68

Simulation of the water balance in a dry zone tank cascade

Yoshiyuki Shinogi[1], Ian W. Makin[1], D. D. Prabath Witharana[2]

Abstract
Daily observations of hydrological variables have been made to estimate flows at reservoirs in the Tirrapane cascade in North Central Province. The observations have been used to calibrate a physically based water balance model. This paper presents the observed data and discusses the form of the model and initial calibration results.

Introduction
There are approximately 2,500 working village tanks[3] in North Central Province of Sri Lanka, most of which are members of the 450 cascade systems identified in *Rajarata*. The cascades of inter-connected irrigation tanks are an essential element in successful agricultural systems of the dry zone. Although the cascade systems are recognized as vital links in enabling agricultural production, the hydrology of the systems is not adequately understood. Future rehabilitation and development of such systems depends critically on improved understanding of the system hydrology (Amerasinghe *et. al*., 1998).

The paper reports a study of the hydrology of a typical tank cascade (Tirrapane). The objective of the study is to develop recommendations for better water management in cascade systems. From improved understanding of the hydrological characteristics recommendations will be developed to assist farmers within cascade to maximize returns to the limiting resource; water. This paper is developed on earlier research that developed a simple water balance model of the Tirrapane cascade (Itakura, 1995). The paper extends the earlier model and presents the calibration of an improved physically based model. Further detailed field measurements of the cascade characteristics and a longer time series of hydrological data are now available for calibration.

Study Site
The Tirrapane cascade is located about 20km south of *Anuradhapura*, Fig. 1. Table 1 summarizes key statistics for the tanks and villages in the cascade. The command area of each tank is small (less than 40ha), however each is important for sustainable agricultural production in the villages. Paddy rice is the major irrigated crop during both *Maha* and *Yala* seasons. In common with much of *Anuradhapura*, the annual cropping intensity is only around 100%, typically 75% in *Maha* and 24% during *Yala* (Agricultural statistics of Sri Lanka,1995).

Reddish Brown Earth (RBE.) and Low Humic Gley (LHG.) soil are the main series in NCP. A soil survey (summarized in Table 2) of the study site indicates that well drained RBE represent about 62% of the catchment of the Meegassagama tank. The soil map of the cascade is shown in Fig. 2.

The Agro-ecological region's classification at the study site is *DL1*. Mean monthly meteorological data from Maha Iluppallamma Agricultural Research Station, located about 8km from the study site is summarized in Fig.3. This shows that monthly Penman potential evapotranspiration exceeds rainfall for all but three months (October through December).

---

[1] International Irrigation Management Institute
[2] Department of Agrarian Services
[3] Village tanks are defined as reservoirs providing irrigation to command areas of less than 80ha.

Rainfall during the *Maha* season averages 1,120mm, a similar figure to the reference evapotranspiration of 1,010 mm. Rainfall events tends to be of high intensity and short duration resulting in rapid runoff and suggests water shortage may be expected to constrain agricultural production. During *Yala* evapotranspiration, at 1,435mm greatly exceeds average rainfall of only 371mm. Even during *Yala* rainfall tends to be concentrated during April, although runoff during this season is relatively uncommon.

During either season extended periods without rainfall can result in *agricultural droughts* when irrigation is essential for crop production. Investments in field crops are lost on occasions due to water scarcity. One objective of this study is to establish whether better water management practices can reduce the incidence of yield damaging stress by improving the scheduling of water releases. The first stage is to develop a better understanding of the hydrological processes within a typical cascade.

Field Observations

Measurements of important hydrological and physical characteristics of the Tirrapane cascade have been made during 1997 and 1998. Fig. 4 illustrates the observation network.

Hydrological observations are made twice daily at the five village tanks. Tank water levels are observed manually at all tanks. In addition an autographic record of water level is obtained from a pressure sensor in Meegassagama tank, recorded by digital logger. Releases at Meegassagama tank are measured at parshall flumes located downstream of the four tank sluices. Fig.5 presents tank water heights and rainfall observations between July 1997 and February 1998. Note that in July and August 1997 all tanks were dry.

Groundwater levels are measured daily at seven agro-wells in the Meegassagama command area and at sample wells in the command areas of the other tanks. Soil moisture records are maintained from two tensiometers located in the catchment.

Daily rainfall and evaporation measurements are made at four manually recorded rain gauges and at two evaporation pans. Daily maximum and minimum temperatures are also recorded at the sites of the evaporation measurements.

Soil physical characteristics have been determined through soil surveys conducted during September/October 1997, before the 1997/98 *Maha* season. In addition to classification of the soil series measurements included infiltration tests, soil hardness by penetrometer, soil moisture characteristics, saturated hydraulic conductivity, and dry bulk density are done.

Soil moisture characteristics are summarized in Table 3 for the most extensive soils in the Meegassagama section of the cascade. The average soil water content in the well-drained R.B.E. between saturation and soil moisture at pF3.0 is approximately 250mm.

The results of infiltration tests in the command area and tank bed of Meegassagama are summarized in Table 4. The final intake rate is relatively low, particularly for the clay soils (2.0 mm/d) and in the tank bed (0.7 mm/d). For the RBE. soils, the Kostiakov infiltration coefficient (n) is above 0.5 for the sands and RBE soil, while the clays and tank beds have an n value of below 0.5.

Water balance model

A daily water balance model is proposed for estimation of water resources in dry zone cascades, equation 1.

$$dS_t=\left\{ \sum_{i=1}^{n}(Qa_{i,t})+\sum_{j=1}^{m}(Sp'_{j,t}+Rf_{j,t})\right\} - \left\{ \sum_{k=1}^{l}(W_{k,t})+Sp_t+S\&P_t \right\} \quad (1)$$

Where:

dS_t	=	Change in tank storage (m^3)
$Qa_{i,t}$	=	Rainfall inputs to tank (m^3)
$Sp'_{j,t}$	=	Spill discharge from upstream tanks (m^3)
$Rf_{j,t}$	=	Return flow from upstream irrigation release, (m^3)
$W_{k,t}$	=	Water issue from tank, for sluice (k) (m^3)
Sp_t	=	Spill discharge(m^3)
$S\&P_t$	=	Seepage (Horizontal)&Percolation (Vertical) (m^3)
n	=	Number of surface (soil) classes considered
m	=	Number of upstream tanks
l	=	Number of irrigation sluices
t	=	time step (day)

Runoff is a function of catchment area, rainfall and soil moisture content. The general form of the runoff equation for a homogeneous soil class is shown in equation 2.

$$Qa_{i,t}=\sum_{i=1}^{n}\left[A_i*\left\{R_t-E_{i,t}-(Sm_{THi}-Sm_{i,t})\right\}\right] \quad (2)$$

Where:

A_i	=	Area of surface class (i), (m^2)
R_t	=	Rainfall at time (t) over the area, (m)
$E_{i,t}$	=	Estimated Evaporation from soil class (i) (m)
Sm_{THi}	=	Runoff threshold Soil Moisture content of soil class (i), (m)
$Sm_{i,t}$	=	Soil moisture content of soil class (i) at time (t), (m)

In this model runoff is assumed to occur once soil moisture content equal the defined threshold value (Sm_{THi}), equation 3. A conceptual model of the soil moisture regime is presented in Fig. 6. Three categories of surface are considered: open water, exposed tank bed, and the catchment. Equation 2 is rewritten for these three conditions as:

Rainfall contribution to tank water surface, in this case the tank bed is covered with water and therefore the soil is saturated and so change in soil moisture ($Sm_{1,t}$) is zero:

$$Qa_{1,t}=Az'_t*(R_t-E_{1,t}) \quad (3a)$$

Rainfall contribution from exposed tank bed:

$$Qa_{2,t}=(Az-Az'_t)*\{R_t-E_{2,t}+(Sm_{TH2}-Sm_{2,t})\quad\} \tag{3b}$$

Rainfall contribution from catchment area:

$$Qa_{i,t}=A_i*\{R_t-E_{i,t}+(Sm_{THi}-Sm_{i,t})\} \tag{3c}$$

Where:

Az	=	Maximum water surface area of tank (m^2)
Az'_t	=	Tank Water surface area at time (t), (m^2)
A_i	=	Catchment area, excluding maximum tank water area *(Az)*, (m^2)
Sm_{TH2}	=	Runoff threshold soil moisture content of exposed tank bed (m)
Sm_{Thi}	=	Runoff threshold soil moisture content of surface (i), (m)
i	=	Soil class (i = 3 to n)

Note: Qa for any soil class is zero for $Sm_{i,,t}$ less than the threshold moisture content (Sm_{THi}).

Soil moisture content is computed from equation 4, subject to the limit that $Sm_{i,t}$ does not exceed Sm_{THi}.

$$Sm_{i,t}=Sm_{i,t-1}+R_t-Evt_{i,t} \tag{4}$$

Where

$$Evt_{i,t}=\alpha(Sm_{i,t-1})*Ev_t \tag{5}$$

$$\alpha=Sm_{i,t-1}/Avm_i \tag{6}$$

Where

Avm_i	=	Total Readily available soil moisture for surface class (i) (mm/m)

Seepage losses from the tank are assumed to be a function of water spread area, equation 7.

$$S\&P_t=fz(Az'_t) \tag{7}$$

Where

fz	=	Seepage loss function, derived from observed data.

Spillway discharge is computed from the broad crested weir equation, equation 8.

$$Sp_t=K*b*(h_t-h_{crest})^{1.5} \tag{8}$$

Where

K	=	Discharge Coefficient, assumed as Unity (1.0)
b	=	Weir crest length (m)
h_{crest}	=	Weir crest level (m)

h_t = Tank water level (m)

Irrigation return flows from upstream tank releases are computed as a function of upstream release and linear distance between tanks, equation 9.

$$Rf_t = \sum_{k=1}^{m} (fy_k * W_{k,t}) \qquad (9)$$

Where

fy = Return flow ratio. $(0 \leq fy \leq 1)$

For the purposes of this study *fy* has been fixed, relative to Meegassagama at 0.2 for Bulankulama Tank and 0.4 for Vendarankulama tank.

Discharges resulting at downstream tanks due to spills at upstream tanks are computed from equation 10.

$$Sp'_t = \sum_{i=1}^{m} (\beta_{i,t} * Sp'_{i,t}) \qquad (10)$$

Where

β = Empirical coefficient.

Values for d*S*, *Sp'*, *R*, *Ev*, *Wi* and Sp in equation (1) are measured by field observations. Values for *Qa*, *Rf* and *S&P* are computed from the water balance.

Model Calibration

To calibrate the model realistic values for parameters *Qa*, *Rf* and *S&P* must be determined. Parameter values have been estimated by trial and error for different hydrologic conditions.

The model is designed to simulated runoff generation in catchments with inhomogeneous surface(soil) classes. However, for these initial simulations, the soils at Tirrapane have been assumed to be homogenous. Therefore, threshold soil moisture limits (Sm_{TH1}, Sm_{TH2}) have been determined for two conditions; firstly the catchment area (Sm_{TH3}) estimated at 330mm, and secondly the exposed tank bed, (Sm_{TH2}) estimated as 400mm. Total readily available soil moisture (Avm_i) is estimated at 300mm.

The coefficients of return flow (β) from upstream tanks have been fixed as constants for Vendarankulama (0.57) and Bulanklama (0.67).

Tank seepage losses have been determined a tank water balance during periods of no rainfall (and assumed no inflow) as a function of tank water spread area, equation 11. For Meegassagama the seepage loss is predicted as:

$$S\&P_t = -0.03 * ln(h_t) + 0.032 \qquad (11)$$

when $(0 \leq h_t \leq 2.9)$

Simulation results

Initial simulation results are presented in Fig. 7 and Fig. 8 for the calibration period. The model predicts the observed tank storage at Meegassagama reasonably well for the period before the start of reservoir spill (2/1/1998). The peak tank storage is over-estimated, as is the rate of tank drawdown following the end of spill (10/1/98). Overall the correlation coefficient (r^2) is 0.92 between the observed and simulated time series.

The components of the Meegassagama tank water balance are summarized in Table 5 for the period 22/7/97 to 22/2/98. Total rainfall in this period was 1119.4mm and pan evaporation was 855.8mm. The model indicates that 36.9% and 17.2% of the water stored at Meegassagama derived from rain falling directly on the tank surface and runoff discharge , respectively.

Return flows from irrigation releases at upstream tanks accounted for approximately 29,000m^3 (Bulankulama 20,698m^3 and Vendalankulama 8,577m^3), equivalent to about two percent of inflow. Evaporation and seepage losses from the tank are estimated at about 28.5% of total inflows. Only about eleven percent of inflow was released for irrigation, the remainder was lost to tank surface evaporation (11.5%) and spillway flow (34.3%). Approximately 27% of the total inflow remained in storage at the end of the simulation period.

Discussion

A representation of the soil moisture regime is presented in Fig.6. The water balance model presented here makes use of two parameters from the conceptual soil moisture model.

First, readily available moisture is the proportion of the total soil moisture storage available for crop use, defined as the difference in moisture content at pF2.0 and at pF3.0. pF2.0 is equivalent to field capacity, the moisture content at the end of gravitational drainage. pF3.0 is the moisture content when crops suffer the moisture stress .

Second, threshold soil moisture content (Sm_{TH}) is the moisture content at which runoff can first occur. This moisture content lies between field capacity (pF2.0) and saturation moisture content. For the RBE soils, typical of Tirrapane cascade, the threshold is assumed to be 330mm/m. Any rainfall addition to the soil profile once the computed moisture content equals 330 is assumed to be instantaneous runoff. At soil moisture contents of less than this threshold, evaporation is the only process considered as reducing soil moisture. Evaporation rates are determined from reference evaporation in proportion to soil moisture content.

Rainfall in the dry zone is characterized by intense but relatively localised storms. In such conditions runoff estimates based on areal rainfall estimates may differ significantly from observed flow rates. Spatial disaggregation of soils and rainfall is proposed as a based on daily rainfall

The average tank seepage loss is estimated at 6.2mm/d, while final intake-rate of the tank bed is 0.7mm/d. These figures are comparable with earlier estimates of tank seepage and percolation losses at Vendarakulama of 4.5mm/d, Itakura (1995).

Conclusions

A physically based water balance model has been calibrated for one system based a single season of hydrological data and measurements of the physical characteristics of the catchment. The model is shown to estimate observed time series of tank storage adequately and therefore it is proposed that the model is able to predict water availability in the Tirrapane cascade from standard meteorological observations. This model needs further refinement in order to enable adequate prediction of *Yala* season conditions as it currently overestimates tank drawdown rates after the *Maha* season. Inclusion of soil moisture parameters is believed to be essential for accurate prediction of runoff rates.

Reference

1. J. Itakura,1995; Water balance model for planning rehabilitation of a tank cascade irrigation system in Sri Lanka, IIMI, Working papers No. 37

2. Amerasinghe, U. A. , Sakthivadivel,R,Murray Rust, H.,1998;Impact assessment of rehabilitation in the Gal Oya left bank, IIMI research report 18, p.23

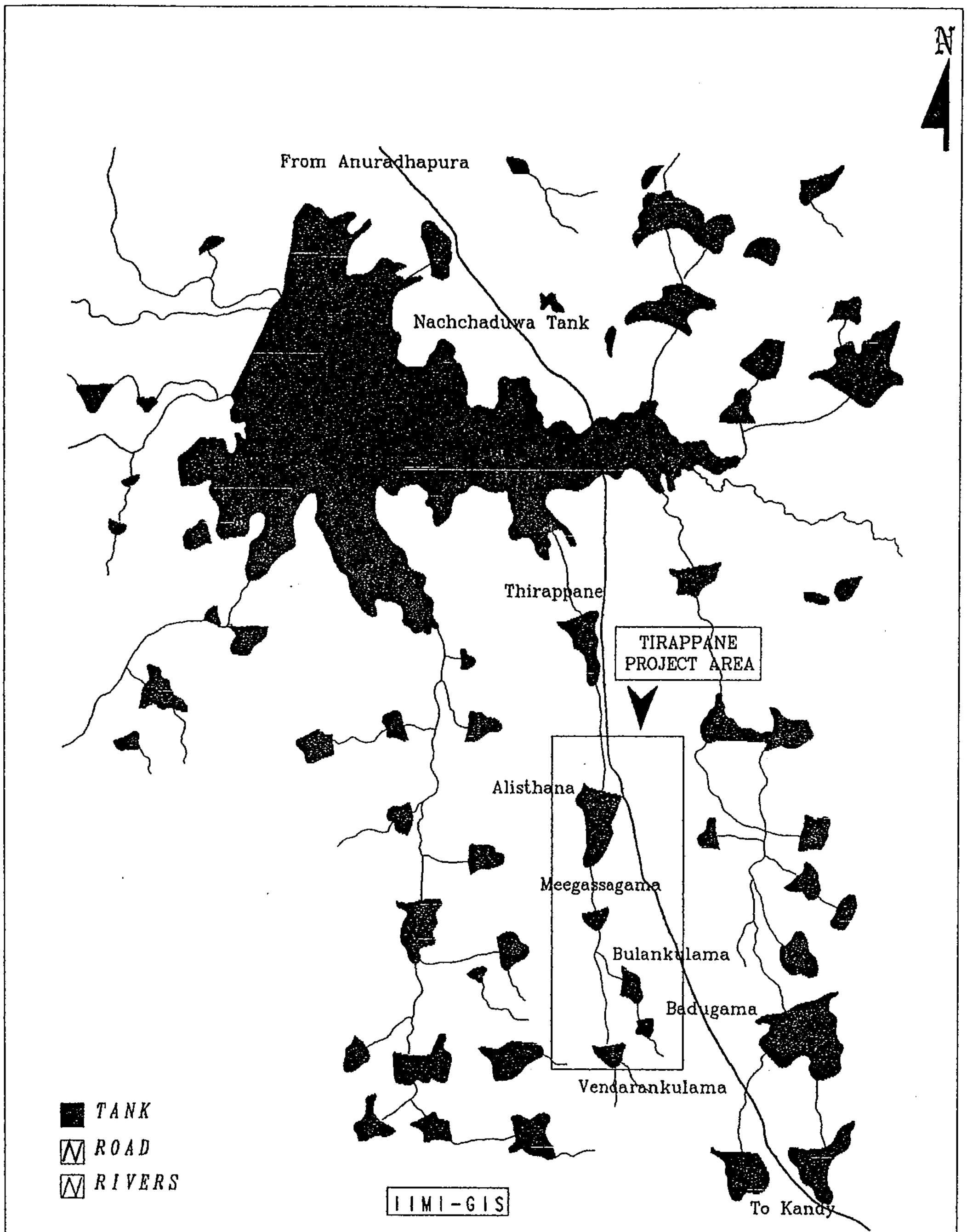

Fig:1 Nachchaduwa Tank & Neighbouring Tank Cascade System.

Table 1 General description of each tank

Tank	Nominal Command Area(ha)	Number of Families	Average Irrigated Area(km²)	Catchment Area (km²)	Height (m)	Water Spread Area(km²)	Effective capacity (m³)
Vendarankulama	18.2	17	1.07	2.4	2.9	0.11	220,000
Meegassagama	32.5	34	0.96	3.33	3.0	0.24	360,000
Alisthana	39.1	35	0.93	3.25	2.8	0.42	580,000
Badugama	2.4	2	0.55	0.25	2.2	0.04	80,000
Bulankulama	17.1	41	0.42	1.13	2.1	0.1	100,000

Table 2 Soils in the Catchment in Meegassagama

Soil type	Percentage(%)
RBE Well Drained	25.29
RBE Well Drained Moderate	24.54
RBE Well Drained Shallow	11.97
RBE Moderate well Drained	3.87
RBE Imperfect Drained	11.84
LHG Poorly Drained Moderate	10.63
LHG Poorly Drained Fine	0.81
Rock	6.98
Water	4.07

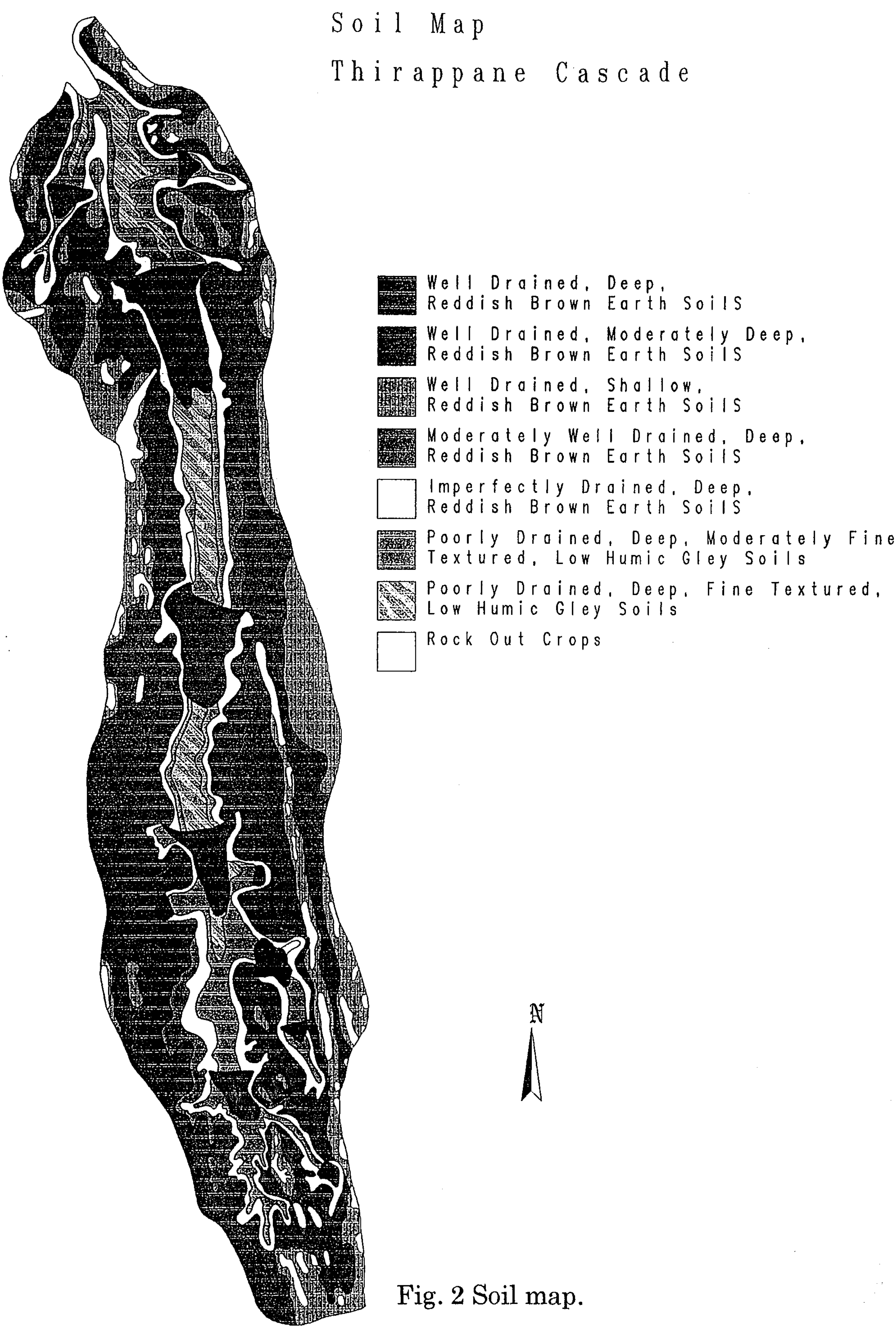

Fig. 2 Soil map.

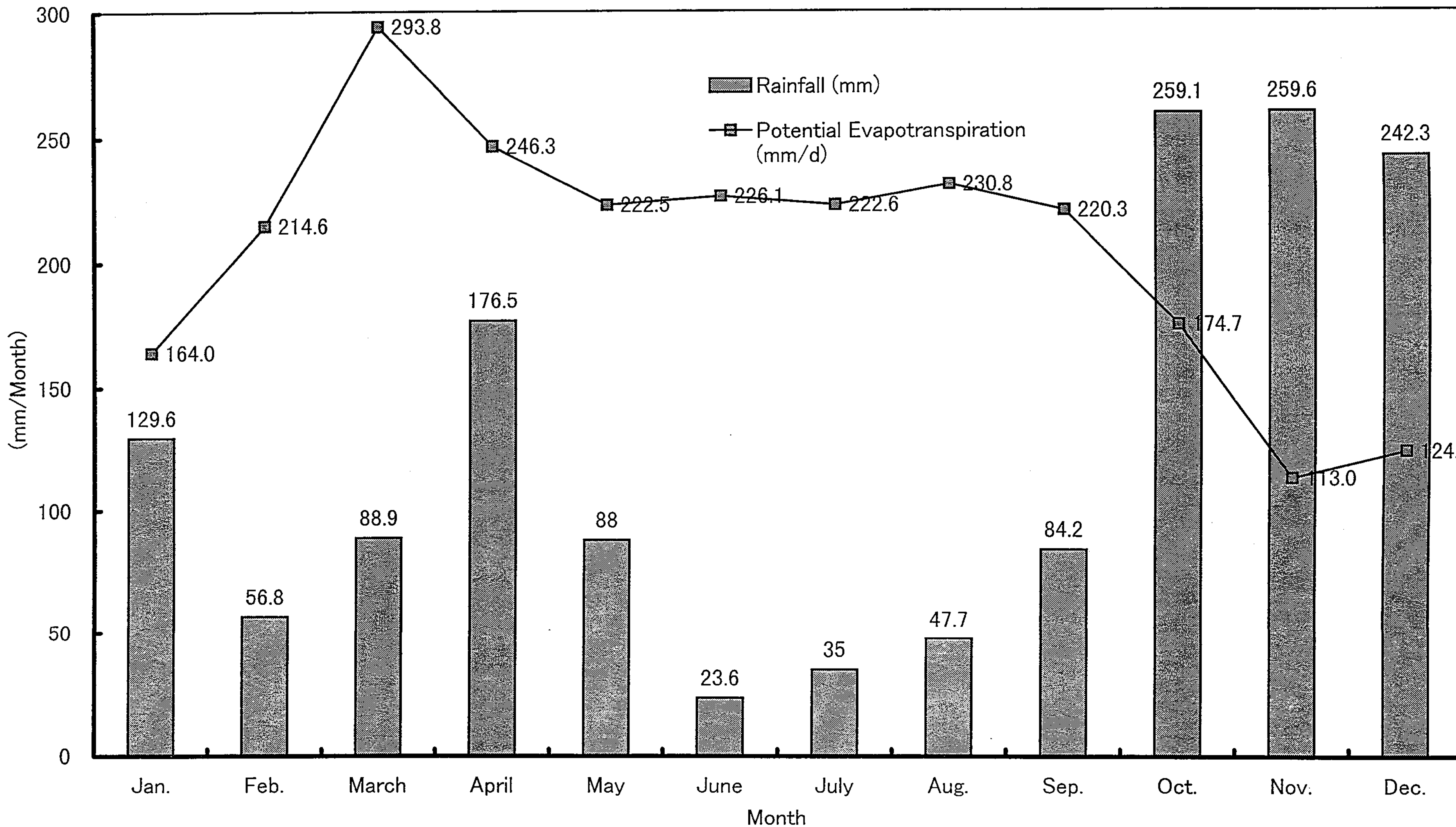

Fig.3 Rainfall and Potential evapotranspiration.

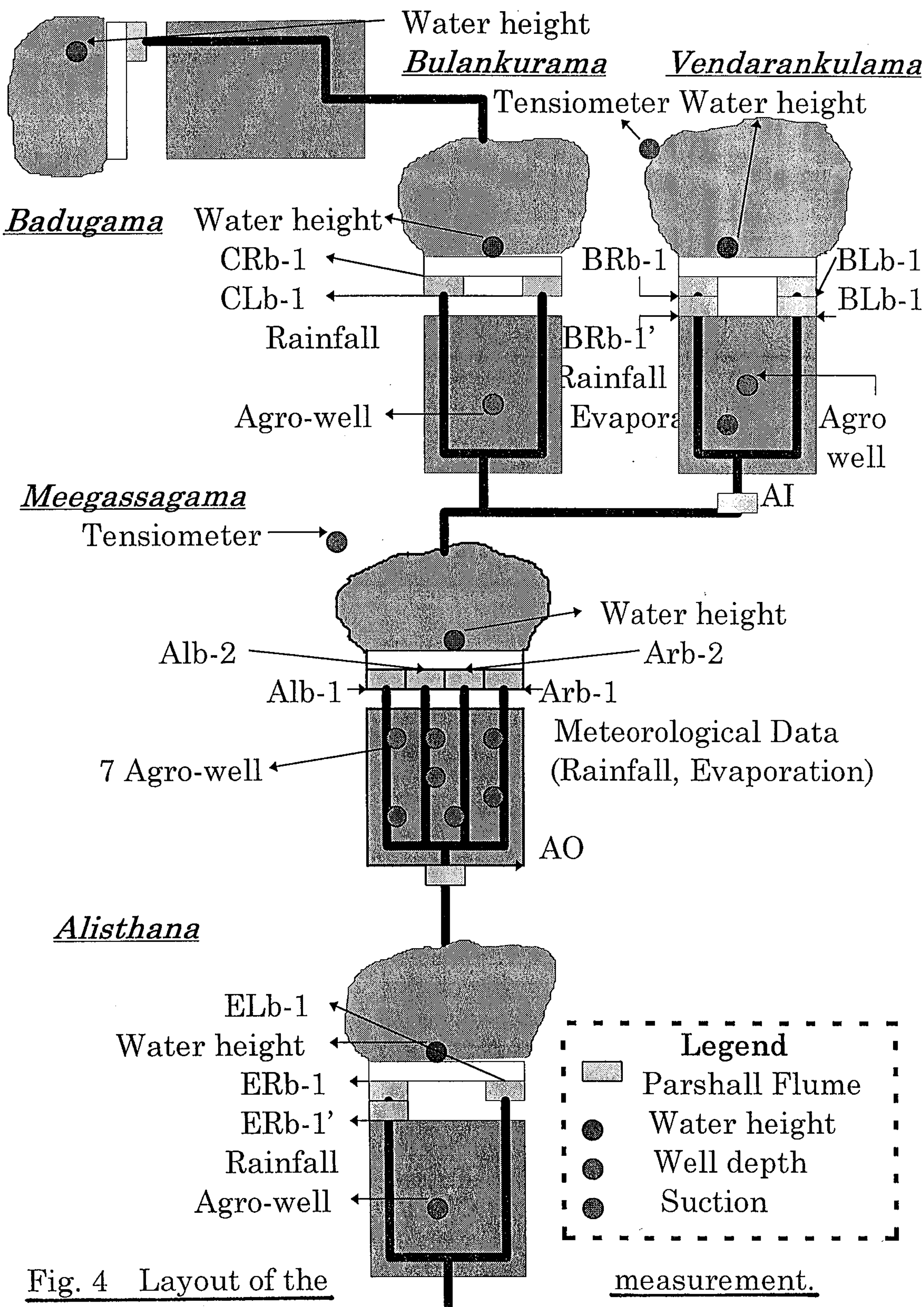

Fig. 4 Layout of the measurement.

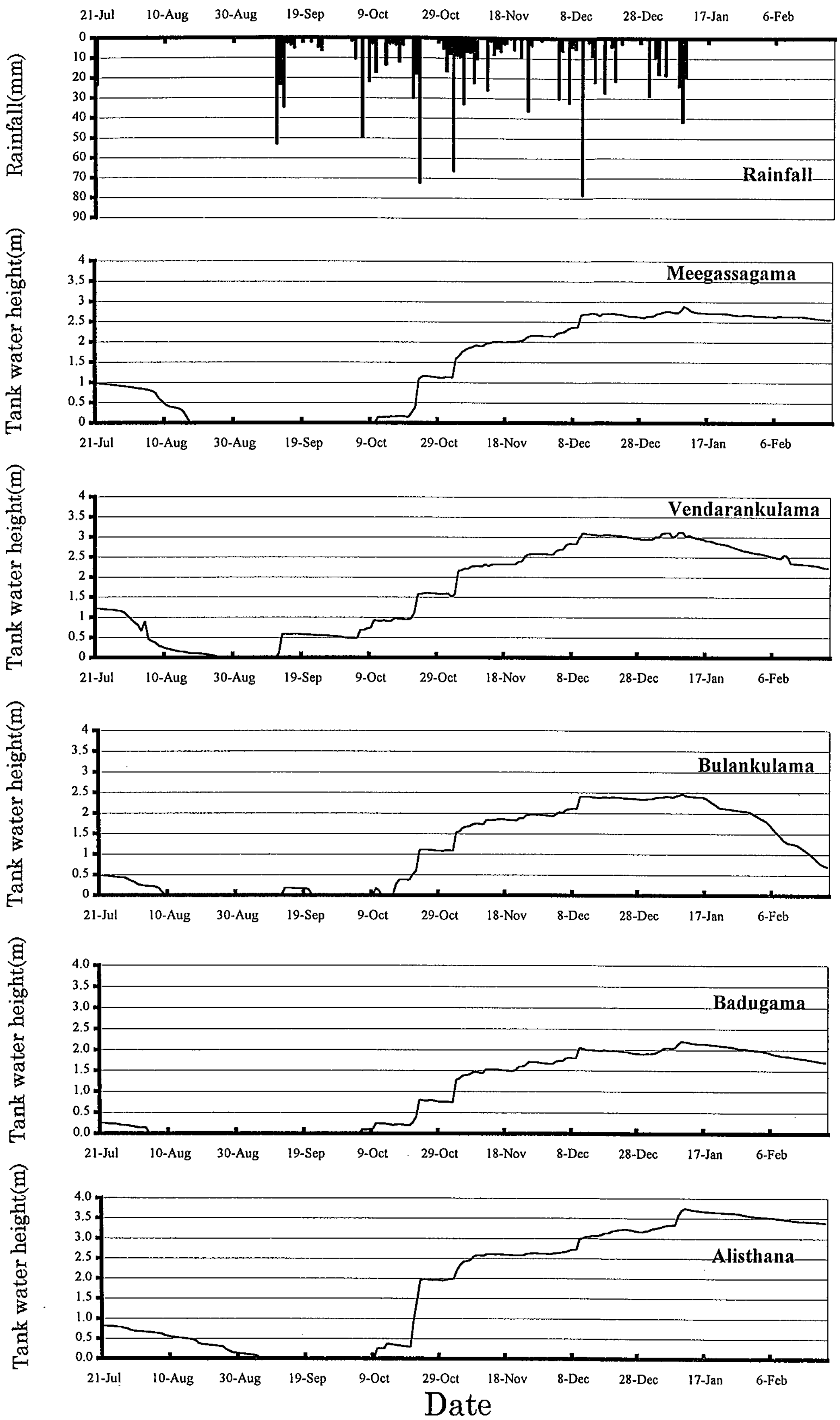

Fig. 5 Tank water height at each tank.

Table 3 Soil Physical Properties in Meegassagama catchment area.

Soil	Occupation (%)	Soil water content(%;mm/m)				
		Saturation	pF 2.0	pF 3.0	Readily available	Sat.-pF2.0 (Sat.-pF3.0)
RBE Well drained Deep soil	25.3	408	296	237	59	112 (171)
RBE Well drained Moderate deep	24.5	385	318	266	52	67 (119)

Readily available soil moisture is defined as the moisture range pF 2.0 and pF 3.0.

Table 4 Result of the Infiltration test

Soil	Initial Soil Water Content (%)	Basic Infiltration (Ib; mm/d)	Constant n	Constant c
Sand	18.84	31.3	0.57	0.44
Reddish Brown	19.27	64.4	0.55	1.01
Clay	27.36	2.0	0.33	0.24
Tank bed	31.20	0.7	0.23	0.23

$D=ct^n$ (Kostiakov Equation)

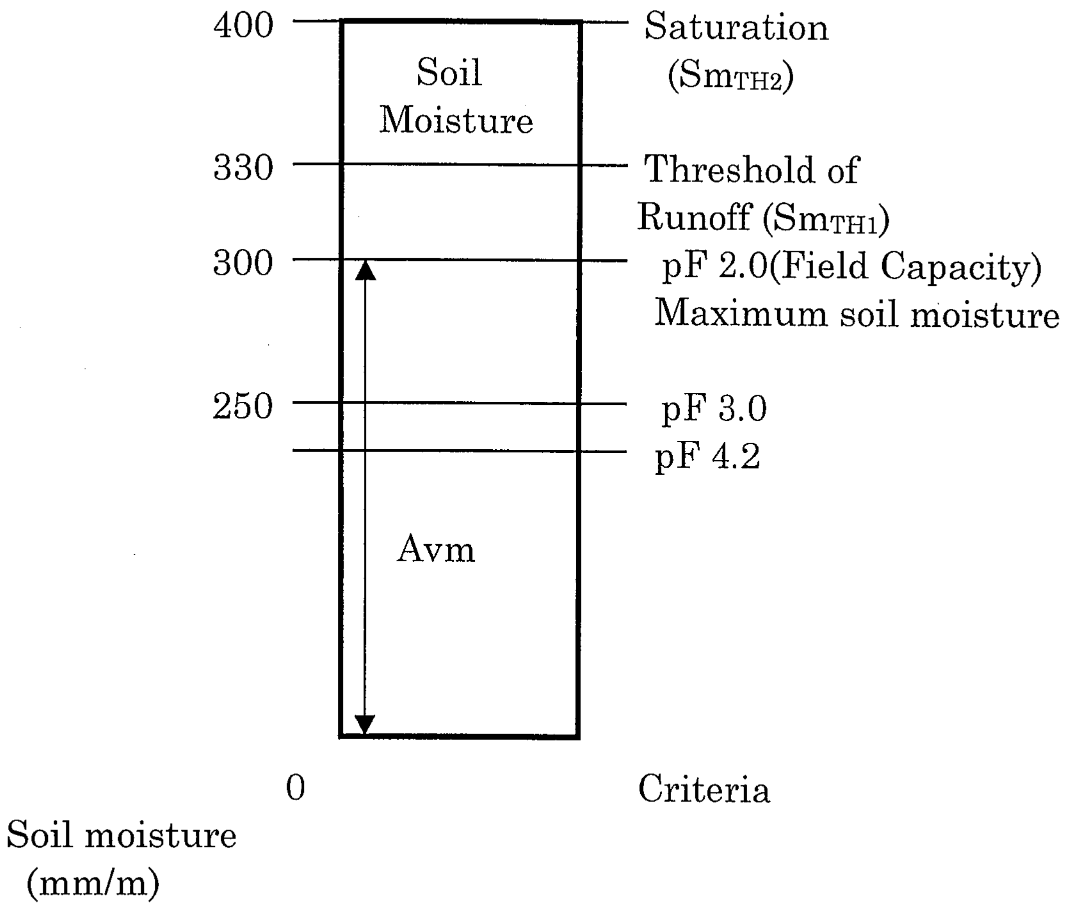

Fig. 6 Schematic idea of the model on soil moisture.

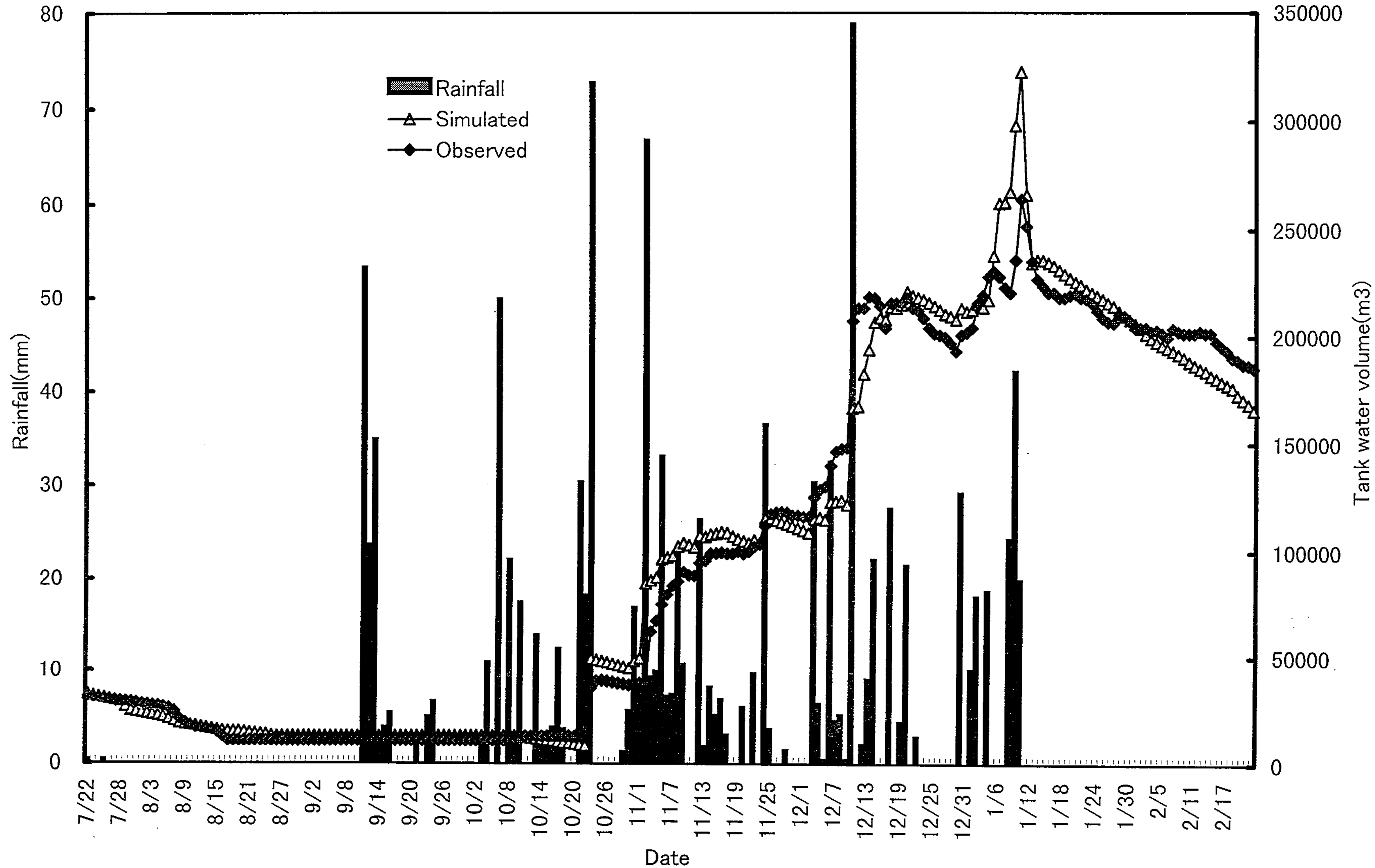

Fig.7 Tank water volume(Simulated and observed).

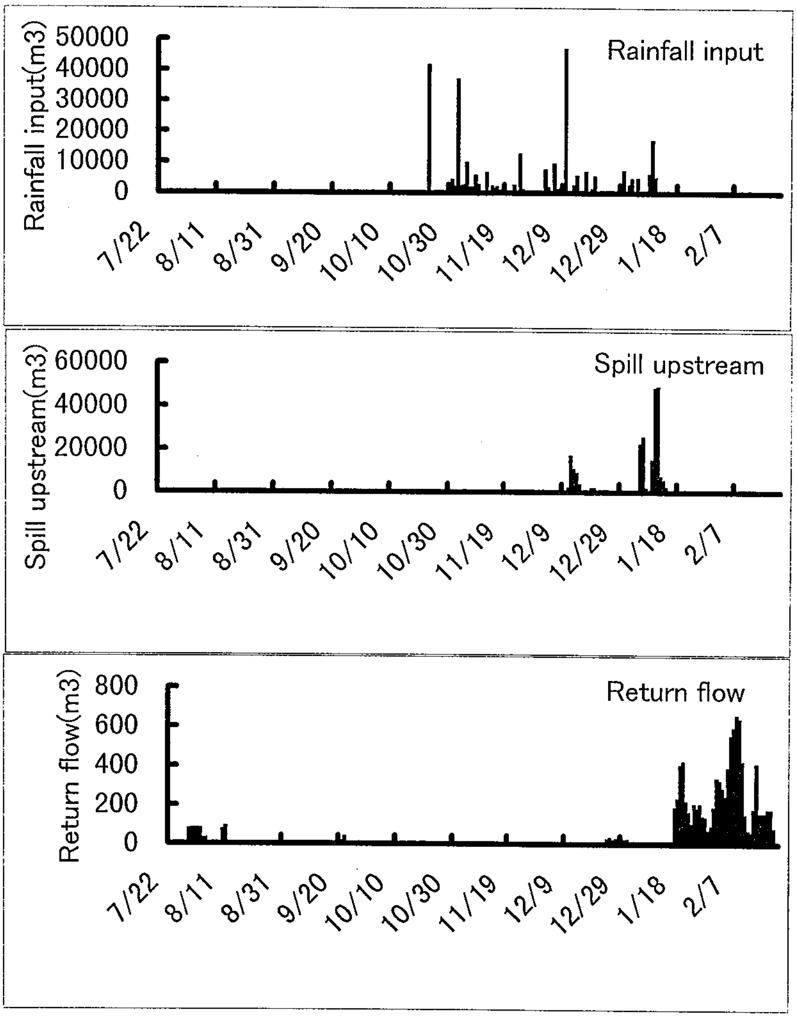

Fig. 8 Simulated result of each component(Input).

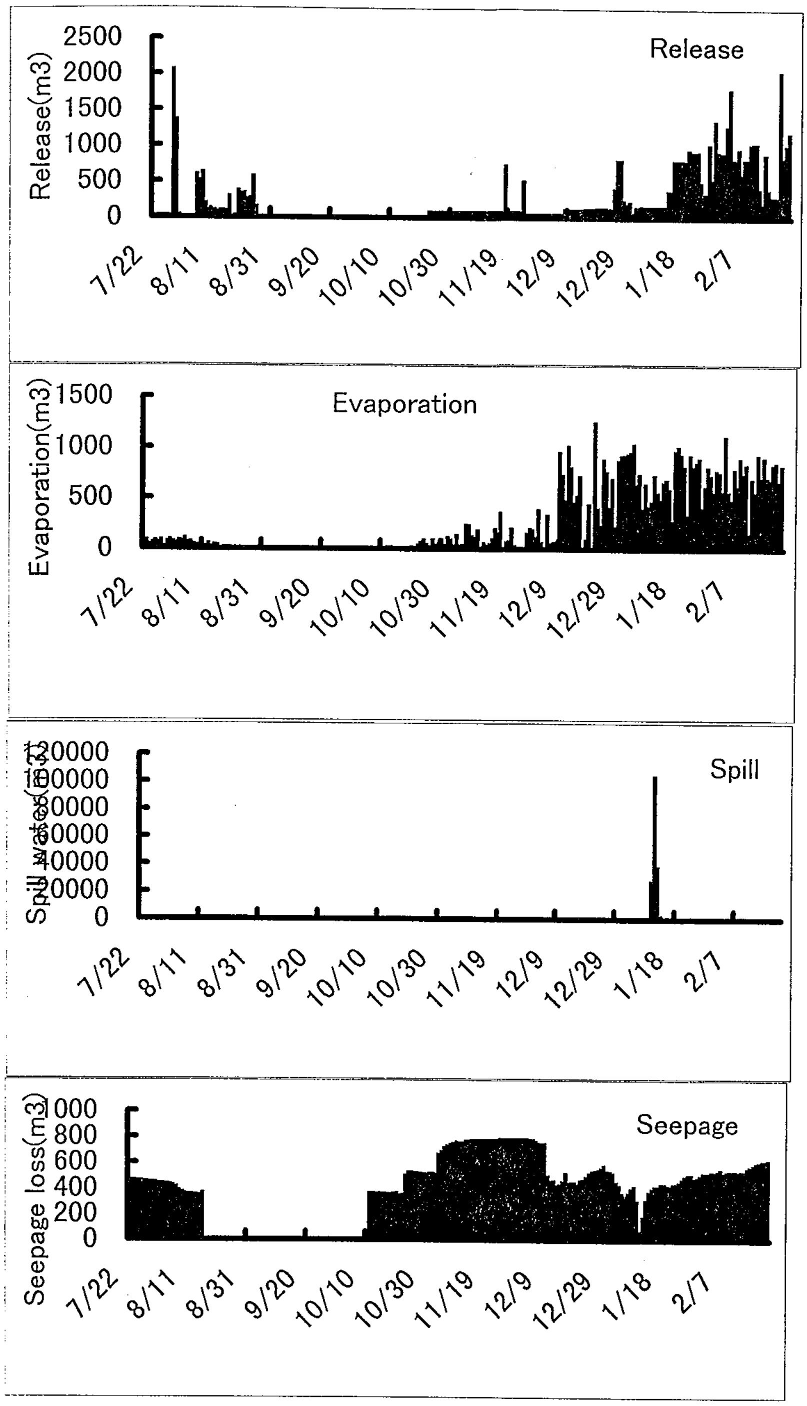

Fig. 8 Simulated result of each component(Output).

Table 5 Water balance around Meegassagama

	Rainfall	Runoff	Return Flow	Spilled water	Total
Input(m^3) (%)	269,538 (36.9)	85,650 (17.2)	9,994 (2.0)	218,246 (43.9)	497,778 (100.0)
	Release	Seepage loss	Evaporation	Spill water	Total
Output(m^3) (%)	52,946 (14.5) (10.6)*	84,395 (23.1) (17.0)*	56,998 (15.6) (11.5)*	170,845 (46.8) (34.3)*	365,184 (100.0) (73.4)*

Initial Volume; 32,722m^3, End Volume; 165,316m^3

Periods; July 21,1997 to February 14,1998

( ) mean percentage, while ( )* mean percentage of inflow