -82500
Alis thana	444 419	466761 178441	141583 70292	335100 0	143098 107718	195567 111966	312375 90299	31490 4 0	-22500 -61250
Thirappane	476 311	674998 174779	177340 99580	543934 0	211582 170948	273611 179998	436441 245112	35293 9 0	121700 - 363400

Table 17. Total wafer balance in the second observation year.

Top value: 1992/1993 maha (from 01 October 1992 to 31 March 1993)

Bottom value: 1993 yala (from 01 April 1993 to 30 September 1993)

Tank	Ri	QAI	QBi	QCi-1	QDi	QEI	QFI	QGi	dSi
Vendaran kulama	867 161	153223 10189	50289 6334	0 0	48130 14471	52988 15052	93393 0	0 0	9000 -13000
Bulan kulama	952 203	109620 6331	31987 1556	7495 0	32421 2570	37108 2680	76072 6137	0 0	3500 -3500
Meegassagama	972 303	255531 13450	86525 14103	73206 0	88357 26959	97324 26634	185830 16460	0 0	43750 -42500
Alis thana	891 192	425013 36227	16491 5 24440	114511 0	170681 82798	185086 79671	248672 6947	0 0	100000 - 108750
Thirappa ne	764 173	525698 61235	13793 5 30384	155412 0	157899 147423	172942 134144	274904 5052	0 0	213300 195000

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
Number of periods spill of water occurred	1	1	3	3	3
Total QG (1000 m3)	8	4.3	27.6	31.5	35.3
QG by self-catchment	8	4.3	15.3	3.9	3.8

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
1991/1992 maha	53	61	73	68	66
1992 yala	65	83	66	71	59
1992/1993 maha	48	46	49	58	53
1993 yala	100	100	100	100	100

Table 20. Through-flow ratio of the tank water.

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
Effective tank capacity	(1000 m ³) 220	100	360	580	790
Annual outflow	(1000 m ³)				
the first year (1)	479	265	931	1276	1871
the first year (2)	398	222	655	961	1518
the first year (3)	211	94	267	403	682
the second year (1)	224	157	442	774	892
the second year (2)	93	82	202	256	280
Through now	(times/year)				
the first year (1)	2.2	2.7	2.6	2.2	2.4
the first year (2)	1.8	2.2	1.8	1.7	1.9
the first year (3)	1.0	0.9	0.7	0.7	0.9
the second year (1)	1.0	1.8	1.2	1.3	1.1
the second year (2)	0.4	0.8	0.6	0.4	0.4

Notes:

The first year: from 16 November 1991 to 31 August 1992
The second year: from 01 October 1992 to 30 September 1993
The first year (1) includes QD, QE, QF and QG.
The first year (2) includes QD, QE and QF.
The first year (3) includes only QF.
The second year (1) includes QD, QE and QF.
The second year (2) includes only QF.

Table 21. QF per hectare.

	Vendarankulama	Bulankulama	Meegassagama	Alisthana	Thirappane
QF per hectare	(mm/ha)				
1991/1992 maha	935	503	591	964	1666
1992/1993 maha	513	445	572	987	926
Nominal command area	(ha)				
	18.2	17.1	32.5	39.1	34.5
Tank capacity	(1,000 m ³)				
	220	100	360	580	790

Notes:

1991/1992 maha: 16 November 1991- 31 March 1992 (137 days)
1992/1993 maha: 01 October 1992 -31 March 1993 (182 days)
Bulankulama can receive water through the drainage of Vendarankulamain.

Annex 1

Details of Water Balance Analysis

Tables 16 and 17 show the components of the water balance for five tanks for all sample seasons, and Figures 27-1 to 27-3 show the change over time of QD, QE, Ev and WA for the second year data. Although the peak pan evaporation occurred during the last period of September, the calculated peak in evaporation **loss** from the tank, QD, did not occur until the **last** period of January, as the latter term is also influenced by the surface area of the tank, WA, which peaks in the fifth period of December. Peak values of seepage and percolation losses, QE, coincided with the peak in WA. As was mentioned earlier, water discharge from all tanks, QF, was lower during maha **1992/93** than in the previous year, due to a shorter irrigation period, reduced tank discharge and hence smaller command areas.

The duration and intensity of spillage are given in Table 18. As was expected, QG was largest in the downstream tanks because of accumulation as water flows through the cascade.

Figures 29 and 30 show the fluctuation in the composition of outflow without considering spill (QG), and with QG in Figures 31 and 32. Of all outflow components, only discharge (QF) was used for irrigation. The percentages of outflow, not directly beneficial to irrigation, are presented in Table 19. The significant difference between the two maha seasons results from the larger amount of return flow, QC, in the first maha season. It is noteworthy that during the main irrigation season nearly 50 percent of the stored water cannot be utilized for irrigation. The typically shallow depth of these tanks accounts for the relatively high evaporation losses.

Rainfall and estimated runoff as calculated from the water balance model are plotted side by side in Figures 33 and 34. Errors resulting from measurement deficiencies and the bold assumptions made in the water balance model accumulate in the runoff values (QA), as these are the last to be calculated. This also accounts for the few negative QA values that were calculated by the model. The plots of Figures 33 and 34 clearly show the difference in runoff response to rainfall events in maha and yala, which was discussed before. Seasonal QA values of the downstream tanks were larger than those of the upstream tanks, reflecting the differences in size of the catchments.

Figures 35 and 36 show the change over time in the composition of inflow into the tanks. The pie charts of Figures 37 and 38 depict the composition of inflow during the two maha seasons. It is obvious that return flow, QC, including spill, is important in the operation of the tank cascade. The ratio of annual outflow volume to effective tank capacity (the so-called throughflow ratio) is presented in Table 20. These throughflow ratios are not high, and there is a striking difference between the data of the two years. In the second year, only about one half of the tank volume was available for irrigation, with the exception of Bulankulama where the ratio was higher (second year 2). Table 21 shows the amount of water available for irrigation in the command areas (QF/ha), together with the size of the command and the capacity of the tank. The water duty in mm/ha varies widely between command areas, but—as was to be expected—it is closely related to the ratio of tank volume to size of command area. The sequence of the tanks in decreasing order of the ratio of storage capacity to size of the command is Thirappane, Alisthana, Vendarankulama, Meegassagama and Bulankulama, which is nearly the same sequence as the QF/ha values for the two years. From the available data, which admittedly is too little for this type

of a conclusion, it appears that the ratio of tank volume in thousands of cubic meters to command area in hectares should be at least 12 to have a viable system for tank-based irrigated agriculture under the conditions of this particular catchment area. Further studies that take into account issues such as field sizes, land consolidation, water distribution arrangements and other management and maintenance aspects would be required to substantiate this conclusion.

ANNEX 2

Possible Improvements in the Model

The water balance model was shown to be effective in illustrating mean system response characteristics, which are important for a better intuitive understanding of the cascade system. However, simplification of flow data into discrete coefficients does not give the model adequate flexibility to indicate system responses to varying conditions. Use of static runoff coefficients is probably the greatest deficiency of the model as it is applied to simulate the effect of system modifications or management interventions. It is shown in the paper that the runoff coefficients vary with the season and from year to year, depending mainly on the soil moisture conditions in the catchment areas.

In an effort to deal with these shortcomings, a predictive model was developed that accounted for changes in the soil moisture conditions in the catchment. The coefficients were modeled as linear variables of soil moisture, where the relative level of the water table in the soil between adjacent tanks is used as a proxy for the moisture conditions. Constant head boundaries between two adjacent tanks provide the lower limit of the water table and complete saturation of the soil profile represents its upper limit. Moreover, linear horizontal flow characteristics were assumed to occur with changes in the water table. Change in storage in the soil profile is then related to change in water table level through the specific yield function of the soil. Rates of inflow and outflow from the soil profile are governed by Darcy's Law. Thus the runoff coefficient varied between zero under conditions of prolonged drought to a maximum value effective after long periods of relatively intense rain.

The coefficient of seepage and percolation was also allowed to vary linearly between zero when the water table is at its highest level, and a maximum value when the gradient between the tank and the water table between the tanks is at its maximum value. The return flow coefficient was split into two separate variables to account for the fact that part of the return flow percolates to the groundwater and is not subject to evaporation whereas some of the surface flow is lost by evaporation along the way.

Preliminary results show a better correlation between simulated and observed values than was obtained with the original model. However, the suggested improvements are not without their limitations and some inconsistencies remain between observed and simulated data that are hard to explain. It is possible that some of the observed data may be suspect, for example, when "observed" storage seems to exceed the stated maximum volumes of the tanks, as was the case in December 1991.

The relative close match between the model and actual values (obtained with the original model as well as the improved model) may be deceptive when simulation is based on the data of only a couple of years. The rainfall runoff coefficients seem to offer the most room for error in the model. After periods of particularly intense rain, especially when occurring after earlier days of rainfall, the observed runoff volumes increased markedly-more than was captured by the improved model. This suggests that the runoff coefficient is not a simple relation of the aggregate wetness of the soil profile as was assumed in the improved model, but may be sensitive to hydraulic conditions at the soil surface.

In conclusion, it is felt that a more accurate modeling would require greater knowledge of the soil physical conditions and hydraulic gradients in the soil than can be easily obtained or can be warranted by the limited scope of this study.

(Note: This comment was prepared by the editor who gratefully acknowledges the assistance received from Daniel Jenkins of Cornell University.)

