A COMPARATIVE STUDY OF THE APPLICATION OF TWO CATCHMENT MODELS TO THE BABAK RIVER BASIN LOMBOK ISLAND - INDONESIA

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By

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Abstract

A common problem in water resources planning in Eastern Indonesia, particularly in the Province of West Nusa Tenggara (NTB), is the lack of streamflow data. In general the available runoff data do not cover periods of more than one decade and are often insufficient for design purposes. Rainfall data, however, can have records that are two or three decades in length. To extend the length of the streamflow records, rainfall data may be transformed into streamflows using a catchment rainfall-runoff model. Two conceptual catchment models, the Tank Model and Mock's Model, are proposed for this transformation of rainfall into runoff. Both models require mean areal precipitation and evapotranspiration as inputs. The Tank Model requires daily inputs values, while Mock's Model requires monthly input values. Two variations of the Tank Model (configurations with three and four tank components) were studied.

Three year data periods (1973-1975) were employed for calibration, and the subsequent three year periods (1976-1979) were used for verification. By a trial and error method, a set of parameters for the four component Tank Model were obtained and suggested for modelling daily runoff of the Babak River. The model with three tanks did not give a good representation of low flows. By the same method, a set of parameters

for the Mock Model were obtained; these are considered satisfactory for monthly flow modelling. Mock's Model is considered suitable for preliminary water resources studies, where monthly time steps are appropriate. The choice of a suitable model varies with the purposes and the availability of data. Additional rain gauges in the basin are recommended to improve the results of the model. For basins located near the Babak River basin and for basins with similar catchment characteristics, the obtained parameters for both the Tank Model and Mock's Model can be used as initial values.

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Abbreviations

°C	:	Degree in Centigrade
Ditjen Air	:	Directorate General of Water Resources Development (under the Ministry of Public Works of Indonesia)
Fig.	:	Figure
Kecamatan	:	Sub District
km^2	:	Square Kilometres
$km\ hr^{-1}$	:	Kilometre per hour
$mm\ day^{-1}$	:	Millimetres per day
mm	:	Millimetre
Mt.	:	Mount
NTB	:	West Nusa Tenggara Province
P3SA-NTB	:	Water Resources Development Planning Study
WMO	:	World Meteorological Organization

Chapter 1

Introduction

1.1 Background

Water resources planners in Lombok Island, as well as in other islands in Eastern Indonesia, face problems with regard to the availability of streamflow data. Only few river basins have substantial continuous records of streamflow. Most have data for a short period or none at all. The Government of Indonesia (through the Ministry of Public Works) began installing streamflow measurement instruments during the early 1970s. Financial difficulties and natural disasters, such as floods, however, have led to discontinuities in the records in several years. On the other hand, rainfall data are available for longer periods of record, due to the fact that rainfall measurement is simpler and requires less skilled labour.

This thesis concentrates on the Babak River basin which shares these runoff data problems. The Babak River basin in Lombok Island (Fig. 1.1) has several years of streamflow observation. From an engineering point of view, such a short period of record is insufficient for water resources planning. An irrigation project, for example, requires at least 20 years or more years of recorded streamflow data in order to determine the yield reliably. For water resources planning purposes, a lack of streamflow

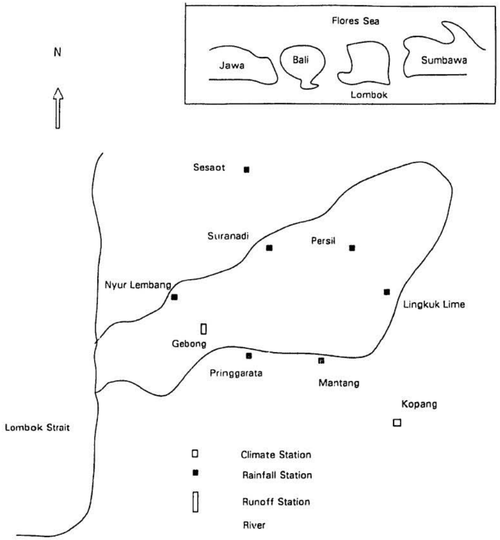


Fig. 1.1: Babak River Basin

data can lead to either an underestimation or overestimation of the project cost or, conversely, an underestimation or overestimation of the size of the target service area. To solve the problem of the shortage of runoff data, transformation of rainfall data into runoff data is required. Catchment modelling is one of several methods to accomplish such transformation.

The purpose of this thesis is to carry out a detailed assessment of a daily catchment model as applied to the Babak River basin, and compare the results with a monthly model. The model used is the Tank Model (Sugawara, 1961, 1967), using either daily or monthly time steps. The reasons for the choice of this model are: (1) the model has been used for several river basins in Indonesia with good success and (2) because of its simplicity, where all mathematical operations can be perform on a pocket calculator, makes the model suitable for areas with limited computer facilities, such as the case in Lombok.

As a comparison, Mock's Model (which is designed for monthly time steps only) was also used. It is considered suitable for preliminary planning in which monthly flows is more important than daily flows. Mock's Model is chosen because it was developed based on the particular features of the Indonesian climate. This model has been adopted by the Ministry of Public Works of Indonesia and is recommended for use throughout the country, especially for irrigation planning (Ditjen Air, 1985).

1.2 Available Data

Collection and observation of runoff data from the Babak River at Gebong was undertaken from 1973 until 1985. Several years of data are missing. However, six complete years of data are available. The catchment area upstream of the gauging station is 194 km^2. Rainfall data in the basin are available for the period from 1970 to 1989. However, these records show some discontinuity and some missing data for several years. This is usually caused by the malfunctioning of the rainfall gauging instruments or by a change of the gauge location. In addition, climatic data are available from the nearest station (Kopang), for a nine year period. The available data are presented in Table 1.1.

1.3 Objectives of the Study

The objectives of the study can be stated as follows:

1. To obtain suitable parameters of the Tank Model for the Babak River Basin, which can be used to transform the daily rainfall data into daily runoff data. By summing up the daily runoff data, the monthly runoff data can be obtained for comparison with the monthly model.
2. To obtain the parameters of Mock's Model for the Babak River basin, which can be used to transform the monthly rainfall data into the monthly runoff data.
3. To compare the monthly results of both models and make recommendations to the agencies and professionals concerned with water resources development in Lombok Island and other Islands in Eastern Indonesia.

Table. 1.1: *Available Data for the Babak River Basin*

A. Precipitation and Runoff

Station Name	Data Type	1973 1974 1975 1976 1977 1978 1979 Jfma..sond Jfma..sond Jfma..sond Jfma..sond Jfma..sond Jfma..sond Jfma..sond	Remark
Suranadi	Precipitation	**==	Available untill 1988
Persil	Precipitation	==***********	missing untill 1982, then available until 1986
Lingkuk Lime	Precipitation	==*******	missing till 1980 then available until 1988
Mantang	Precipitation	==	Available untill 1990
Pringgarata	Precipitation	==	Available untill 1990
N. Lembang	Precipitation	=====================***==	Available untill 1988
Sesaot	Precipitation	*******===	Available untill 1988
Gebong	Runoff	****===**================****	Available untill 1983, but several month are missing

B. Climate

Station Name	Data Type	1980 1981 1982 1983 1984 1985 1986 Jfma..sond Jfma..sond Jfma..sond Jfma..sond Jfma..sond Jfma..sond Jfma..sond	
Kopang	Climate	***===	Available untill 1989

* missing data

1.4 Outline of the Thesis

The background of the thesis has been presented in the previous section along with the objectives of the study. The next chapter describes the study area. Theoretical considerations of the models are discussed in Chapter 3. The methodology used for calibration and verification is discussed in Chapter 4. The summary of the results and a discussion described are in Chapter 5. Finally, the conclusions and recommendations of the study are presented in the Chapter 6. The appendices can be found after the references.

Chapter 2

Description of Study Area

2.1 Study Area and Land Use

The Babak River is located in Lombok Island, Indonesia (Fig. 1.1). This region lies just south of the equator, between 8.5° and 8.7° South Latitude and between 116° and 116.5° East Longitude. The head waters are located on the south western side of Mt. Rinjani (elevation 3726 m). The total catchment area is 286 km^2 (or approximately five percent of the whole island), which makes it the second largest basin on the island. The main land uses of the basin are presented in Table 2.1.

Table 2.1: Land Use of Babak River Basin, (1985)

No	Type of Land Use	Percentage
1	Horticulture	35
2	Paddy fields	28
3	Forests	32
4	Villages	5

The population of Kecamatan Narmada and Kecamatan Mantang, the two subdistricts within the basin, is 92,516 (1985). The population is employed mainly in the agricultural industry. There are also minor employment opportunities in trade, government administration and private services.

2.3 Climate and Hydrology

The basin has a tropical climate with temperatures ranging from about 25° to 29°C. The daily wind speed is light, averaging 5 km/hr. There are two distinct seasons, a wet season and a dry season. The wet season is from November to April and the dry season is from May to October. The climate is strongly influenced by altitude. Precipitation in the lower basin is considerably less than in the upper basin. Seven rainfall gauges are in operation both within and around the basin. The lengths of record vary from three years to more than twenty years.

Rainfall in this region displays a diverse spatial pattern. Downstream of the river basin, for example, at Gerung, the mean annual rainfall is 1496 mm; the highest recorded was 2152 mm, the lowest was 876 mm. In the central part of the basin, the mean annual rainfall is 2051 mm; the highest recorded was 2726 mm, the lowest was 1064 mm. Upstream, where the elevation is higher, the mean annual rainfall is 2418 mm; the highest recorded was 4125 mm; the lowest recorded was 1415 mm.

2.2 Sources of Data

The data for this study were obtained from the sources listed below.

1. Hydrology Section (NTB Provincial Water Resources Division) provided the rainfall and climate data.

2. South Lombok Irrigation Project provided the runoff data.
3. NTB Regional Office of the Central Bureau of Statistics provided the population data, as well as the land use data.
4. NTB Water Resources Development Planning Study (P3SA-NTB), Division of the Provincial Wate: Resourcer Service provided the gauging locations, some climate data, and also some runoff data.

Chapter 3

Rainfall-Runoff Models

3.1 General

This chapter discusses two rainfall runoff models which are used to transform rainfall data into streamflows data for the Babak River. The first model is the Tank Model, a lumped-conceptual model which is based on daily rainfall data. The second model is Mock's Model, also a lumped-conceptual model, but Mock's Model uses monthly data as its input. The Tank Model is categorized as a conceptual catchment model which has no limitations on its use either in geographical area or in the size of basin. Mock's Model is also a conceptual model; the use so far has been limited to Indonesia. The input requirements for both models are discussed at the end of this chapter.

3.2 Tank Model

The Tank Model was developed by Sugawara (1961, 1967) based on the analysis of data collected from several Japanese rivers. During the early stages of development, the model was designed as either a simple or a storage tank model. A simple tank model consists of only one tank with one side outlet at the bottom. A storage type model consists of a tank with either one or more side outlets above the bottom and one bottom outlet. Later, a combination of simple and storage tank models, arranged either serially or in parallel was used. The next few sections discuss the Tank Model and the basic theory underlying the model.

3.2.1 The structure of the Tank Model

The Tank Model is a simple model which consists of several tanks, vertically ordered either in series, parallel or a combination. Fig. 3.1 (a), shows a series type of the Tank Model which is used in this study. The input (which represents an equivalent value of mean basin rainfall) enters the first tank. Some of the accumulated water will flow through the side outlet and some will infiltrate down into the second tank. The process is repeated for each of the lower tanks.

Evapotranspiration from the basin is taken into account by extracting a specified amount of water from the first tank, or from the lower tank if there is no water available in the first tank. The calculated discharge is the sum of the outflows from each tank. From Fig. 3.1 (b), it can be seen that the model also represents the zonal groundwater profile.

3.2.2 The behaviour of the Tank Model

In spite of the simplicity of its structure, the behaviour of the Tank Model is quite complex and various types of responses have been described based on several types of rainfall input. Consider for example, a Tank Model which consists of three tanks, arranged vertically as shown in Fig. 3.2. The first tank output is related to direct runoff,

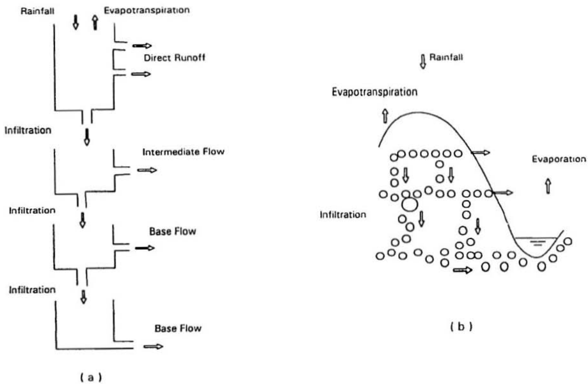


Fig. 3.1: Tank Model Structure. (a) Vertically Series Storage Type; (b) Zonal Groundwater Profile.

while the second and the third tank outputs are related to intermediate and base flow respectively. Four alternative inputs and their responses are given below (Sugawara et al., 1984).

a. Low Precipitation

If inputs representing low precipitation are added into the model, the water accumulation in the first two tanks will not reach the level of the side outlet as shown in Fig. 3.2 (a). Therefore, the rainfall will infiltrate down into the third tank without any outflow from the first and second tanks. Consequently, the storage in the third tank will show little change due to additional infiltration from the second tank. Because the storage remains approximately constant, the outflow from the third tank will have little change. The storage in the third tank corresponds to groundwater storage. In a real river basin, base flows are nearly constant because there is a large amount of groundwater storage. Accordingly, if there is low precipitation over the basin, there will be little change in the river flows.

b. Moderate Precipitation

If inputs representing moderate precipitation are introduced into the model, the water storage in the first tank will not reach the level of the side outlet, but the water level in the second tank will rise to the level above the side outlet as shown in Fig. 3.2 (b). Therefore, there will be a discharge from the second tank. Accordingly, if moderate precipitation occurs over the river basin, the river discharge will increase slowly and then will gradually decrease.

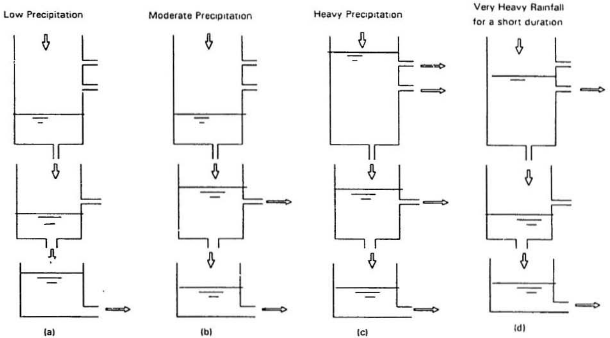


Fig. 3.2: Tank Model characteristics. (a) Low precipitation will cause increasing storage in the first and second tank, but the water level will not reach the side outlet level, and water will infiltrate to the third tank and cause a little change in the storage and discharge from the third tank. (b) Moderate precipitation will lead to an increase in storage in the second tank, with outlet discharge; (c) Heavy precipitation will increase storage in the first and second tank. Large discharge will occur from the first tank, then reduce quickly to intermediate discharge from the second tank; (d) Very heavy rainfall for a short duration will increase storage in the first tank and produce discharge from it, but no water will be discharged from the second tank.

c. Heavy Precipitation

If inputs representing heavy precipitation are added to the model as shown in Fig. 3.2 (c), the storage in the first and second tanks will rise up quickly, exceeding the level of the side outlet. As a result, the discharge will also increase quickly. The discharge comes mainly from the side outlet of the first tank, which represents the surface flows. The amount will be large, but it will reduce quickly until the remaining discharge takes the form of intermediate flows. Similarly, in a real basin, if heavy precipitation occurs, the discharge in the river will increase rapidly to reach the peak discharge, then quickly reduce to the intermediate discharge level.

d. Very heavy rainfall with a short duration

If the input represents very heavy rainfall with a short duration, the Tank Model would appear as shown in Fig. 3.2 (d). There will be discharge from the first tank without intermediate flow from the second tank. Over time, however, the condition would revert to the condition of (c), and with intermediate flow from the second tank. In some cases, for very heavy rainfall with a short duration, however, only surface flows appear, without intermediate flows.

3.3 Theoretical basis of the Tank Model

3.3.1 Simple Tank Model.

The simple Tank Model, also called the exponential type model, consists of a tank with a side outlet at the bottom. This model is based on the hypothesis that the discharge from a tank is proportional to the storage depth above the outlet. Consider for example, a simple Tank Model with a storage height of $h(t)$ as shown in Fig. 3.3 (a). The flow $q(t)$ can be written as follows:

$$q(t) = h(t) \quad \alpha \tag{3.1}$$

where: $q(t)$ is the out flow (mm/day), $h(t)$ is the storage height (mm) and α is the outlet coefficient (day^{-1}). Assuming, that there is no additional water in the tank, from time t = 0 to t = 1 or (Δt = 1), the decreasing storage height from height h_o at time t=0 to height h_1 at time t=1 is Δh, therefore the outflow q can be expressed as:

$$-q = \frac{dh}{dt} \tag{3.2}$$

The minus sign means that the discharge is an outflow. If the initial outflow is q_o, with respect to equation 3.1, the water storage and outflow will decrease exponentially with elapsing time. Thus, equation 3.1 can be written:

$$q(t) = q_o \exp\ (-\ \alpha\ t) \tag{3.3}$$

where; q_o = q at t = 0.

If q_o= h α, a constant flow, the storage volume will drain out after time T.

$$T = \frac{h}{\alpha\ h} = \frac{1}{\alpha} \tag{3.4}$$

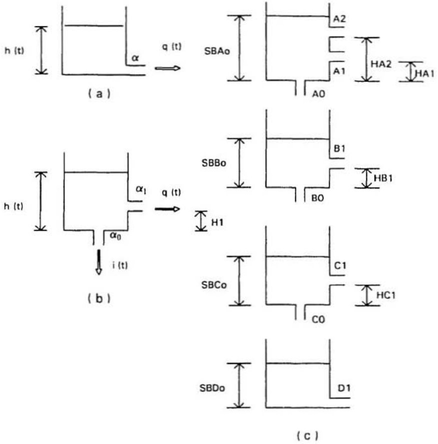


Fig. 3.3 Tank Model Types. (a) Simple Tank Model (b) Storage Type Tank Model; (c) Series Storage Type Tank Model with its Parameters Notations

where T is the time required for depleting the storage volume. T is called the *time constant*, which is used for determining the initial parameters of the Tank Model. In case there is additional input (p) either from precipitation or infiltration from the preceding tank, the outflow (q) is a special case of the unit hydrograph. Sugawara (1961) solved the relationship between the input (p) and output (q) from such tank as follows:

$$q(t) = \int_0^{\infty} p\ (t-s)\ \alpha e^{-\alpha s}\ ds \tag{3.5}$$

where q (t) is outflow, s is a function of storage and α is an outlet coefficient.

3.3.2 Storage Type Model

The storage type model is based on the hypothesis that both discharge and infiltration are functions of the stored water. Fig. 3.3 (b), shows the storage type model. If the height of the storage in the tank is $h(t)$, and $h(t) < H_1$, there is no outflow from the tank. Therefore, the value of H_1 is analogous to the initial loss for soil moisture retention. This type of tank is usually used in the top or second position. For the storage type tank, the outflow of $q(t)$ and the infiltration $i(t)$ can be expressed as follows (Sugawara cited in Sumarto, 1987):

$$\begin{aligned} q(t) &= (h(t) - H_1)\ \alpha_1 \\ i(t) &= h(t)\ \alpha_0 \end{aligned} \tag{3.6}$$

where α_o and α_1 are the coefficient of the bottom and side outlet expressed in units of day $^{-1}$ and H_l is the height of the side outlet. These equations have the condition that $h(t) > H_l$.

3.3.3 Series Storage Type Model

The series storage type model used in this study denotes a vertically ordered configuration, as shown in Fig. 3.3 (c). This structure corresponds to the zonal structure of the underground water profile as mentioned earlier. This structure also explicitly represents the three components of discharge: high, intermediate, and base flows. The series storage type model is the type that is most often used for low flow analysis or flood analysis. The complete mathematical description of the series storage type model, however, is very complex since it consists of several tanks with non-linear equations.

3.4 Mock's Model

Mock (1973) developed a rainfall runoff model based on his experience in analyzing hydrological data in Indonesia. The model is based on the Thornthwaite Water Balance Model (1948) with some modifications and additional components and parameters. The changes are: the utilization of Penman's method instead of Thornthwaite's method for the calculation of potential evapotranspiration, additional components of base flow and storm runoff, and a modification in the calculation of actual evapotranspiration. In this thesis, however, the actual evapotranspiration is calculated based on the recent modifications proposed by the Institute of Hydraulic Engineering Bandung (1991).

3.4.1 Soil Moisture

Two properties of soil moisture which are relevant to Mock's Model are Soil Moisture Capacity and Soil Moisture Surplus.

a. Soil Moisture Capacity

Soil moisture capacity is defined as the capability of the soil to retain water. Depending on the type and structure of soil and the type of vegetation growing in the surface, the soil moisture capacity can range from one or two centimetres per 30 centimetres depth for sandy soil to ten centimetres or more for clay (Thornthwaite and Mather, 1957). For Indonesia, where the soil type is volcanic, the soil moisture capacity ranges from 200 to 300 mm. This value is comparable to other volcanic regions such as Costa Rica (Calvo, 1986). The soil moisture during any given month is determined by the soil moisture of the preceding month, minus the water loss over that month. The water loss is defined as the difference between the precipitation and the actual evapotranspiration. In the event that the difference is greater than zero, the water loss is equal to zero since the amount of precipitation can meet the requirements for evapotranspiration. If, however, the difference is less than zero, the soil moisture of that particular month will decrease. This means that the available precipitation fails to supply the potential needs of the vegetation.

b. Soil Moisture Surplus (Water Surplus)

Water surplus is defined as the excess of water available for runoff and infiltration. It occurs mainly during the rainy season, when precipitation is always greater than evapotranspiration. The values of the water surplus can be obtained by simple calculation, with precipitation treated as an input, potential evapotranspiration as output, and soil moisture as a reserve which can be drawn on and refilled (whenever the precipitation is larger than evapotranspiration and the soil moisture values below its capacity).

3.4.2 Groundwater Storage and Runoff

The calculated runoff is derived from three model components: base flow, direct runoff and storm runoff (Fig 3.4). To calculate the runoff from the model, the following working assumptions are made (Mock, 1973).

a. The infiltration should be proportional to the monthly water surplus. In order to determine the infiltration rate, the coefficient of infiltration can be estimated by considering the geological structure and topography of the basin. A cross check of this calculation can be performed by either checking the maximum storage value derived from the calculation or by comparing the calculated water surplus with the actual runoff.

b. The groundwater flows into the surface stream are proportional to the storage volume *V*:

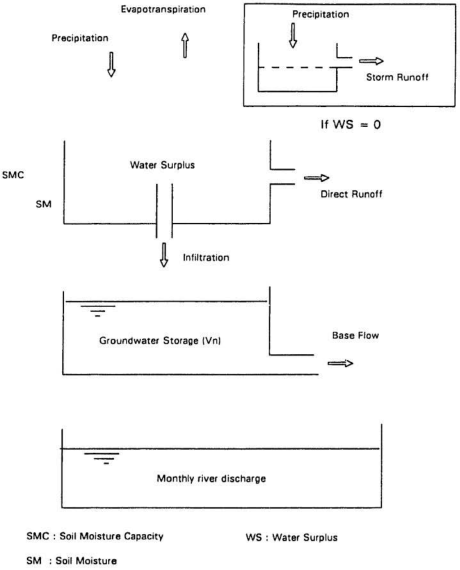


Fig. 3.4: Mock's Model Diagram

$$q = 2\,a\,V$$

$$V = \frac{q}{2a} \tag{3.7}$$

where a is assumed to be a constant with the time differential $\Delta t = 1$ month, q is the flow (mm/month) into surface streams and V (mm) is the groundwater storage. c. In the case where there is no infiltration, the recession of groundwater flows follows the principle

$$q_t = q_o\,K^t \tag{3.8}$$

where K is assumed to be a constant with the time differential $\Delta t = 1$ month. The relationship between a and K is given by Mock (1973) as:

$$K = \frac{(1 - a)}{(1 + a)} \tag{3.9}$$

or

$$a = \frac{(1 - K)}{(1 + K)} \tag{3.10}$$

In reality the recession flows do not exactly follow the above formula as K increases with time. This means that the groundwater flows faster than its assumed value at the beginning and more slowly over time.

d. The storage volume (V_t) is calculated as follows (Mock, 1973):

$$V_t = V_{t-1} + I\,\Delta t - \frac{1}{2}\,(q_{t-1} + q_t)\,\Delta t \tag{3.11}$$

where I is the infiltration at time t and q_{t-1} is the outflow at time t-1. From equation 3.7, equation 3.11 becomes:

$$V_t = \frac{1 - a\,\Delta t}{1 + a\,\Delta t}\,V_{t-1} + \frac{\Delta t}{1 + a}\,I \tag{3.12}$$

For $\Delta t = 1$ month, then

$$V_t = \frac{1 - a}{1 + a}\,V_{t-1} + \frac{1}{1 + a}\,I \tag{3.13}$$

Simplifying, it can be written as:

$$V_t = K\,V_{t-1} + \frac{1}{2}\,(1 + K)\,I \tag{3.14}$$

where V_t is the groundwater storage at time t, and K is the monthly recession coefficient. The base flows are calculated based on the differences between the infiltration and the changes in groundwater storage. It can be expressed as follows:

$$
\begin{aligned}
Q_t &= \frac{1}{2}\ (q_{t-1} + q_t)\ \Delta t \\
&= I\ \Delta t\ -\ (V_{t-1}\ -\ V_t) \\
&= I\ \Delta t\ -\ \Delta V
\end{aligned}
\tag{3.15}
$$

where Q_t is the base flow at time t. The direct runoff is calculated from the difference between the water surplus and the infiltration. The calculated runoff is a summation of the direct runoff and the base flow. In the event that the soil moisture is below capacity, an iterative procedure is required to obtain the soil moisture and soil storage at time t. This procedure is discussed in detail in Chapter 4.

3.4.3 Storm Runoff

The storm runoff component of the model was proposed by Mock (1973), and is based on the phenomenon that during the dry season when there is no water surplus, some direct runoff occurs as a result of storm rainfall. The amount of the storm runoff is assumed to be a small percentage of the total precipitation. In the model calculation, the percentage of the impermeable layer is adopted as the representation of that portion of the basin which produces the direct storm runoff. The fact that some of the precipitation directly becomes runoff, causes the soil moisture deficit to increase and decreases the water surplus especially in the early part of the wet season. A reasonable approach for dealing with the magnitude of storm runoff can be obtained by comparing observed flood flows during the dry season to the base flow.

3.5 Model Inputs

The model inputs for the Tank Model are daily mean areal precipitation, evapotranspiration and daily runoff data. Mock's Model make use of the same kinds of inputs but on a monthly basis. A slight difference in Mock's Model is the introduction of the estimated actual evapotranspiration which is influenced by the availability of the monthly soil moisture.

3.5.1 Precipitation

Mean daily and monthly areal precipitation are the major inputs for the Tank and Mock's model, respectively. The rainfall data can be obtained from the stations which are located within the basin itself or obtained from the additional data at the nearest station outside the drainage area. Due to the variability of rainfall, it is desirable to obtain the mean areal rainfall using data from several stations. The mean areal precipitation can be calculated using the arithmetic mean method, the Thiessen Polygon method, the isohyetal method or using multiple regression analysis. In principle the mean areal precipitation is given as follows:

$$P_a = \sum_{i=1}^{n} W_i \, P_i \tag{3.16}$$

where :

P_a is the mean areal rainfall

P_i is the observed rainfall at station i

W_i is the weighting factor coefficient of station i

n is the number of observed rainfall stations.

The difference in the result obtained whether using the Thiessen Polygon method, the arithmetic mean, the isohyetal method, or multiple regression analysis depends on the weighting factor given to each station by each method. Thiessen's Polygon method gives the weighting factor as:

$$w_i = \frac{a_i}{a}, \quad w_2 = \frac{a_2}{a}, \quad \ldots\ldots\ldots \; w_n = \frac{a_n}{a} \tag{3.17}$$

where a is the total catchment area and a_i is area of polygon i.

The arithmetic mean gives the same weighting factor for every station, since the mean areal precipitation is an average of the total rainfall at a particular unit of time. Therefore, the weighting factor is given as:

$$w_1 = w_2 = \ldots\ldots\ldots \; w_n = \frac{1}{n} \tag{3.18}$$

where n is the number of rainfall stations.

The isohyetal method gives the weighting factor as:

$$w_i = \frac{A_i}{A} \tag{3.19}$$

where A_i is the area between two successive isohyets, A is the total catchment and P_i is the average rainfall between two successive isohyets.

The multiple regression method gives the weighting factor for each station based on the equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \tag{3.20}$$

where: Y is the dependent variable (runoff) in mm/day

X_1, X_2, ... X_n are independent variables (rainfall depth) in mm

β_0, β_1, ... β_n are the regression coefficients

The values of β_1, β_2, ... β_n are the regression coefficient of each rainfall station. The weighting factor for each station is approximately:

$$w_i = \frac{\beta_i}{\sum_{i=1}^{n} \beta_i} \tag{3.21}$$

In the case where the rainfall data are almost the same for each station, the arithmetic mean is a special case of the multiple regression method.

Each method gives an approximation of the mean rainfall for a given time. Each method has its limitations, due to the fact that it is impossible to measure rainfall at every point in the basin. In this thesis, the four methods were evaluated. The results are very similar, except for the multiple regression analysis. In the case of the result of the multiple regression analysis, the stations located outside the basin have higher weighting factor than the stations located within the basin. This result seem physically unlikely.

Since the results from the other three methods are almost similar, hence for simplicity, the arithmetic mean was used in this thesis.

3.5.2 Evapotranspiration

The other input variable for both the Tank Model and Mock's Model is evapotranspiration. In this thesis, Penman's method is used to calculate the potential evapotranspiration. This method has been selected because it is considered to be suitable for tropical regions since it uses temperature and climatic data such as humidity, sunshine duration, latitude and wind speed. The general formulation of Penman's method is expressed as follows (Mock, 1973):

$$Ep = \frac{(AH + 0.27D)}{(A + 0.27)}$$

$$H = R(1 - r)(0.18 + 0.55S) - B(0.56 - 0.092\sqrt{ed}) \qquad (3.22)$$
$$(0.1 + 0.9S)$$

$$D = 0.35\,(ea - ed)\,(k + 0.01w)$$

where:

Ep is the potential evapotranspiration in mm H_2O/day

A is the slope of the vapour pressure curve at mean air temperature in mm H_2O/day

B is the black body radiation at mean air temperature in mm H_2O/day

ea is the saturated vapour pressure at mean air temperature in mm Hg

ed = *rh x ea* is the actual vapour pressure in mm Hg

rh is the relatuve humidity in %

H is an expression of drying power or net radiation in mm H_2O/day

R is the solar radiation on a horizontal surface above the atmosphere in mm H_2O/day.

r is the reflection coefficient (Albedo)

S is the the ratio of actual to possible hours of bright sunshine in %

k is the coefficient of roughness for the evaporating surface

w is the wind speed at two metre height in miles/day

The evapotranspiration values calculated using Penman's method are presented in Table 3.1.

Table 3.1: Potential Evapotranspiration Estimates (Ep)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ep (mm/day)	3.3	3.5	3.5	3.4	3.3	3.0	2.9	3.4	3.8	4.1	3.9	3.4

In this study, the values of the potential evapotranspiration are used as negative input for the Tank Model. The evapotranspiration is subtracted from the top tank, and if the top tank is empty, from the second tank. If both tanks are empty, evapotranspiration is subtracted from the third tank and so on. The problem is whether the value varies or not according to the tank from where evapotranspiration is subtracted. It may be related to the availability of soil moisture. In this thesis, the evapotranspiration is assumed to be equal to the potential evapotranspiration throughout the year. This is because the values of the actual evapotranspiration have been implicitly taken into account by the Tank Model's coefficient (i.e. lumped with tank coefficients).

Mock's Model which considers the soil moisture each month, uses the actual evapotranspiration as negative input. The actual evapotranspiration is discussed in the next section.

3.5.3 Actual Evapotranspiration Estimates

Actual evapotranspiration should be equal to potential evapotranspiration during the rainy season when the soil moisture reaches its capacity. During the dry season, when rain is sparse, soil moisture decreases and the actual evapotranspiration should be lower than the potential evapotranspiration. A method to calculate the actual evapotranspiration was proposed by Thornthwaite and Mather (1957) based on the hypothesis that in a particular month, where the precipitation is less than the potential evapotranspiration, the actual evapotranspiration is equal to the precipitation plus the amount of water drawn from the soil moisture storage. Mock (1973) proposed an approach for calculating the actual evapotranspiration using the term *limited evapotranspiration*. This is calculated as follows:

$$\Delta E = [\frac{d\ m}{30}]\ Ep \qquad (3.23)$$

where ΔE is the difference between the potential and actual evapotranspiration (Ea) in mm/month. Ep is the potential evapotranspiration in mm/month, d is the number of days per month when the surface is dry and m is the estimation of non vegetative soil in percent units. Mock also found a general relationship between the dry surface days and the number of rainy days for Indonesia. The relationship is expressed as:

$$d = \frac{3}{2}\ (18 - n) \qquad (3.24)$$

where n is the number of rainy days. The equation (3.23) can be rewritten as:

$$\Delta E = \frac{m(18 - n)}{20} Ep \tag{3.25}$$

In practice, however, estimates for m are difficult to find. To avoid this drawback, a slight modification of Mock's Model was proposed by the Institute of Hydraulic Engineering Bandung (1991). It is based on the hypothesis that the rate of the evapotranspiration is proportional to the amount of the remaining water in the soil as postulated by Thornthwaite and Mather (1955) and Budyko (1948, cited in Nguyen and Berndtson, 1986). If the soil moisture content is one quarter of the total capacity, for example, then the rate of evapotranspiration will be one quarter of the potential evapotranspiration. Thus,

$$Ea = \frac{SM}{SMC} Ep \tag{3.26}$$

where SMC is the soil moisture capacity and SM is the soil moisture content for a particular month. A chart summarizing the iterative calculations is presented in the methodology section along with a summary of the entire Mock's Model procedure. In this thesis the actual evapotranspiration was calculated using the evaporation equation 3.26.

Chapter 4

Methodology

This chapter discusses the method used in the process of calibration and verification of the rainfall-runoff models. Before the catchment models were applied, the lag time between the occurrence of rainfall and runoff must be determined first. To obtain the parameters of the catchment models, the trial and error method was used for both the Tank and Mock's Model. For evaluation of the result, the criteria used were those used by the World Meteorological Organization (WMO), (1986).

4.1 Determination of Lag Time

The lag time between the occurrence of rainfall in the basin and the runoff occurrence in the gauging station was calculated using cross correlation analysis. Cross correlation analysis is a statistical procedure to obtain the correlation between two concurrent time series at various lag times. For rainfall and runoff data, the highest coefficient shows the appropriate lag time between the rainfall in the basin and the occurrence of runoff at the gauging station. The result of the analysis is presented in Fig 4.1.

The lag time with the highest correlation coefficient is zero. This means that the runoff occurs on the same day as the rainfall. Due to the system of the rainfall observation in the basin (today's rainfall amount is basically the total rainfall from 7.00 am previous day to 7.00 am today), the lag time is therefore, actually equal to one day.

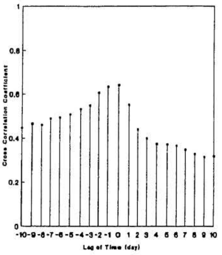


Fig. 4.1: Cross Correlation Analysis Result

4.2 Tank Model Calibration

General discussions of the Tank Model were presented in Chapter 3. The following sections provide a more detailed discussion of the model, because to calibrate the Tank Model, an understanding of the structure of the Tank Model is important. Assuming that the configuration is a vertically structured storage type model, the tanks can be labelled A, B, C and D respectively. The relevant computations for the model are given in the following sections.

4.2.1 Runoff Generation

a. Computation of Water Storage

The inputs representing the mean areal precipitation are added directly to the top tank. The abstraction due to evapotranspiration is assumed to take place simultaneously. The storage in the top tank, before the runoff calculation, is:

$$SA_{(t)} = SBA_{(t-1)} + P_{(t)} - E_{(t)} \tag{4.1}$$

where $SA_{(t)}$ is the storage of tank A at time t, $SBA_{(t-1)}$ is the storage balance of tank A at time $(t-1)$, $P_{(t)}$ is the mean areal precipitation at time (t) and $E_{(t)}$ is the evapotranspiration at time t.

In the case where the amount of precipitation cannot supply the evapotranspiration requirement and the first tank contains insufficient water for evapotranspiration, the evapotranspiration requirement will be taken from the lower tank (second tank). In the case where the second tank also contains insufficient water for evapotranspiration, water will be extracted from the third tank. The same procedure can be applied to the fourth tank if the third tank also fails to meet the requirement. The storage equation (which is the same for the second, third and fourth tanks) can be expressed as:

$$SB_{(t)} = SBB_{(t-1)} + QA0_{(t)} - EB_{(t)}$$

$$SC_{(t)} = SBC_{(t-1)} + QB0_{(t)} - EC_{(t)} \qquad (4.2)$$

$$SD_{(t)} = SBD_{(t-1)} + QC0_{(t)} - ED_{(t)}$$

where; $SB_{(t)}$ is the storage of tank B at time t, $SBB_{(t-1)}$ is the storage balance of tank B at time (t-1), $QA0_{(t)}$ is the infiltration from tank A and $EB_{(t)}$ is the evapotranspiration that may have to be deducted from tank B. $SBB_{(t)}$ is the storage balance of tank B at time t, which is described in the following section.

b. Computation of Runoff

The runoff and infiltration from each tank are calculated by taking into account the storage of the individual tanks in the following way. For tank A:

$$QA2_{(t)} = (SA_{(t)} - HA2) \times A2$$

$$QA1_{(t)} = (SA_{(t)} - HA1) \times A1 \qquad (4.3)$$

$$QA0_{(t)} = SA_{(t)} \times A0$$

where $QA2_{(t)}$ is the discharge from the upper outlet of tank A at time t, $QA1_{(t)}$ is the discharge from the lower outlet of tank A at time t and $QA0_{(t)}$ represents the infiltration from tank A at time t. $A2$, $A1$ and $A0$, respectively, are the coefficients of the upper, lower and bottom outlets of tank A. $HA1$ is the height of lower outlet and $HA2$ is the height of the upper outlet.

The storage balance of the tanks A, B, C and D at time t can be expressed as follows:

$$
\begin{aligned}
SBA_{(t)} &= SA_{(t)} - QA2_{(t)} - QA1_{(t)} - QA0_{(t)} \\
SBB_{(t)} &= SB_{(t)} - QB1_{(t)} - QB0_{(t)} \\
SBC_{(t)} &= SC_{(t)} - QC1_{(t)} - QC0_{(t)} \\
SBD_{(t)} &= SD_{(t)} - QD1_{(t)}
\end{aligned} \tag{4.4}
$$

These storage balance values are used as the initial conditions for time $(t+1)$.

In a similar fashion, the discharge from the second, third and fourth tanks can be expressed as follows:

$$
\begin{aligned}
QB_{(t)} &= (SB_{(t)} - HB1) \times B1 \\
QC_{(t)} &= (SC_{(t)} - HC1) \times C1 \\
QD_{(t)} &= (SD_{(t)}) \times D1
\end{aligned} \tag{4.5}
$$

The total runoff is the summation of the discharges from each tank.

$$
Q_{(t)} = QA2_{(t)} + QA1_{(t)} + QB_{(t)} + QC_{(t)} + QD_{(t)} \tag{4.6}
$$

4.2.2 Determination of the Initial Parameters of the Tank Model

In the application of the Tank Model, there is no exact formula for accurately determining its parameters. This is because the parameters depend upon the soil structures, geological features, land use within the basin and the river course itself. Two approximations of the parameters have been suggested for initial calculations. Both sets of the suggested parameters and their respective derivations are given below.

a. Suggested Parameters based on the Analysis of Several Japanese Rivers

These parameters are based on Sugawara research (1980):

Top tank (First tank).		
Outlet Coefficients	0.1 - 0.5	day^{-1}
Height of the lower runoff outlet	10 - 20	mm
Height of the upper runoff outlet	30 - 60	mm
Second Tank		
Outlet Coefficients	0.03 - 0.1	day^{-1}
Height of the runoff outlet	0 - 50	mm
Third tank		
Outlet Coefficients	0.001 - 0.005	day^{-1}
Height of the runoff outlet	0 - 30	mm
Fourth tank		
Outlet Coefficients	0.0005 - 0.005	day^{-1}

These above values represent general cases for Japanese river basins, however, they can be used as the initial parameters for river basins outside of Japan which have similar climate. Based on these values, hydrographs of the calculated and observed runoff are compared, then the parameters are adjusted as required based on visual comparisons of these two hydrographs. This requires numerous trials, since each value of the parameters has to be adjusted individually. The initial storage values for the first and second tanks are taken as equal to zero. This implies that the starting time for simulation should be in the driest period of the year.

b. Initial Parameters based on the Relationship between the Catchment Area and the Time Constant

The method proposed by Sugawara et al., (1984) uses the characteristics of a Simple

Tank Model. As discussed in Chapter 3, for a Simple Tank Model, T is a time constant and $T = 1/\alpha$. The derived α is simply divided in two, for the bottom and side outlet of the top tank. The summation of coefficients of the lower tank is taken as $1/r$ of the summation of the coefficients of the upper tank, where r is the ratio between the summation of the coefficients of the upper tank over the lower tank. Based on the analysis of several Japanese rivers, an empirical formula for calculating the time constant is given as:

$$T = 0.15\sqrt{A}.$$

where T is the time constant and A is the catchment area (km^2). For rivers outside of Japan, some adjustments are likely to be required. In addition, the initial parameters should be well balanced and in harmony, which means that the parameter must satisfy the following guidelines:

1. The ratio between the side outlet coefficient to the infiltration coefficient in the first, second and third tanks should be in close agreement (i.e. $A1/A0 \approx B1/B0 \approx C1/C0$).
2. The ratio between the sum of the side outlet coefficients and infiltration coefficients of the top tank to the second and to the third tank should be in close agreement with the square of its ratio ($A1+A0 : B1+B0 : C1+C0 = r : r^2 : r^3$). A recommended value of r is 5 (Sugawara et al., 1984). In this thesis, the first set of guidelines for the initial parameters was used with adjustments based on the calculated and observed hydrographs.

4.2.3 Trial and Error Calibration

Once the initial parameters have been selected, they must be adjusted to ensure that the final model gives a good representation of catchment response. This process is called calibration. The adjustments of the tank coefficients depend on which part of the hydrographs do not match. For example, if the peak flows do not match then coefficients of the top tank should be adjusted. If the base flows do not match, then the coefficient of the third and four tank should be adjusted. The basic principle for calibrating the Tank Model is based on the procedure suggested by Sugawara (1980). More details on the principles underlying the calibrations are given in the accompanying diagrams presented in Fig. 4.2 to Fig. 4.4.

4.2.4 Automatic Calibration

Despite the fact that the trial and error method is usually used to calibrate the Tank Model, there have been three attempts to develop an automatic calibration method. The methods devised by Maruyama, et al., (1975), Sugawara (1979) and Ozaki (1980) are presented below.

a. Maruyama, et al., (1975)

Maruyama attempted to determine the parameters of the Tank Model by using non linear optimization. The Powell Conjugate Gradient Method was employed in order to derive the optimum parameters. The working principle of this method involves the minimization of the objective function with regard to the unknown variables. In general the objective function Fo can be written as follows:

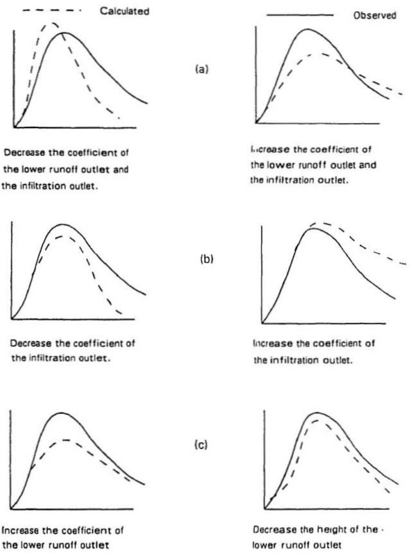


Fig. 4.2: Single Tank Component Adjustment Guidelines. (a) Lower runoff outlet adjustment; (b) infiltration adjustment (c) Height lower runoff adjustment.

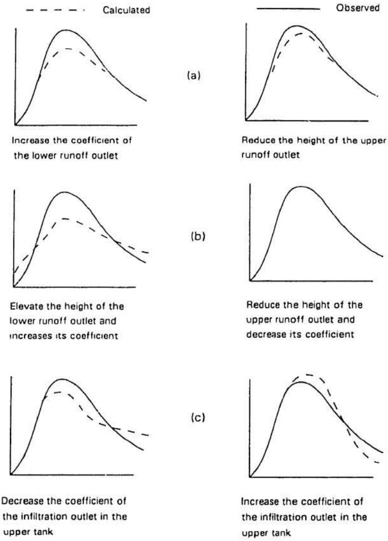
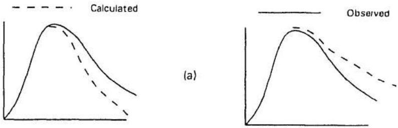
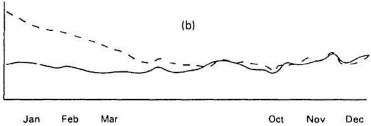


Fig. 4.3: Single and Two Tank Components Adjustment Guidelines. (a) and (b) Upper and lower outlet adjustment; (c) Two tanks; infiltration outlet adjustment.

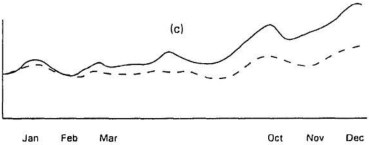


Increase the coefficient of the runoff outlet in the lower tank or reduce its height.

Decrease the coefficient of the runoff outlet in the lower tank or increase its height



Reduce the initial storage from tank which has large fluc - tuation outflow, then try a new outlet coefficient



Increase the coefficient from the tank which has large out flow fluctuation, then try a new coefficient

Fig. 4.4: Two Tanks and Low Flow Adjustment Guidelines. (a) Lower tank runoff adjustment; (b and c) Low Flow adjustment.

$$Fo(x_1,\ldots\ldots x_{16}) = \sum_{i=1}^{n} \left| \frac{Q_c(t) + \alpha}{Q_o(t) + \alpha} - 1 \right| \qquad (4.7)$$

where x_1 .... x_{16} are the parameters of the Tank Model, Q_o is the observed discharge, Q_c is the calculated discharge and α is a constant assumed to be the average of the observed discharge.

b. Sugawara (1979)

Sugawara (1979) introduced feedback procedures for automatic calibration of the Tank Model. Two methods were introduced, the hydrograph comparison method and the duration curves comparison method. The procedure is carried out by comparing two criteria obtained from the observed and calculated hydrograph from the model. The two criteria are the volume of discharge and the shape of the hydrograph. The feedback procedure start from the initial model parameters, and the parameters are adjusted based on the two criteria.

c. Ozaki (1980)

Ozaki (1980) introduced a method for automatic calibration based on a non linear dynamic model, combined with the use of the Akaike Information Criteria (AIC). The method focussed on the determination of the model structure and its coefficients.

In this thesis, automatic calibration using the Sugawara's method was considered. The obtained parameters tended to become larger and did not self correct, thus leading to unsatisfactory results. Therefore, the trial and error method was used here. In fact, using the trial and error method led to a better understanding of both the model and the catchment response.

4.3 Mock's Model Calibration

To calibrate Mock's Model, it is first necessary to understand how the model works. The following section discusses monthly runoff generation using Mock's Model.

4.3.1 Runoff Generation

The principle of runoff generation for Mock's Model is as follows:

a. Potential Water Loss (Pe)

The potential water loss (*Pe*) is defined as the difference between precipitation and actual evapotranspiration. This difference shows the periods of moisture excess or deficit. The equation can be expressed as:

$$Pe = P - Ep \tag{4.8}$$

where *Pe* is the potential water loss, *P* is precipitation and *Ep* is potential evapotranspiration.

b. Soil Storage and Soil Moisture

The negative value of the difference between potential evapotranspiration and precipitation causes a decrease in the soil moisture. Parallel with the decreased soil moisture, the soil storage also changes. In addition, the decrease in the soil moisture causes a reciprocal effect in the actual evapotranspiration. Therefore, these components are interrelated. In order to solve this problem, an iterative procedure is required, by which the soil moisture (*SM*) and soil storage (*SS*) values can be obtained at a particular time t. Unlike the original Thornthwaite method, which used tables for calculating the actual evapotranspiration (Thornthwaite and Mather, 1957), Mock used limited evapotranspiration which takes into account the factors of non vegetative surface and dry surface days. In this thesis the actual evapotranspiration was calculated based on the magnitude of the soil moisture for a given month (Institute of Hydraulic Engineering Bandung, 1991). For any particular month, the potential evapotranspiration was calculated using Equation 3.21.

c. Soil Moisture Surplus or Water Surplus

Water surplus can be defined as the excess of precipitation over evapotranspiration by considering the amount of soil moisture. If there is no excess, the water surplus is equal to zero. In general, the water surplus can be calculated as:

$$WS = P - Ea \tag{4.9}$$

where WS is the water surplus and $(P - Ea) > 0$.

d. Infiltration

Infiltration is calculated based on the water surplus availability and is taken into account by the coefficient of infiltration. It is given as:

$$I = COI \times WS \tag{4.10}$$

where I is the infiltration and COI is the coefficient of infiltration.

e. Storage Volume

The storage volume for a particular month is calculated based on the formula presented earlier in Equation 3.14.

f. Base Flow

The base flow for a particular month is calculated based on the difference between the incoming infiltration and the different values representing the storage volume at time t. The formula used to calculate the base flow value is given by Equation 3.15

g. Direct Runoff

The direct runoff (DRO) is defined as the difference between the available water surplus and infiltration and can be calculated as

$$DRO = WS - I \tag{4.11}$$

h. Storm Runoff

During the dry season, when the water surplus is zero, some amount of precipitation becomes runoff directly. In the calculation discussed earlier, the storm runoff is found by taking into account the percentage of the impermeable layer, as

$$SRO = P \times IMLA \tag{4.12}$$

where SRO is direct storm runoff and $IMLA$ is percentage of the impermeable layer. This equation requires the condition that $WS = 0$.

i. Total Runoff

The total runoff is calculated by summing up the base flow, direct runoff and storm runoff. A flow chart of the Mock Model runoff computation procedure is presented in Fig. 4.5 and Fig. 4.6.

4.3.2 Initial Parameters for Calibration

Similar to the Tank Model's calibration, Mock's Model calibration is also conducted by trial and error. Mock's model however, has fewer parameters, and is therefore simpler. For the initial calibration, the following values (which are derived from several Javanese river basins) are suggested (Mock, 1973):

Soil Moisture Capacity (*SMC*) = 200 - 300 mm

Monthly recession coefficient K = 0.25 - 0.92

The other parameters, such as the coefficient of infiltration (*COI*), impermeable layer (*IMLA*) and initial storage (*Vo*), can be obtained by trying a value and comparing the calculated and observed hydrographs.

4.4 Verification

The foregoing section, which discussed the calibration method, was to find the parameters of the models which can produce a good fit between the calculated and the measured discharge. This is accomplished by adjusting the parameters, and checking the performance of the model based on graphical and numerical criteria. To test the parameters, to see whether the model can produce a series of runoff simulations that give

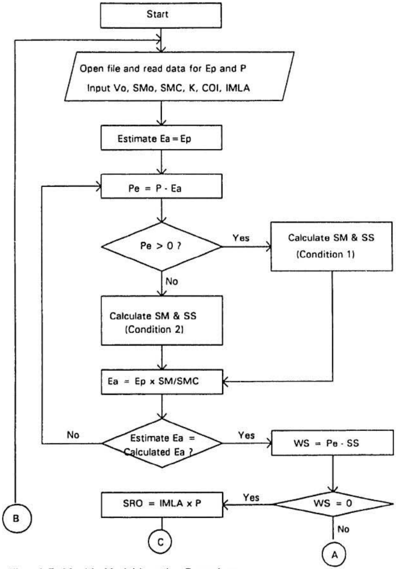


Fig. 4.5: Mock's Model Iterative Procedure.

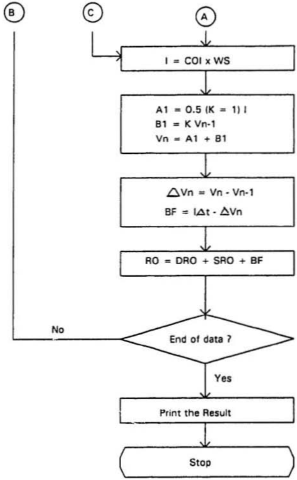
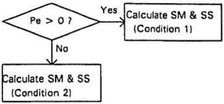
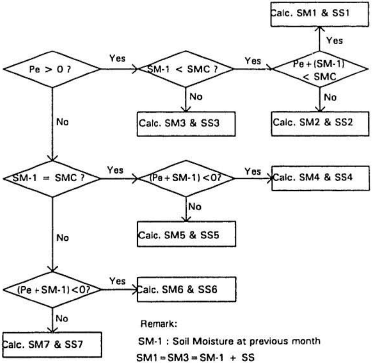


Fig. 4.5: (Continued)





Remark:

SM-1 : Soil Moisture at previous month

SM1 = SM3 = SM-1 + SS

SM4 = SM6 = 0, SM2 = SMC

SM5 = SM7 = SM-1 + Pe

SS1 = SS4 = SS5 = SS6 = SS7 = Pe

SS2 = SMC-(SM-1); SS3 = 0

Fig. 4.6: Detail Calculation for Soil Moisture (SM) and Soil Storage (SS)

a good fit to the observed discharge in a given year, a verification period is required. In other words, the verification period is a necessary testing phase. With respect to the model performance, many researchers have proposed both graphical and numerical criteria. In this thesis, four graphical criteria and three numerical criteria are used to test the model performance. These are described below.

4.4.1 Graphical Criteria

The graphical criteria consist of four graphs, which can be used subjectively to evaluate the model performance. The four graphical criteria are:

a. Comparison of Hydrographs

The hydrographs of the observed and calculated discharges are plotted. The plot shows the magnitude of both the calculated and observed discharge as a function of time.

b. Comparison of Duration Curves

The duration curves of the calculated and observed discharges are plotted. The plot shows the magnitude of the calculated and observed discharges in descending order versus the percent of time the discharge was exceeded. If there are only small discrepancies between the calculated and the observed discharges, the curves will appear close together.

c. Comparison of Daily Flows

This graph shows the comparison of the calculated and observed discharge in ascending order on a linear scale. Good simulated discharge data will be closely scattered along the line of perfect agreement.

d. Comparison of Daily Maximum Flows

This graphical criterion is useful for checking the magnitude of the high flows between the observed and the predicted discharge.

WMO (1986), in their intercomparison of rainfall-runoff project, suggested that the comparison of hydrograph of the calculated and observed discharge as the most important criterion. The duration curves comparison of the calculated and observed discharge is also considered to be an important criterion. Likewise, the scatter diagram of the daily maximum calculated and observed discharges is also considered to be extremely useful. These graphical criteria were used in both the calibration and verification phases for both daily and monthly discharges.

4.4.2 Numerical Criteria

Three numerical criteria were used in this study. They are given in WMO (1986). The numerical criteria used are:

a. The Nash Sutcliffe Coefficient, R^2

The Nash Sutcliffe Coefficient was proposed by Nash and Sutcliffe (Nash and Sutcliffe 1972, cited in Martinec and Rango, 1986). The formula is given as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_o - Q_c)^2}{\sum_{i=1}^{n} (Q_o - \overline{Q_o})^2} \tag{4.13}$$

where Q_c is the calculated discharge, Q_o is the observed discharge, $\bar{Q}_o$ is the average observed discharge and n is the number of days of discharge. It should be noted however, that for the Intercomparison Project, WMO used the term NTD instead of R^2, but both equations are in fact identical.

b. The Deviation of the Runoff Volume

The deviation of the runoff volume is given as (WMO, 1986 cited in Martinec and Rango, 1989):

$$D_v \ (\%) = \frac{\sum_{i=1}^{n} |V_o - V_c|}{\sum_{i=1}^{n} V_o} \times 100\% \qquad (4.14)$$

where V_o is the volume of the observed discharge and V_c is the volume of the calculated discharge. WMO referred to this term as PD. The criteria of R^2 and D_v are considered to be particularly useful criteria (WMO, 1986).

c. Ratio of Mean Error to the Mean Observed Discharge (RME)

The criterion is given by WMO (1986) as:

$$RME = \frac{\sum_{i=1}^{n} (Q_c - Q_o)}{n \overline{Q_o}} \qquad (4.15)$$

It is especially useful if the analysis of volume of the water is the main objective rather than analysis of peak flows. The following values are considered ideal when assessing the performance of a model (WMO, 1986):

R^2 or NTD = 1.   RME = 0. D_v or PD = 0.

The complete results for both calibration and verification (using either graphical or numerical criteria) are presented in Chapter 5. For the purposes of this study, the selected numerical criteria have been limited to three, although other criteria are available to measure the performance of the model. Using too many criteria would only serve to increase the difficulties in judging the performance of the model.

Chapter 5

Results and Discussion

This chapter discusses the results of the calibration and verification of the two rainfall-runoff models. The general performance of the models in both the calibration and verification phases is the major concern of this chapter. The models discussed are Tank Model with four tank components, Tank Model with three tank components, and Mock's Model.

5.1 Tank Model (four tank components)

The sixteen parameters of Tank Model as estimated by trial and error during the calibration phase are presented in Table 5.1. The calibration period was three years, from 1973/1974 to 1975/1976 inclusive. The calibration results of 1975/1976 are presented in Fig. 5.1., as an example. These figures compare the observed and calculated hydrographs, duration curves, and maximum daily flows. The verification results for 1976/77 are presented in Fig. 5.2. The results based on the numerical criteria of the daily data, for both calibration and verification phases are presented in Table 5.2 and 5.3. The graphical and numerical results for all years are presented in Appendix C.

Table 5.1: Tank Model Parameters Obtained

Tanks	Parameters	Notation*)	Value
First Tank	Upper side outlet Coefficient	A2	0.21
	Lower side outlet Coefficient	A1	0.15
	Bottom outlet Coefficient	A0	0.25
	Height of the upper side outlet	HA2	55
	Height of the lower side outlet	HA1	15
	Initial Storage	SBA_0	0
Second Tank	Side outlet Coefficient	B1	0.08
	Bottom outlet Coefficient	B0	0.1
	Height of the side outlet	HB1	10
	Initial Storage	SBB_0	0
Third Tank	Side outlet Coefficient	C1	0.00175
	Bottom side outlet Coefficient	C0	0.002
	Height of the side outlet	HC1	10
	Initial Storage	SBC_0	600
Fourth Tank	Side outlet Coefficient	D1	0.002
	Initial Storage	SBD_0	650

*). The notation refers to Fig. 3.3 (c).

Discussion:

The following discussion is based on the results summarized above.

a. In general, the estimated parameters (from the calibration period) produced good results in the verification phase. This means that the parameters are suitable representations of the simplified mathematical abstraction of the rainfall-runoff

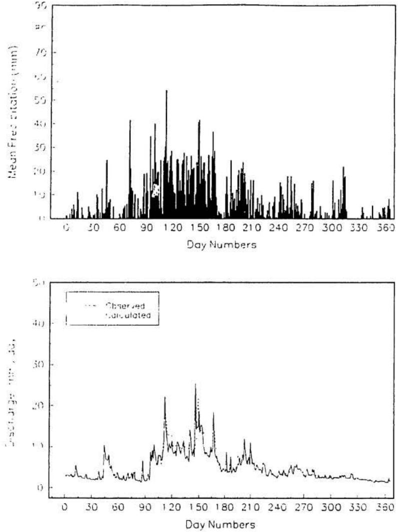
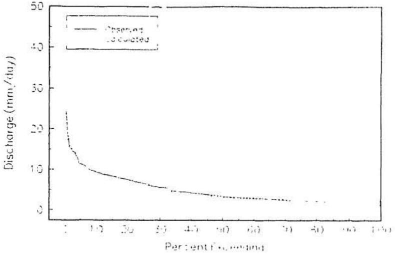


Fig. 5.1: Tank Model (four tanks) Calibration - 1975/1976. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

(c)



(d)

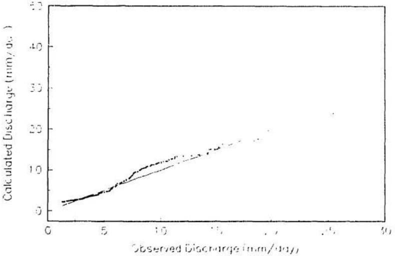


Fig. 5.1: (Continued)

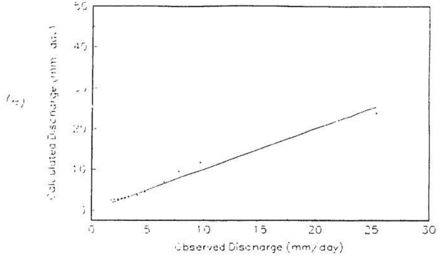


Fig. 5.1: (Continued)

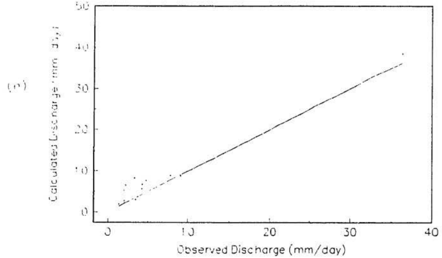
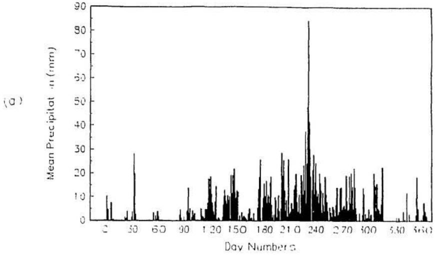


Fig. 5.2: (Continued)



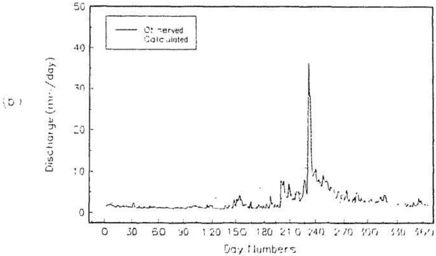


Fig. 5.2: Tank Model (four tanks) Verification - 1976/1977. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

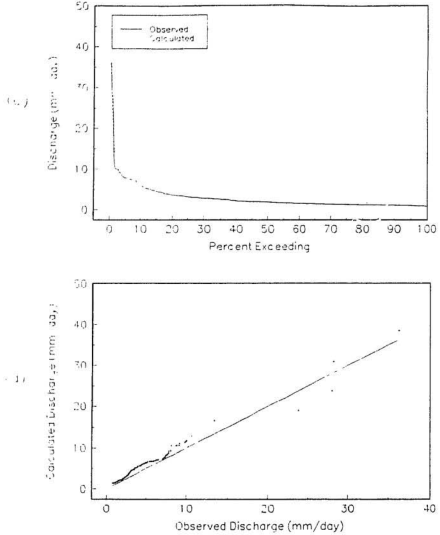


Fig. 5.2: (Continued)

Table 5.2: Result of Tank Model Calibration based on Numerical Criteria

Criterion	1973/1974	1974/1975	1975/1976	1973-1976
R^2	0.54	0.63	0.66	0.64
D_v	0.29	0.28	0.27	0.28
RME	-0.10	-0.11	0.08	-0.06
Σ Qcal (10^3 mm yr^{-1})	2.00	2.47	1.91	6.38
Σ Qobs (10^3 mm yr^{-1})	2.22	2.78	1.77	6.77
Av Qcal (mm day^{-1})	5.49	6.77	5.22	5.82
Av Qobs (mm day^{-1})	6.09	7.62	4.83	6.18
Error (%)	-9.80	-11	+8	-5.8

Error (%) = (Av Qcal-Av Qobs) x 100 / Qobs

Table 5.3: Result of Tank Model Verification based on Numerical Criteria

Criterion	1976/1977	1977/1978	1978/1979	1976-1979
R^2	0.72	0.55	0.45	0.66
D_v	0.45	0.33	0.30	0.36
RME	0.24	-0.14	-0.11	-0.002
Σ Qcal (10^3 mm yr^{-1})	1.31	0.76	1.02	3.01
Σ Qobs (10^3 mm yr^{-1})	1.06	0.89	1.15	3.01
Av Qcal (mm day^{-1})	3.60	2.49	3.72	3.27
Av Qobs (mm day^{-1})	2.91	2.90	4.20	3.28
Error (%)	+23	-14	-11	≈ 0

Error (%) = (Av Qcal-Av Qobs) x 100 / Qobs process in the Babak River basin. Moreover, the simulated discharges in both calibration or verification phases, indicate that the chosen model is quite suitable for runoff modelling of the Babak River. A point that should be noted is that a simple model can in fact simulate a complex system of the rainfall runoff process.

b. At certain periods (December 1974, August and September 1975, November 1976), there are large discrepancies between the calculated and observed discharges. These discrepancies may be accounted for by one or more of the following factors:

1. Unreliable Discharge Data.

   Although in general it was assumed that the data are reliable, data error can occur due to observer or instrument error. A gauging instrument that has been covered by flood debris can yield an inaccurate reading of the water level. This error can lead to an inaccurate discharge record until the problem has been remedied.

2. Occurrence of Localized Rainfall.

   In Indonesia, localized rainfall over small areas often occurs, and it occasionally has a heavy intensity with short duration. If this kind of rainfall is recorded at one of the rainfall gauging stations used in this model, the calculated discharge will be large, while the observed discharge will show only minor changes. By contrast, if some areas with no raingauges have localized rainfall, the calculated discharge will show no changes, but the observed discharge may be larger. These features of localized rainfall are similar to Sugawara's (1979) findings, which suggest that rainfall in tropical regions shows a high degree of localization.

With respect to the causes of the discrepancies (whether it is over or under estimation), the most likely explanation is the first, since the discrepancies occur over a month. Localized rainfall occurs in short periods of time as can be seen in the comparison of hydrograph.

c. Observing the hydrograph both during the calibration and verification phases, it appears that periods used for calibration represent a series of wet years, while the period of verification indicate a series of dry years. Considering that the parameters were obtained from the wet year periods, the simulated discharge in the verification phase can be expected to be different from the observed. Despite this fact, the results of the verification phase are fairly good.

d. Based on the comparison of daily maximum flows, it can be observed that the calculated and observed discharge are closely scattered along the line of perfect agreement. This means that the model can provide a satisfactory simulation of peak flows.

e. The simulated low flow discharges during the calibration period are well fitted to the observed discharges as shown in the comparison of hydrographs. During the verification phase, however, the calculated low flows are slightly underestimated. This may be caused by the aggradation in the river bed in the runoff observation site, which in turn causes inaccurate discharge observation. Another possibility of the underestimation of the calculated low flows is that the obtained parameters itself, which are obtained from the wet years.

f. The numerical criteria, especially the Nash and Sutcliffe coefficient show better results for the monthly discharges than for the daily discharges (R^2 = 0.84 and

$R^2=0.64$ for monthly and daily discharges respectively) for the entire period. This result can be expected due to greater variability in the daily discharges; monthly discharges generally has less variability. The verification shows a similar result with $R^2=0.79$ and 0.66 for monthly and daily discharges respectively.

g. The volume deviation criteria (D_v), for the calibration phase is less than 0.3 for daily simulation, while the result for monthly simulation is less than 0.2. In any particular year with low runoff, the deviation is greater than in a year with high runoff.

5.2 Tank Model (three tank components)

The model parameters, thirteen parameters in total, derived from the calibration phase are presented in Appendix D. The calibration period used to derive the model parameters and the verification period were the same as for the four tanks components case.

Discussion.

In general, the calibration results of the Tank Model with three tank components are satisfactory, although for certain periods there is evidence of discrepancies. With regard to the results over the entire period, the discrepancies can be accounted for following the same discussion as that presented earlier for the four components Tank Model. For the verification period, the model simulation shows satisfactory results for both intermediate and high flows.

For low flows, however, the calculated discharges underestimated the observed values, especially in the second and the third year. This phenomenon indicates th-' the Tank Model with three tank components is not suitable for use in low flow analysis. It could be used for normal and high analysis, in cases where the low flows are not significant. The slight advantage of this model is that this model requires fewer parameters, but in general the four tank component Tank Model is suggested.

The result of this study confirms Sugawara's findings that two tanks are necessary for base flow simulation.

5.3 Mock's Model

The parameters of Mock's Model obtained from the calibration period are presented in Table 5.4. The calibration results are presented in Fig. 5.3. In general, using the estimated parameters, the model produces good results in the verification period. The graphical measurements of the model's performance during the verification period are presented in Fig. 5.4.

Table. 5.4: Parameters of Mock's Model

Parameter	Notation	Value
Impermeable Layer	IMLA	0.10
Coefficient of Infiltration	COI	0.50
Monthly Coefficient of Recession	K	0.70
Soil Moisture Capacity	SMC	200
Initial Soil Moisture	SM_0	200
Initial Storage Value	V_0	200

(a)

(b)

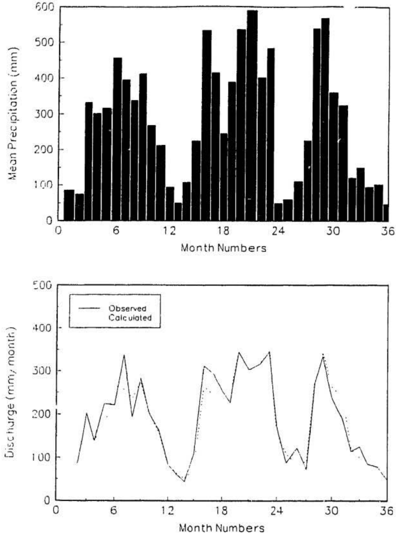
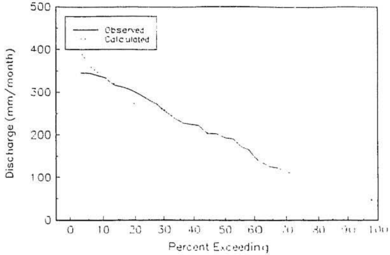


Fig. 5.3: Mock's Model Calibration for 1973-1976. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Monthly Flows.

(c)



(d)

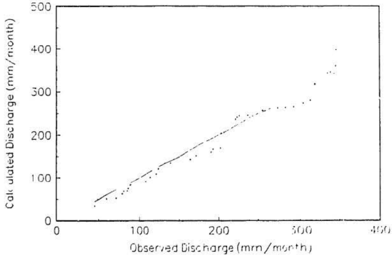
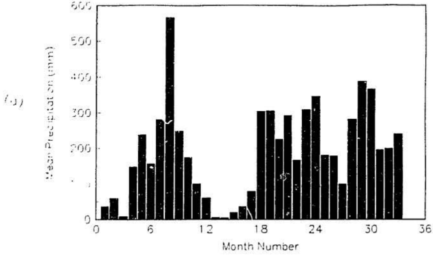


Fig. 5.3: (Continued)



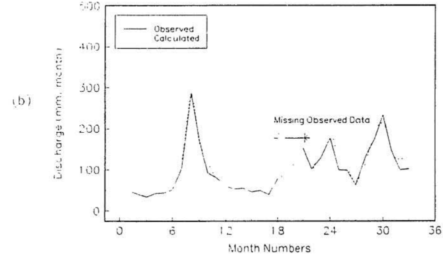
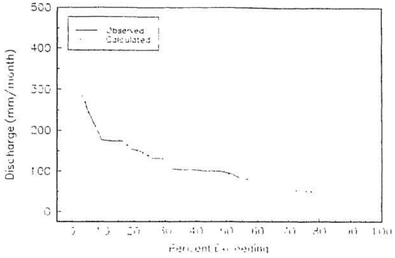


Fig. 5.4: Mock's Model Verification for 1976-1979. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Monthly Flows.

(c)



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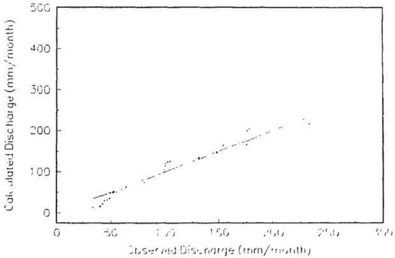


Fig. 5.4: (Continued)

Table 5.5: Result of Mock's Model Calibration based on Numerical Criteria

Criterion	1973/1974	1974/1975	1975/1976	1973-1976
R^2	0.71	0.82	0.92	0.85
D_v	0.16	0.14	0.14	0.15
RME	-0.08	-0.04	0.01	-0.04
Σ Qcal (10^3 mm yr^{-1})	2.04	2.68	1.78	6.5
Σ Qobs (10^3 mm yr^{-1})	2.22	2.78	1.77	6.77
Av Qcal (mm day^{-1})	170	223	148	180
Av Qobs (mm day^{-1})	185	231	147	188
Error (%)	-8	-3	$\approx$0.0	-4

Error (%) = (Av Qcal-Av Qobs) x 100 / Qobs

Table 5.6: Result of Mock's Model Verification based on Numerical Criteria

Criterion	1976/1977	1977/1978	1978/1979	1976-1979
R^2	0.97	0.56	0.81	0.86
D_v	0.13	0.32	0.14	0.19
RME	0.04	-0.19	0.05	-0.02
Σ Qcal (10^3 mm yr^{-1})	1.1	0.71	1.21	3.03
Σ Qobs (10^3 mm yr^{-1})	1.1	0.89	1.15	3.01
Av Qcal (mm day^{-1})	91.85	71.4	134.66	97.66
Av Qobs (mm day^{-1})	88.53	88.72	128	100
Error (%)	+3	-19.5	+5	-2

Error (%) = (Av Qcal-Av Qobs) x 100 / Qobs

Discussion:

a. In general the model and its estimated parameters can be accepted as the representation of a simplified mathematical abstraction of the monthly rainfall-runoff process in the Babak River basin. As with the Tank Model, in some periods there are large discrepancies between the calculated and observed discharge (e.g. Nov-Dec 1974). With respect to the result as a whole, however, such underestimation may be caused by errors such as those discussed in the section 5.1.b.

b. Two alternative values of soil moisture capacity were studied in this thesis, 200 mm and 300 mm. Based on an examination of the results, a soil moisture capacity value of 200 mm was selected. This value is comparable to that used for other Javanese river basins.

c. The estimated monthly recession coefficient K is 0.7, also comparable to some monthly recession coefficients for several Javanese river basins which range from 0.25 to 0.92. (Mock, 1973). In general, the numerical criteria show good results with $R^2 > 0.8$ and $D_v < 0.2$ for both calibration and verification. The errors in general are less than 10 %, except for 1977/1978 in which the error was 19.5 %.

5.4 Sensitivity Analysis

Sensitivity analysis was performed to evaluate the effect on the model performance due to small changes in each parameter. In this thesis, a change of 15% above and below the obtained values given in Table 5.1 and Table 5.4 was used. The Nash Sutcliffe

Coefficient (R^2) was used as the criterion to judge the model performance. The results of the sensitivity analysis for the obtained parameters of the Tank Model is presented in Fig. 5.5 (a). The sensitivity analysis results of the Tank Model show that the lower side outlet and the infiltration coefficient and the height of the upper outlet of the first tank (i.e. A1, A0, HA2) are the most sensitive parameters.

Adjustment to the Tank Model parameters which show high sensitivity was made. The adjusted parameters are: A1 = 0.13(0.15), A0 = 0.29(0.25) and HA2 = 60(55). The values in bracket show the initially obtained parameters. The other parameters remain unchanged (same as the obtained parameters). Sensitivity analysis for the adjusted parameters was again carried out and the results are presented in Fig. 5.5 (b). The adjusted parameters produce a higher R^2 value ($R^2 = 0.66$) than the result from the initially obtained parameters ($R^2 = 0.64$). However, when a graphical criterion (double mass curve) was used to judge the calculated discharges from the adjusted parameters, the total discharge from the adjusted parameter model are slightly less than the total discharge from the model using the obtained parameters . Fig. 5.5 (c) show the double mass curve of the calculated discharges using both the obtained and adjusted parameters.

The sensitivity analysis result of the Mock Model is presented in Fig. 5.6. It shows that the obtained parameters were near to the optimal values, since increasing or decreasing the values of each parameter gave a lower R^2 value.

Based on these results, it can be concluded that the obtained parameters produced better results than the adjusted parameters identified from the sensitivity analysis in term of the total discharge, however, in term of Nash Sutcliffe Coefficient values, the adjusted

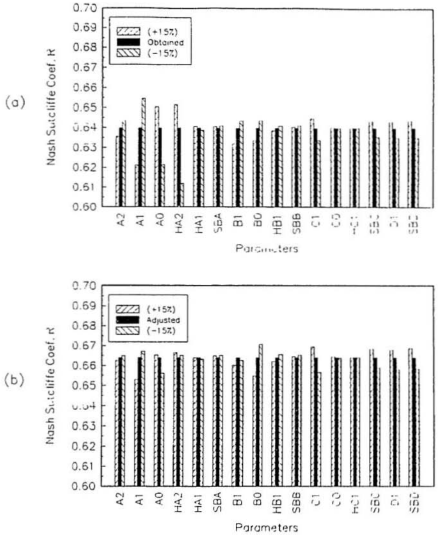


Fig. 5.5: Sensitivity Analysis of the Tank Model (four tanks). (a) Based on the obtained parameters; (b) Based on the adjusted parameters; (c) Comparison of double mass curve using the obtained and adjusted parameters.

(c)

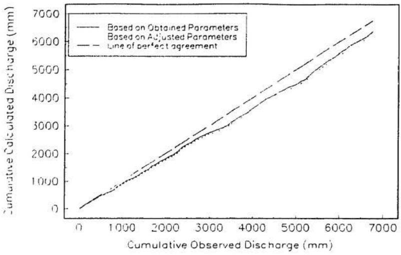


Fig. 5.5: (Continued)

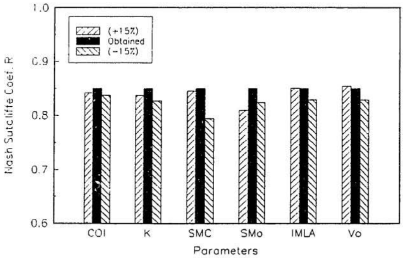


Fig. 5.6: Sensitivity Analysis of Mock's Model.

parameters gave a slightly better results.

5.5 Comparison between the Tank Model and Mock's Model

This section compares the results obtained from the Tank Model (four tank components) and Mock's Model. The hydrographs of the observed and calculated flows of the Tank Model and Mock's Model are shown in Fig. 5.7

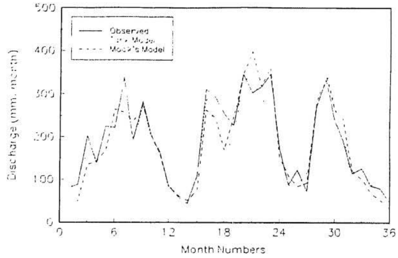
a. Both models can produce discharges with good fit to the observed discharges, either in the calibration or verification period. This means that both models can represent the process of rainfall-runoff in the basin. Mock's Model has the advantage of requiring fewer parameters. Therefore, for preliminary study, Mock's Model is suggested. For detailed study, however, the Tank Model is preferred, since it can simulate daily discharges. The choice of the model will vary with the purposes of the study and the availability of data.

b. The simulated hydrographs suggest an error in either the precipitation or the runoff data. It occurred within the period of Nov-Dec 1974, and the results from both models show significant discrepancies in the same period. As discussed earlier, this may be caused by observer or instrument error.

c. Both models gave good results and are simple to implement. This study supports the adoption of these models for use by professionals concerned with the development of water resources in the study area.

d. With regard to the computational efficiency and computer storage required, Mock's Model requires less storage, since it uses a monthly time step. The Tank Model is

(a)



(b)

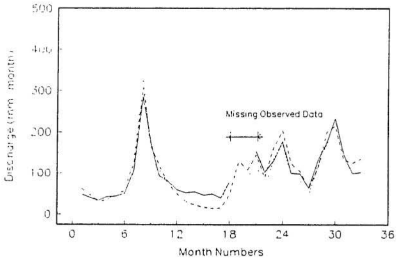


Fig. 5.7: Comparison of the Tank Model (four tanks) and Mock's Model Result. (a) Calibration Period; (b) Verification period.

also easy to use even with a pocket calculator since all the mathematical operations are simple and do not require any iterations. Because of the daily time step, however, repeated si~ulation could be very time consuming without a computer.

Chapter 6

Conclusions and Recommendations

This chapter presents the conclusions and recommendations of this study with respect to the application of two rainfall-runoff models.

Conclusions

1. Based on the result of calibration and the performance of the models during the verification period, it is concluded that the four component Tank Model, whose parameters are presented in Table 5.1, is suitable for simulation of daily flows for the Babak River. Similarly, Mock's Model, with the parameters as presented in Table 5.4. is suitable for simulation of monthly streamflows.
2. From the comparison of the monthly results of both models, it can be concluded that either model gives a good approximation of simulated discharge in general. Mock's Model has the advantage of requiring fewer parameters for discharge simulation, but the Tank Model has the advantage of using daily time steps. The model choice depends on the purposes and availability of data.
3. For the Tank Model, the starting date for either the calibration or the verification phase should be in the driest period. By using the driest period for starting the

calibration, the initial storage for the first and second tanks can be taken to be equal to zero. For Mock's Model, the starting date has no effect, but starting in the driest period is preferred for ease of calibration.

4. The Tank Model with three tank components gives good results for high flows but underestimates low flows. Therefore, it is considered suitable for analysis of normal to high flows. A slight advantage of this model is that it has fewer parameters than the model with four tank components.
5. Attempts were made to calibrate the Tank Model using the automatic calibration method proposed by Sugawara. The results were unsatisfactory. The trial and error method, however, gave satisfactory results and has the additional advantage of providing information and experience about the behaviour of the model.
6. It is possible that a slightly different set of parameters may give the same or better results than these obtained here. However, it would not deviate very much from those obtained because of the dependent nature of the parameters and how they are related to the physical process.

Recommendations

1. For preliminary investigation purposes, the study results support the use of Mock's Model as a suitable monthly rainfall-runoff model, since it has fewer parameters than the Tank Model. For detailed design purposes, however, the Tank Model with four tank components is recommended.
2. For other river basins similar to the Babak River basin, the parameters obtained using either the Tank Model or Mock's Model can be used use as the initial

parameters for calibration. If runoff data are not available and the characteristics of the river basin (soil structure, land use and vegetation) are similar to the Babak River basin, the parameters can be used directly.

3. Some additional rainfall gauging stations are suggested. The objectives of the additional rainfall stations are to derive a better spatial representation in the calculation of the mean areal rainfall, especially with regard to the occurrence of localized rainfall.

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Appendix A

Computer Program for Mock's Model

This appendix presents the computer program for Mock's Model. This program was written in the Quick Basic Language. In principle the computation of monthly runoff are divided into two parts.

1. The Water Balance Computation

   This part includes computations of the iterative procedure to obtain the soil moisture and soil storage at particular month. It also contain the computation for the actual evapotranspiration and water surplus.

2. The Runoff Calculation

   This part includes computations of direct runoff, storm runoff and base flow using the parameters estimated and data file obtain from the first calculation. Total runoff is the summation of the direct runoff, storm runoff and base flow.

MOCK MODEL PROGRAM

This program is a monthly rainfall runoff model based on Mock work's in Indonesia. It was published in "Water Availability Appraisal", *Report for Land Capability Appraisal Indonesia*. This model is adopted by the Ministry of Public Works Indonesia for uses in irrigation planning.

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==================================================

GOSUB initialization
GOSUB water.balance
GOSUB run.off
END
'
initialization:
CLS
INPUT "impermeable layer="; imla
INPUT "initial storage="; vo
INPUT "coefficient of infiltration="; coi
INPUT "monthly coefficient recession ="; k
INPUT "soil moisture capacity="; smc
INPUT " initial soil moisture="; smo

OPEN "b:\file-name1.dat" FOR OUTPUT AS #1
let a = 4: b = 12:
DIM p(a, b): DIM ws(a, b): DIM eact(a, b)
DIM ce(a, b): DIM eto(a, b): DIM pe(a, b): DIM a1(a, b): DIM b1(a, b)
DIM inf(a, b): DIM vn(a, b): DIM dltvn(a, b): DIM bf(a, b):
DIM dro(a, b): DIM ro(a, b): DIM dsro(a, b): DIM storm(a, b)
DIM qo(a, b): DIM sm(a, b): DIM ss(a, b)
vn(1, 0) = vo:
RETURN

water.balance:
=============
CLS
OPEN "b:\file-name2.dat" FOR OUTPUT AS #2
OPEN "b:\file-name3.dat" FOR OUTPUT AS #3
OPEN "b:\file-eto.dat" FOR INPUT AS #4      ' Pot. evapotrans. data
OPEN "b:\file-monthly.dat" FOR INPUT AS #5  ' monthly precipitation

FOR y = 1 TO a
FOR m = 1 TO b
INPUT #5, p(y, m)
INPUT #4, eto(y, m)
```

```
NEXT m
NEXT y
CLOSE #5: CLOSE #4

FOR y = 1 TO a
FOR m = 1 TO b
IF m = 1 AND y > 1 THEN
sm(y, (m - 1)) = sm((y - 1), b)
ELSEIF m = 1 AND y = 1 THEN
sm(y, (m - 1)) = smo
END IF

The calculation of Water Balance
********************************
LET eact(y, m) = eto(y, m)
100 eact(y, m) = ce(y, m)
200 pe(y, m) = p(y, m) - eact(y, m)
IF pe(y, m) > 0 THEN
IF sm(y, m - 1) < smc THEN
IF (pe(y, m) + sm(y, (m - 1))) < smc THEN
ss(y, m) = pe(y, m): sm(y, m) = sm(y, (m - 1)) + ss(y, m)
ELSEIF (pe(y, m) + sm(y, (m - 1))) > smc THEN
ss(y, m) = smc - sm(y, (m - 1)): sm(y, m) = smc
END IF
ELSEIF sm(y, m - 1) = smc THEN
ss(y, m) = 0: sm(y, m) = sm(y, (m - 1)) + ss(y, m)
END IF
ELSEIF pe(y, m) < 0 THEN
IF sm(y, (m - 1)) = smc THEN
IF (pe(y, m) + sm(y, (m - 1))) < 0 THEN
ss(y, m) = pe(y, m): sm(y, m) = 0
ELSEIF pe(y, m) + sm(y, (m - 1)) > 0 THEN
ss(y, m) = pe(y, m): sm(y, m) = sm(y, (m - 1)) + pe(y, m)
END IF
ELSEIF sm(y, (m - 1)) < smc THEN
IF (pe(y, m) + sm(y, (m - 1))) < 0 THEN
ss(y, m) = pe(y, m): sm(y, m) = 0
ELSEIF (pe(y, m) + sm(y, (m - 1))) > 0 THEN
ss(y, m) = pe(y, m): sm(y, m) = sm(y, (m - 1)) + pe(y, m)
END IF
END IF
END IF

ce(y, m) = eto(y, m) * sm(y, m) / smc
```

```
IF ABS(ce(y, m) - eact(y, m)} > .01 THEN
GOTO 100
ELSEIF ABS(ce(y, m) - eact(y, m)) < = .01 THEN
ws(y, m) = pe(y, m) - ss(y, m)
END IF
PRINT
IF ws(y, m) = 0 THEN
dsro(y, m) = imla * p(y, m)
sm(y, m) = sm(y, m - 1) + pe(y, m) - dsro(y, m)
IF sm(y, m) > smc THEN
sm(y, m) = smc
ws(y, m) = sm(y, m - 1) + pe(y, m) - dsro(y, m) - smc
ELSEIF sm(y, m) < sm THEN
sm(y, m) = sm(y, m)
END IF
ELSEIF ws(y, m) > 0 THEN
GOTO 300
END IF
300  PRINT
WRITE #2, ws(y, m)
WRITE #3, dsro(y, m)
NEXT m
NEXT y
CLOSE #2: CLOSE #3
RETURN

'
run.off:
********
CLS
This calculation is based on water balance principle
and refers to Mock, (1973). Water Availability Appraisal,
Report for Land Capability Appraisal, Indonesia.

OPEN "b:\file-name2.dat" FOR INPUT AS #6
OPEN "b:\file-name3.dat" FOR INPUT AS #7
FOR y = 1 TO a
FOR m = 1 TO b
INPUT #6, ws(y, m): INPUT #7, dsro(y, m):
NEXT m
NEXT y
CLOSE #6: CLOSE #7:
FOR y = 1 TO a
FOR m = 1 TO b
```

```
IF m = 1 AND y > 1 THEN
vn(y, (m - 1)) = vn((y - 1), b)
END IF
inf(y, m) = coi * ws(y, m)
a1(y, m) = .5 * (k + 1) * inf(y, m)
b1(y, m) = k * vn(y, m - 1)
vn(y, m) = a1(y, m) + b1(y, m)
dltvn(y, m) = vn(y, m) - vn(y, m - 1)
bf(y, m) = inf(y, m) - dltvn(y, m)
dro(y, m) = ws(y, m) - inf(y, m)
storm(y, m) = dsro(y, m)
ro(y, m) = bf(y, m) + dro(y, m) + storm(y, m)
WRITE #1, ro(y, m)
NEXT m
NEXT y
CLOSE #1
RETURN
END
```

Appendix B

Spreadsheet Computation for the Tank Model

This appendix presents the computation of the Tank Model. The detailed of spreadsheet calculation is divided into three groups.

a. Parameters values (A2, A1, ... SBD_o)

b. Inputs values consist of Evapotranspiration (Ep), Precipitation (P), and Observed Discharge (Qobs).

c. Calculation of the Tank Model consists of calculation for tank A, B, C, D and calculated discharge (Qcal).

Tank Model Computation

Parameters:

A2 :	0.21	
A1 :	0.15	
Ao :	0.25	
HA2 :	55	
HA1 :	15	
SBAo :	0	
B2 :	0	(not used)
B1 :	0.08	
Bo :	0.1	
HB2 :	0	(not used)
HB1 :	10	
SBBo :	0	
C1 :	0.00175	
Co :	0.002	
HC1 :	10	
SBCo :	600	
D1 :	0.002	
SBDo :	650	

	First Tank								Second Tank							
Date (t)	P	Previous Storage Balance	Ep	Storage (SA)	Discharge QA2	QA1	Sub total (QA2+QA1)	Infl. QA0	Storage Balance (SBA)	Previous Infl. Storage from Balance above (QA0)		EB	Storage (SB)	Discharge QB2	QB1	Sub Total (QB2+QB1)
Unit	mm	mm	mm/day	mm	mm/day	mm/day	mm/day	mm/day	mm	mm	mm/day	mm/day	mm	mm/day	mm/day	mm/day
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
01-Jul-73	1	0.00	2.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.91	0.00	0.00	0.00	0.00
02-Jul-73	0	0.00	2.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.91	0.00	0.00	0.00	0.00
03-Jul-73	0	0.00	2.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.91	0.00	0.00	0.00	0.00
04-Jul-73	5.25	0.00	2.91	2.34	0.00	0.00	0.00	0.59	1.76	0.00	0.59	0.00	0.59	0.00	0.00	0.00
05-Jul-73	0	1.76	2.91	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	1.16	0.00	0.00	0.00	0.00

Column Remark:

1 : Date
2 : Precipitation
3 : if t=1, then 3=SBAo, else 3=previous day value of 10
4 : Evapotranspiration
5 : if (3+2)<4, then 5=0; else 5=(2+3-4)
6 : if (5>HA2) then 6=A2x(5-HA2); else 6=0
7 : if (5>HA1) then 7=A1x(5-HA1); else 7=0
8 : 8=6+7
9 : 9=5xA0
10 : 10=5-(8+9)
11 : if t=1, 11=SBBo; else 11= previous day value of 19
12 : 12=9
13 : if (2+3-4)<0, then 13=ABS(2+3-4); else 13=0
14 : if (11+12-13),0, then 14=0; else 14=(11+12-13)
15 : if (14>HB2) then 15=B2x(14-HB2); else 15=0
16 : if (14>HB1) then 16=B1x(14-HB1); else 16=0
17 : 17=15+16
18 : 18=B0x14

18 : 18=B0x14
19 : 19=14-17-18
20 : if t=0, then 20=SBCo, else 20=previous day value of 26
21 : 21=18
22 : if (11+12-13)<0, then 22=ABS(11+12-13), else 22=0
23 : if(20+21-22)<0,then 23=0, else 23=(20+21-22)
24 : if (23>HC1), then 24=(23-HC1)xC1; else 24=0
25 : 25=23xC0
26 : 26=23-24-25
27 : if t=1, then 27=SBDo, else 27= previous value of 32
28 : 28=25
29 : if (20+21-22)<0, then 29=(20+21-22), else 29=0
30 : if (27+28-29)<0, then 30=0, else 30=(27+28-29)
31 : 31=30xD1
32 : 32=30-31
33 : 33=8+17+24+31
34 : Observed Discharge

Except the parameters code and zero, all values are column numbers

Tank Model Computation (Continued)

Third Tank							Fourth Tank								Calculated Discharge			
Infl. QB0	Storage Balance (SBB)	Previous Storage Balance	Infl. from above (QB0)	EC	Storage (SC)	Discharge QC1	Infl. QC0	Storage Balance (SBC)	Previous Storage Balance	Infl. from above (QC0)	ED	Storage (SD)	Discharge QD1	Storage Balance	Disch. Calculation Qcal	Qobs	Remark
mm/day	mm	mm	mm/day	mm/day	mm	mm/day	mm/day	mm	mm	mm/day	mm/day	mm	mm/day	mm	mm/day	mm/day	
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
0.00	0.00	600.00	0.00	1.91	598.09	1.18	1.20	595.72	650.00	1.20	0.00	651.20	1.30	649.89	2.48	3.470	
0.00	0.00	595.72	0.00	2.91	592.81	1.17	1.19	590.46	649.89	1.19	0.00	651.08	1.30	649.78	2.47	2.980	
0.00	0.00	590.46	0.00	2.91	587.55	1.16	1.18	585.22	649.78	1.18	0.00	650.95	1.30	649.65	2.46	3.230	
0.06	0.53	585.22	0.06	0.00	585.27	1.15	1.17	582.95	649.65	1.17	0.00	650.82	1.30	649.52	2.45	2.540	
0.00	0.00	582.95	0.00	0.63	582.33	1.14	1.16	580.02	649.52	1.16	0.00	650.68	1.30	649.38	2.45	2.390	

1 : Date
2 : Precipitation
3 : if t=1, then 3=SBAo, else 3=previous day value of 10
4 : Evapotranspiration
5 : if (3+2)<4, then 5=0, else 5=(2+3-4)
6 : if (5>HA2) then 6=A2x(5-HA2), else 6=0
7 : if (5>HA1) then 7=A1x(5-HA1); else 7=0
8 : 8=6+7
9 : 9=5xA0
10 : 10=5-(8+9)
11 : if t=1, 11=SBBo; else 11= previous day value of 19
12 : 12=9
13 : if (2+3-4)<0 then 13=ABS(2+3-4), else 13=0
14 : if (11+12-13),0, then 14=0, else 14=(11+12-13)
15 : if (14>HB2) then 15=B2x(14-HB2), else 15=0
16 : if (14>HB1) then 16=B1x(14-HB1), else 16=0
17 : 17=15+16
18 : 18=B0x14

18 : 18=B0x14
19 : 19=14-17-18
20 : if t=0, then 20=SBCo, else 20=previous day value of 26
21 : 21=18
22 : if (11+12-13)<0, then 22=ABS(11+12-13), else 22=0
23 : if(20+21-22)<0,then 23=0, else 23=(20+21-22)
24 : if (23>HC1), then 24=(23-HC1)xC1; else 24=0
25 : 25=23xC0
26 : 26=23-24-25
27 : if t=1 then 27=SBDo, else 27= previous value of 32
28 : 28=25
29 : if (20+21-22)<0, then 29=(20+21-22), else 29=0
30 : if (27+28-29)<0, then 30=0, else 30=(27+28-29)
31 : 31=30xD1
32 : 32=30-31
33 : 33=8+17+24+31
34 : Observed Discharge

Except the parameters code and zero, all values are coloum numbers

Appendix C

Results of the Tank Model (four tanks)

This appendix presents the Tank Model (four tanks) calibration and verification result.

The arrangement are as follows:

1. Tank Model (four tanks) Calibration of 1973/1974 and 1974/1975.

2. Tank Model (four tanks) Verification of 1977/1978 and 1978/1979.

3. Tank Model (four tanks) Monthly Calibration.

4. Tank Model (four tanks) Monthly Verification.

5. Result of the Tank Model Calibration and Verification based on Numerical Criteria.

(a)

(b)

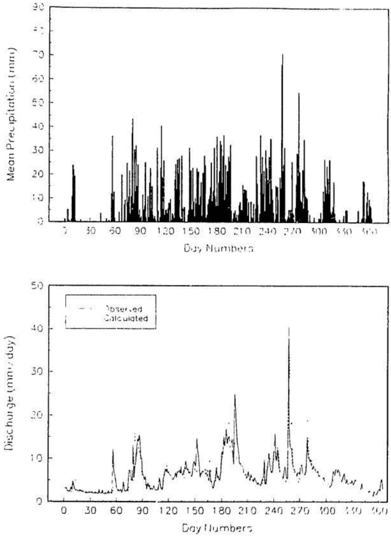


Fig. C.1: Tank Model (four tanks) Calibration - 1973/1974. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

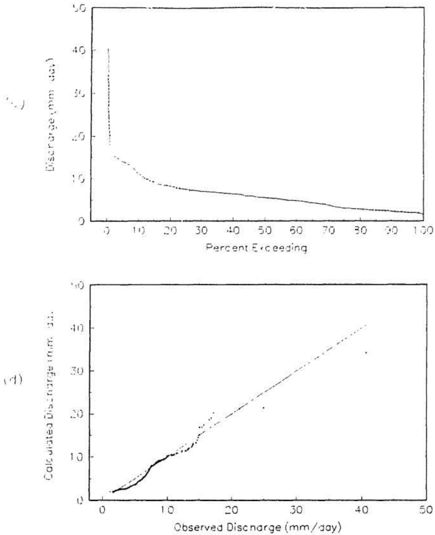


Fig. C.1: (Continued)

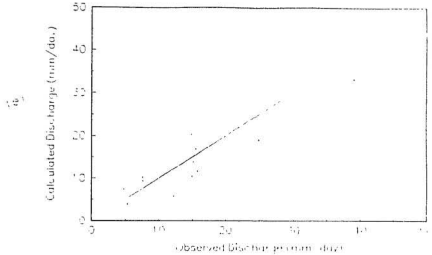


Fig. C.1: (Continued)

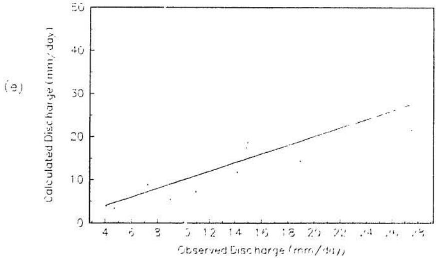
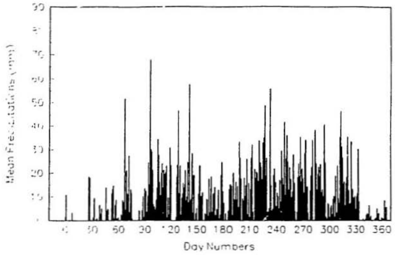


Fig. C.2: (Continued)

(a)



(b)

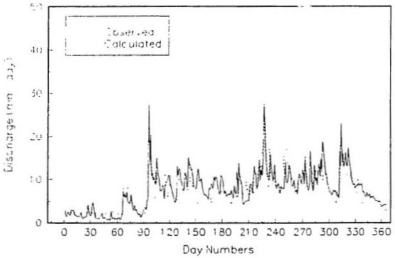
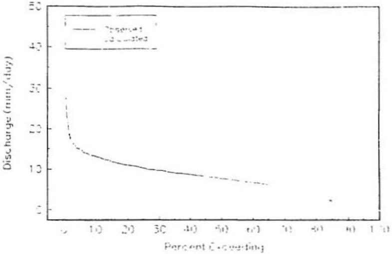


Fig. C.2: Tank Model (four tanks) Calibration - 1974/1975. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

(c)



(d)

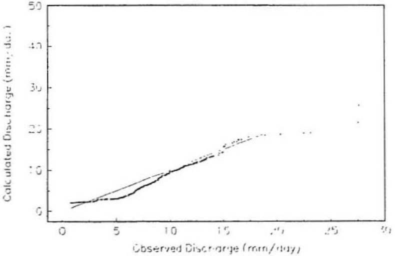


Fig. C.2: (Continued)

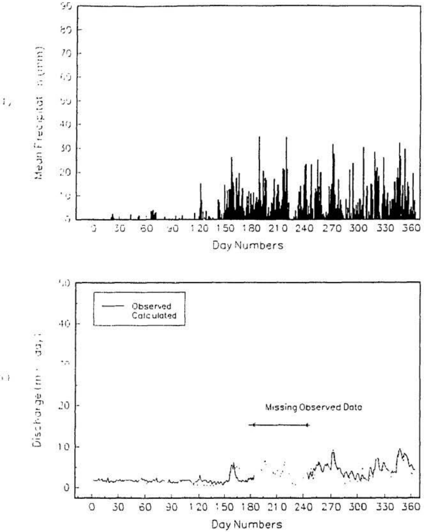
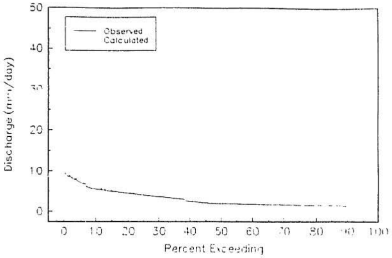


Fig. C.3: Tank Model (four tanks) Verification - 1977/1978. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

(c)



(d)

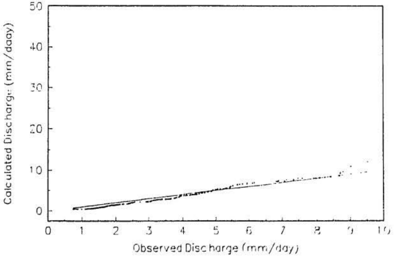


Fig. C.3: (Continued)

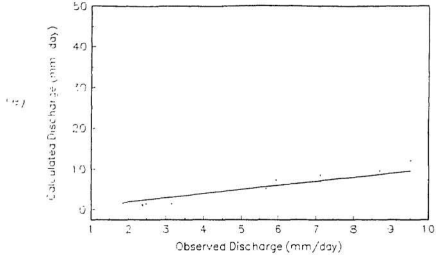


Fig. C.3: (Continued)

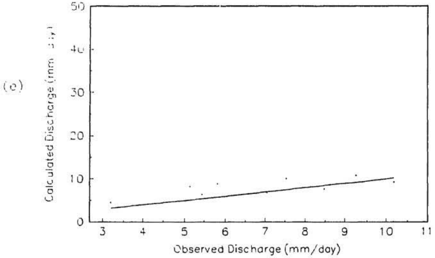


Fig. C.4: (Continued)

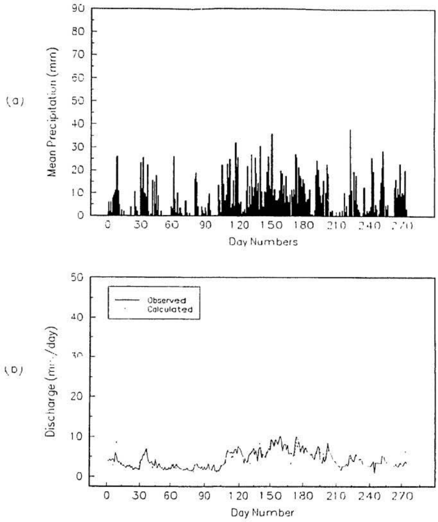


Fig. C.4: Tank Model (four tanks) Verification - 1978/1979. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

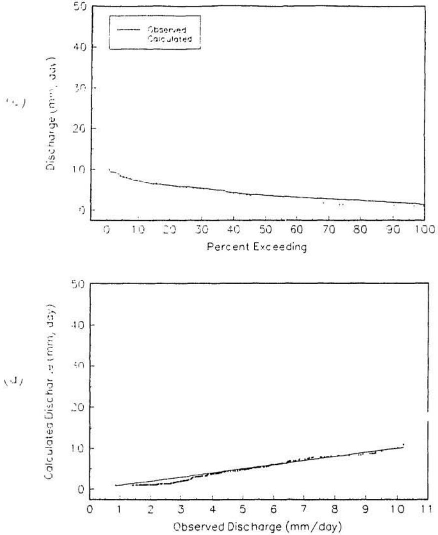


Fig. C.4: (Continued)

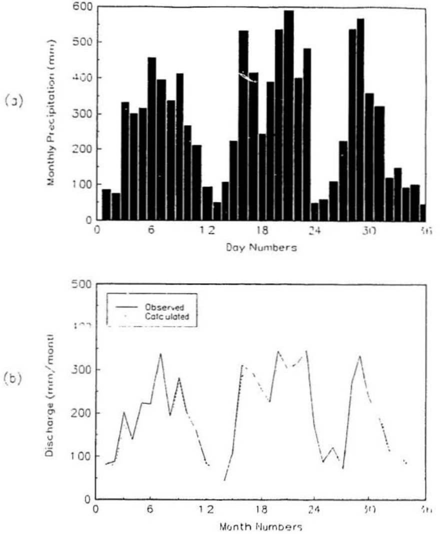


Fig. C.5: Tank Model Calibration - 1973-1976. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Monthly Flows.

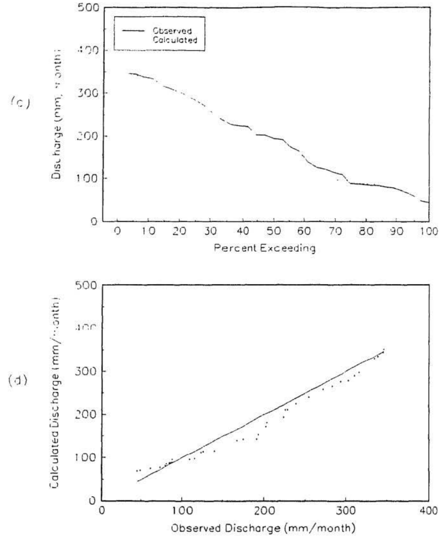
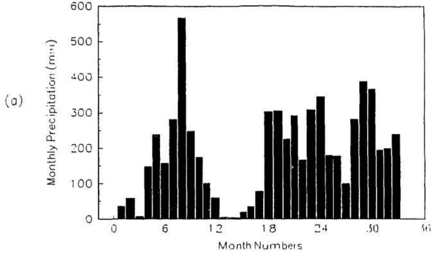


Fig. C.5: (Continued)



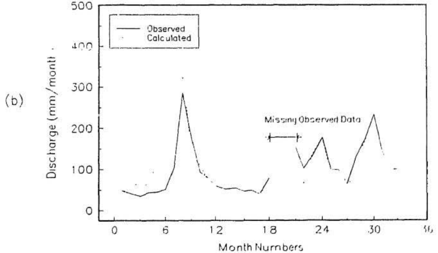
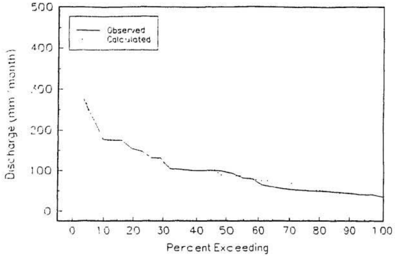


Fig. C.6: Tank Model Verification - 1976-1979. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Monthly Flows.

(c)



(d)

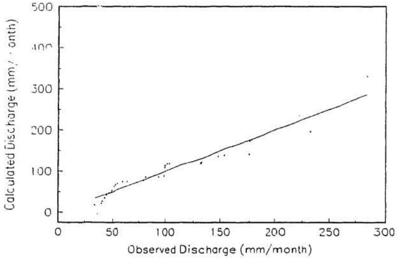


Fig. C.6: (Continued)

Table C.1: Result of Tank Model Calibration (monthly) based on Numerical Criteria

Criterion	1973/1974	1974/1975	1975/1976	1973-1976
R^2	0.80	0.77	0.89	0.84
D_v	0.13	0.17	0.16	0.15
RME	-0.10	-0.11	0.08	-0.06
Σ Qcal (10^3 mm year^{-1})	2.003	2.471	1.909	6.384
Σ Qobs (10^3 mm year^{-1})	2.221	2.78	1.768	6.769
Av Qcal (mm year^{-1})	166.9	205.9	159.1	177.34
Av Qobs (mm year^{-1})	185.09	231.69	147.35	188.04
Error (%)	+9.8	-11	+8	-5.8

Error (%) = (Av Qcal-Av Qobs) x 100/Qobs

Table C.2: Result of Tank Model Verification (monthly) based on Numerical Criteria

Criterion	1976/1977	1977/1978	1978/1979	1976-1979
R^2	0.77	0.72	0.81	0.79
D_v	0.34	0.24	0.14	0.24
RME	0.24	-0.14	-0.11	-0.002
Σ Qcal (10^3 mm year^{-1})	1.31	0.761	1.02	3.09
Σ Qobs (10^3 mm year^{-1})	1.062	0.877	1.15	3.09
Av Qcal (mm year^{-1})	109.42	75.19	113.18	99.79
Av Qobs (mm year^{-1})	88.53	88.72	127.8	99.98
Error (%)	+23	-14	-11	-0.19

Error (%) = (Av Qcal-Av Qobs) x 100/Qobs

Appendix D

Results of the Tank Model (three tanks)

This appendix presents the Tank Model (three tanks) calibration and verification results.

The arrangements are as follows:

1. Parameters of the Tank Model (three tanks).
2. Tank Model (three tanks) Calibration of 1973/1974 until 1975/1976.
3. Tank Model (three tanks) Verification of 1976/1977 and 1978/1979.
4. Tank Model (three tanks) Monthly Calibration.
5. Tank Model (three tanks) Monthly Verification.
6. Result of the Tank Model (three tanks) Calibration and Verification based on Numerical Criteria using daily data.
7. Result of the Tank Model (three tanks) Calibration and Verification based on Numerical Criteria using monthly data.

Table D.1: Tank Model (three tanks) Parameters

Tanks	Parameters	Notation*)	Value
First Tank	Upper side outlet Coefficient	A2	0.21
	Lower side outlet Coefficient	A1	0.15
	Bottom outlet Coefficient	A0	0.25
	Height of the upper side outlet	HA2	55
	Height of the lower side outlet	HA1	15
	Initial Storage	SBA_0	0
Second Tank	Side outlet Coefficient	B1	0.08
	Bottom outlet Coefficient	B0	0.1
	Height of the side outlet	HB1	10
	Initial Storage	SBB_0	0
Third Tanks	Side outlet Coefficient	C1	0.0028
	Initial Storage	SBC_0	800

*). The notation refers to Fig. 3.3 (c).

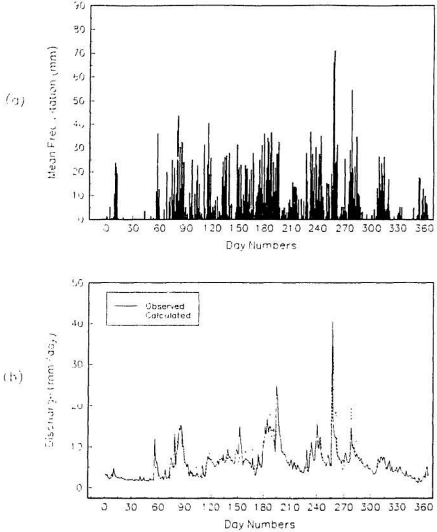
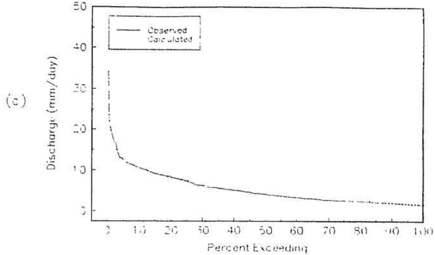


Fig. D.1: Tank Model (three tanks) Calibration - 1973/1974. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.



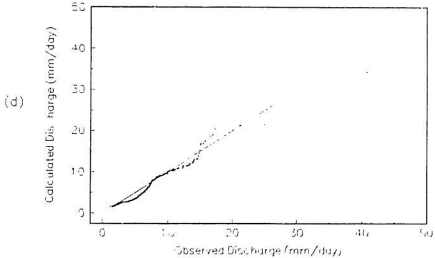


Fig. D.1: (Continued)

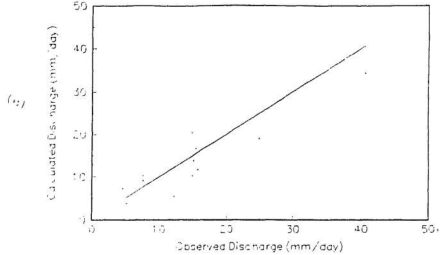


Fig. D.1: (Continued)

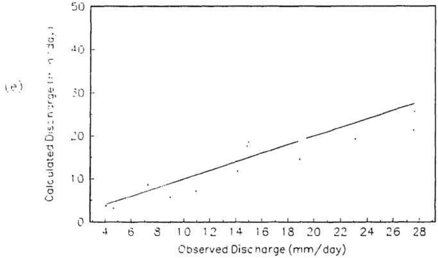


Fig. D.2: (Continued)

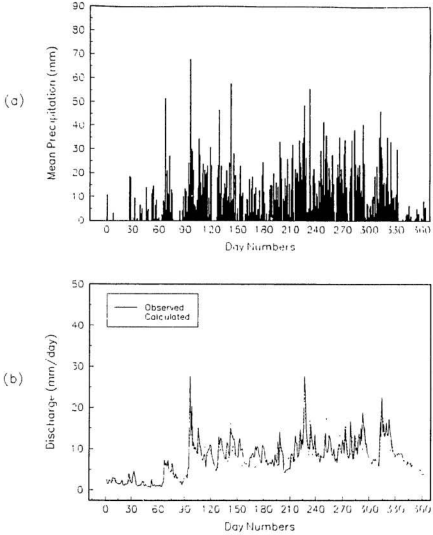
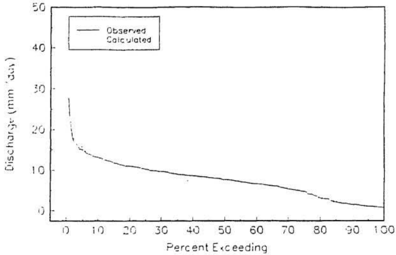


Fig. D.2: Tank Model (three tanks) Calibration - 1974/1975. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

(c)



(d)

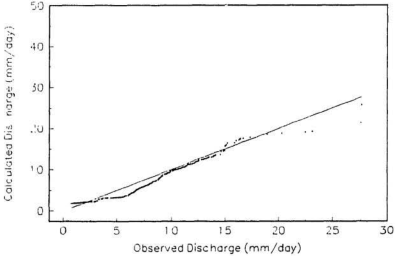


Fig. D.2: (Continued)

(a)

(b)

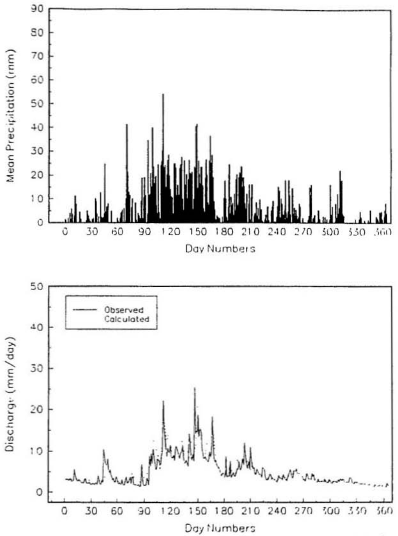
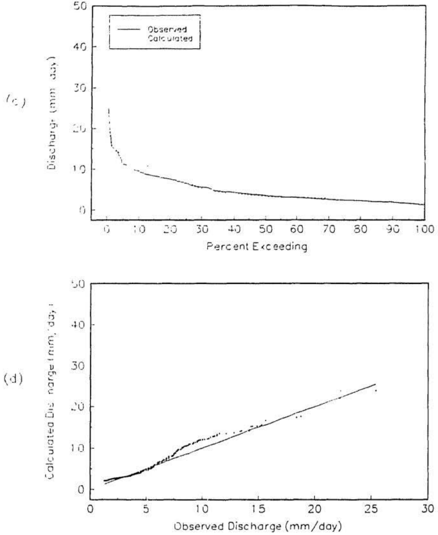


Fig. D.3: Tank Model (three tanks) Calibration - 1975/1976. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.



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(e)

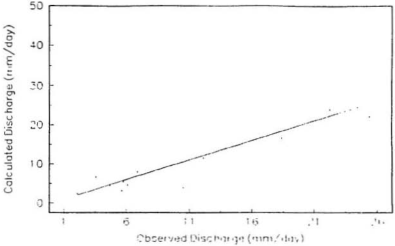


Fig. D.3: (Continued)

(e)

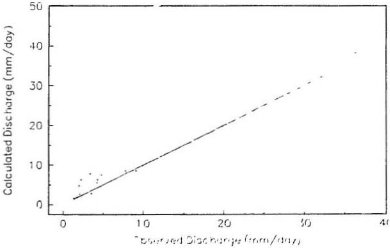
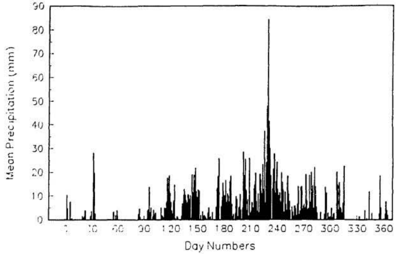


Fig. D.4: (Continued)

(a)



(b)

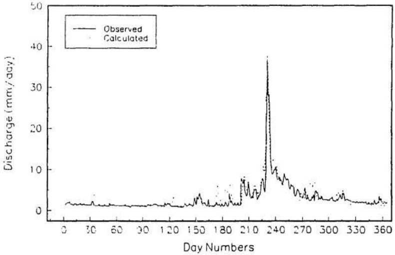


Fig. D.4: Tank Model (three tanks) Verification - 1976/1977. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

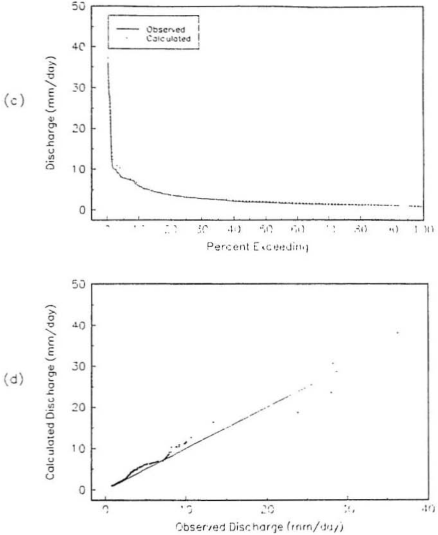
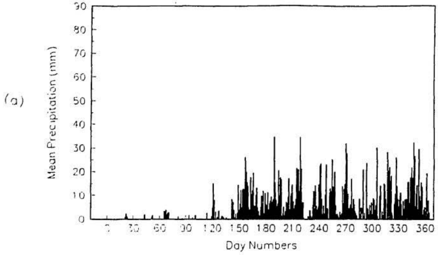


Fig. D.4: (Continued)



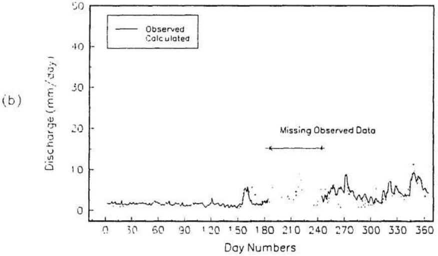
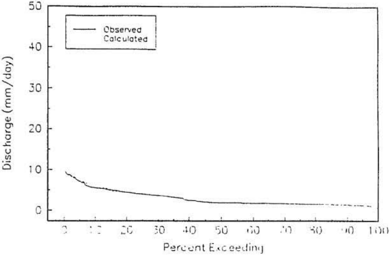


Fig. D.5: Tank Model (three tanks) Verification - 1977/1978. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

(c)



(d)

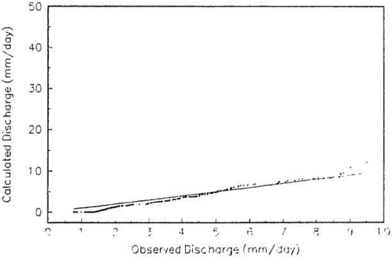


Fig. D.5: (Continued)

(e)

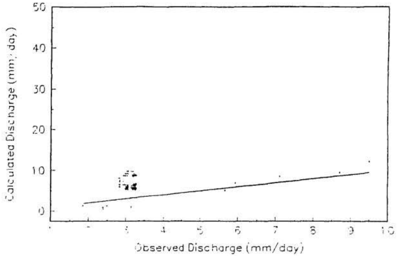


Fig. D.5: (Continued)

(e)

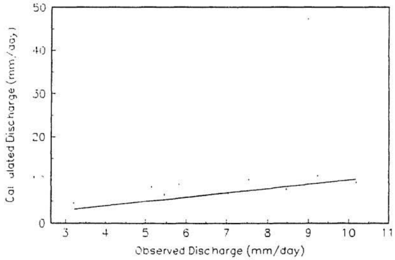


Fig. D.6: (Continued)

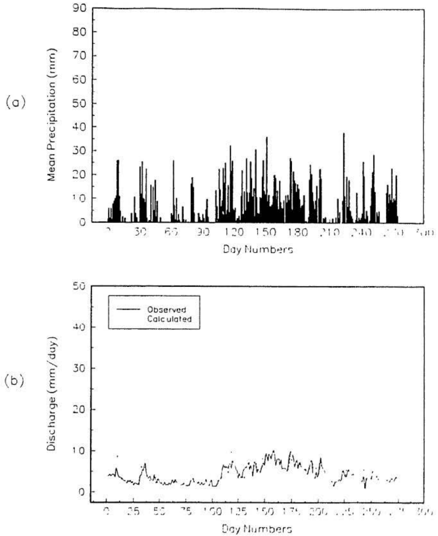
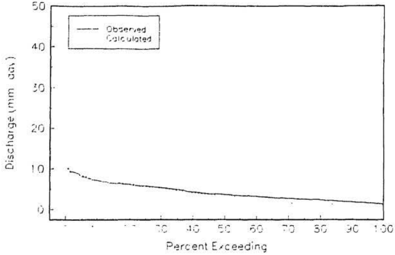


Fig. D.6: Tank Model (three tanks) Verification - 1978/1979. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Daily Flows; (e) Comparison of Observed and Calculated Daily Maximum Flows.

(c)



(d)

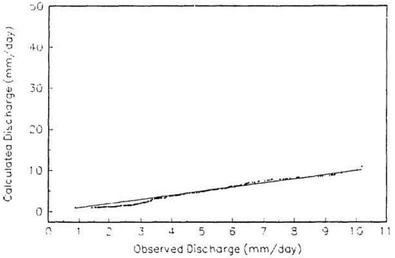


Fig. D.6: (Continued)

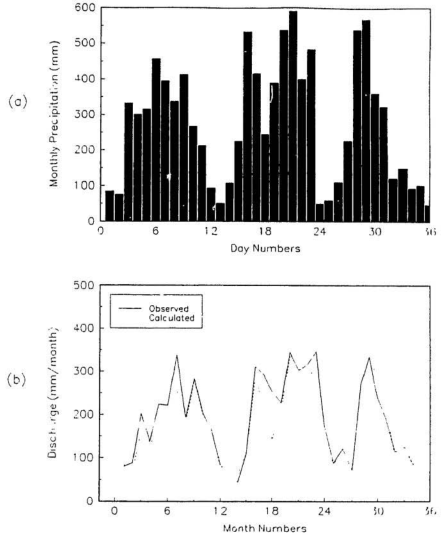
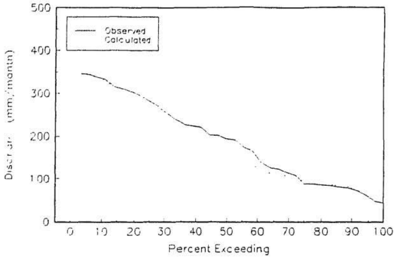


Fig. D.7: Tank Model Calibration - 1973-1976. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Monthly Flows.

(c)



(d)

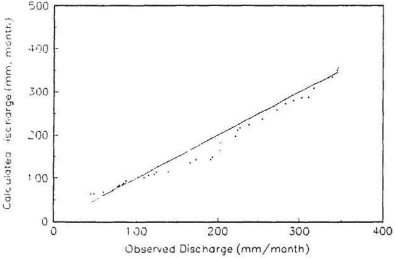


Fig. D.7: (Continued)

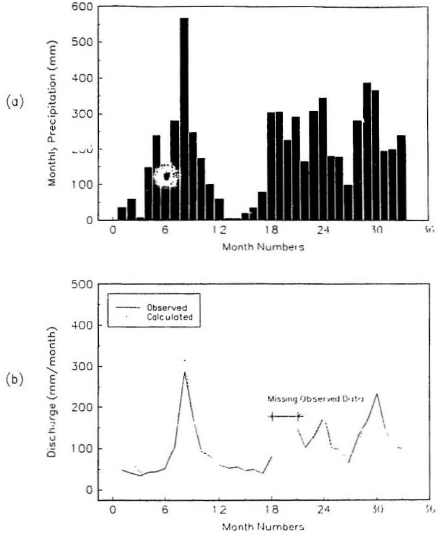
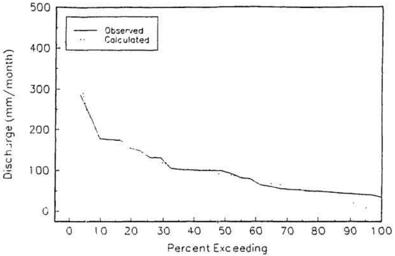


Fig. D.8: Tank Model Verification - 1976-1979. (a) Precipitation; (b) Comparison of Observed and Calculated Hydrographs; (c) Comparison of Observed and Calculated Duration Curves; (d) Comparison of Observed and Calculated Monthly Flows.

(c)



(d)

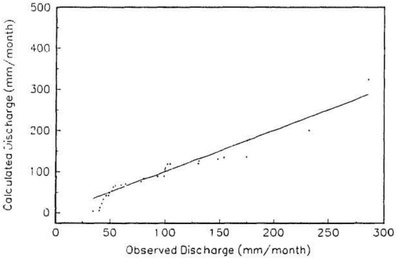


Fig. D.8: (Continued)

Table D.2: Result of Tank Model Calibration based on Numerical Criteria using daily data.

Criterion	1973/1974	1974/1975	1975/1976	1973-1976
R^2	0.53	0.65	0.66	0.64
D_v	0.29	0.27	0.27	0.28
RME	-0.11	-0.10	0.09	-0.05
Σ Qcal (10^3 mm $year^{-1}$)	1.978	2.491	1.931	6.401
Σ Qobs (10^3 mm $year^{-1}$)	2.221	2.78	1.768	6.769
Av Qcal (mm $year^{-1}$)	5.42	6.83	5.28	5.84
Av Qobs (mm $year^{-1}$)	6.09	7.62	4.83	6.18
Error (%)	-11	-10	+9	-5

Error (%) = (Av Qcal-Av Qobs) x 100/Qobs

Table D.3: Result of Tank Model Verification based on Numerical Criteria using daily data.

Criterion	1976/1977	1977/1978	1978/1979	1976-1979
R^2	0.75	0.45	0.47	0.67
D_v	0.40	0.40	0.29	0.36
RME	0.13	-0.24	-0.09	-0.06
Σ Qcal (10^3 mm $year^{-1}$)	1.205	0.677	1.045	2.927
Σ Qobs (10^3 mm $year^{-1}$)	1.066	0.88	1.15	3.01
Av Qcal (mm $year^{-1}$)	3.3	2.21	3.81	3.10
Av Qobs (mm $year^{-1}$)	2.91	2.9	4.2	3.28
Error (%)	+13.43	-23.61	-9.13	-5.54

Error (%) = (Av Qcal-Av Qobs) x 100/Qobs

Table D.4: Result of the Tank Model Calibration based on Numerical Criteria using monthly data.

Criterion	1973/1974	1974/1975	1975/1976	1973-1976
R^2	0.79	0.79	0.89	0.84
D_v	0.13	0.16	0.16	0.15
RME	-0.11	-0.10	0.09	-0.05
Σ Qcal (10^3 mm $year^{-1}$)	1.978	2.491	1.931	6.401
Σ Qobs (10^3 mm $year^{-1}$)	2.221	2.78	1.768	6.769
Av Qcal (mm $year^{-1}$)	164.8	207.63	160.91	177.34
Av Qobs (mm $year^{-1}$)	185.09	231.69	147.35	188.04
Error (%)	-11	-10	+9.2	-5

Error (%) = (Av Qcal-Av Qobs) x 100/Qobs

Table D.5: Result of Tank Model Verification based on Numerical Criteria using monthly data

Criterion	1976/1977	1977/1978	1978/1979	1976-1979
R^2	0.85	0.56	0.85	0.81
D_v	0.27	0.32	0.12	0.24
RME	0.13	-0.24	-0.09	-0.06
Σ Qcal (10^3 mm $year^{-1}$)	1.205	0.677	1.045	2.927
Σ Qobs (10^3 mm $year^{-1}$)	1.066	0.877	1.15	3.09
Av Qcal (mm $year^{-1}$)	100.4	67.8	116.11	94.44
Av Qobs (mm $year^{-1}$)	88.5	87.72	127.8	99.66
Error (%)	-13	-22.7	-9	-2

Error (%) = (Av Qcal-Av Qobs) x 100/Qobs

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