DAILY RAINFALL RUNOFF MODELING FOR DONG NAI RIVER BASIN IN VIETNAM

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By

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CANDIDATE'S DECLARATION

I here certify that the work which is being presented in the dissertation entitled "*DAILY RAINFALL RUNOFF MODELING FOR DONG NAI RIVER BASIN IN VIETNAM*" in partial fulfillment of the requirement for the award of the degree Master of Technology in Water Resources Development submitted in the Water Resources Development Training Center, Indian Institute of Technology – Roorkee is an authentic record of my own work carried out under guidance and supervision of Dr. U.C. Chaube and Dr. S.K. Mishra.

This is to further certify that I have worked for a period from August 2003 to June 2004 for the preparation of this dissertation.

The matter embodied in this dissertation has not been submitted by me for the award of any other Degree.

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ABSTRACT

The importance of rainfall-runoff modeling in planning and management of water resource systems can hardly be overemphasized. The long-term daily rainfall-runoff models are primarily developed for determination of continuous daily flow series from the available precipitation and other meteorological data for augmentation of flow record for use in water availability analyses useful in planning and management of water resources projects. Since the rainfall data are generally available for much longer period than are the stream flow data, long-term hydrologic simulation helps extend the gauged data required for such applications.

There exists a multitude of rainfall-runoff models and these are generally categorized to fall in the category of empirical models, conceptual models, or physically based distributed models, in the increasing order of complexities involved in modeling various processes of the hydrologic cycle. The last two types of models are generally used for daily flow simulation. Despite their comprehensive structure, many of the state-of-the-art physically based models have not yet become standard tools in hydrologic practice in developing countries because (a) most basins in these countries are ungauged and there is little hydrologic data available and (b) these models contain too many parameters, which are difficult to estimate in practice and vary from basin to basin. Although some of these models have been applied to ungauged basins, the fact is that they are not easy for practical applications. Furthermore, when these models are compared on the same basin, they are found to be widely varying in their performance. Thus, what is needed in developing countries is simple models which can provide reasonable simulations and need little data.

The Soil Conservation Service curve number (SCS-CN)-based models seem to satisfy the requirements of developing countries and it is no surprise that they have become popular, despite their lack of sophistication. Theoretically, the SCS-CN method is applicable to any watershed of any size as long as the measured runoff corresponds to the

observed rainfall amount although some restriction have been reported in this regard. Using theoretical arguments, it is possible to apply the SCS-CN method to any basin for long-term hydrologic simulation. In large watersheds, routing of rainfall-excess is predominant whereas it is minimal in small watersheds. Consequently, the SCS-CN method has been used on small basins for long-term hydrologic simulation and several models have been developed in the past two decades.

In this thesis work, the Be river basin which is one of the subcatchments of the Dong Nai basin in Vietnam is selected for hydrologic simulation study. The Be river basin is located between 106°36'E to 107°30' longitude and 10°19'N to 12°20'N latitude. The flow regime at the upstream of the Dong Nai basin is reported to have been a major determinant of the inundation and water quality problems of the basin. The solution to these problems in the downstream part is strongly linked with the hydrology of the upper river system. The lack of availability of long-term data invokes to carry out a rainfall-runoff modeling study, as presented in this thesis work. Thus, long-term hydrological rainfall–runoff modeling was used with an aim to present a hydrological model for augmentation of data useful in integrated water resources planning and management.

To meet the above objective, a simple, 4-parameter SCS-CN based daily flow simulation model was proposed and tested on the data of the Be river system. The simulation results of this model were compared with those obtained from the application of an available, conceptual, process-based, 13-parameter rainfall-runoff (RAM) model and these were found to match with each other closely. In addition, the parameters infiltration capacity I_{max}, crop factor Makkink f, initial depth of the unsaturated zone L_{Bv0}, N° of reservoirs slow component ground water discharge n, time constant reservoir unpaved surface $K_{surface}$, time constant slow groundwater discharge K_{slow} showed to be the sensitive parameters in RAM application. On the other hand, the parameter b_f determining the base flow contribution, was most sensitive in application of the SCS-CN-based model. The major advantage of the SCS-CN based model is that it is easy to understand, grasp, and apply compared to the process-based RAM model which embodies not only sophistication in its structure but also requires skill to run the model using a large set of field data. The former requires only rainfall and runoff data only as input whereas the latter does a large set of data besides these.

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LIST OF SYMBOLS

a	conversion factor unit	($a = 10/(24*3600)$)
A_{open_water}	open water surface	(ha)
A_{paved}	other paved surface	(ha)
A_{sewer}	sewer paved surface	(ha)
A_{total}	total surface	(ha)
$A_{unpaved}$	unpaved surface	(ha)
B_{max}	maximum storage in surface depressions	(mm)
B_{t-1}	storage in surface depressions	(mm)
β	distribution code quick and slow components ground water discharge	
c	vertical hydraulic resistance	(day)
c_p	specific heat of air at constant pressure	($c_p = 1004.6$ J/kg/K)
C	constant to convert units from kg/m^2/s to mm/day	($C = 86400$)
d	number of reservoirs quick component ground water discharge (in case of Krayenhoff van de Leur parallel linear reservoirs)	
Δh	hydraulic head difference	(m)
Δt	time step	(day)
e_a	actual vapour pressure for the air at 2 m height	(kPa)
e_s	saturation vapour pressure for the air temperature at 2 m height	(kPa)
$E_{a,t}$	actual evapotranspiration	(mm/day)
$E_{r,t}$	reference evapotranspiration of grass	(mm/day)
f	crop factor Makkink	
f_0	Makkink factor for open water	
F	cumulative infiltration excluding I_a	
Φ_{t-1}	actual moisture storage	(mm)
$\Phi_{pF=0}$	moisture storage at pF = 0	(mm)
$\Phi_{pF=2}$	moisture storage at pF = 2	(mm)
$\Phi_{pF=4.2}$	moisture storage at pF = 4.2	(mm)
γ	psychrometric constant	($\gamma = 0.067$ kPa/K at the sea level)
I_a	initial abstraction	(mm/day)
I_{max}	infiltration capacity	(mm/day)
I_{t-1}	infiltration intensity	(mm/day)
k_0	time constant reservoir open water surface	(day)
k_p	time constant reservoir other paved surface	(day)
k_{sewer}	time constant reservoir separated sewer system	(day)
k_s	time constant reservoir slow component ground water discharge	(day)
k_q	time constant reservoir quick component ground water discharge	(day)
$k_{surface}$	time constant reservoir unpaved surface	(day)
k_{quick}	time constant fast groundwater discharge	(day)
k_{slow}	time constant slow groundwater discharge	(day)
K	reservoir storage coefficient	
K_{wet}	adjustment coefficient	
L	latent heat of vaporization	($L = 2.45 \times 10^6$ J/kg)

L_{Bv0}	initial depth of the unsaturated zone	(mm)
λ	initial abstraction coefficient	
m	N° of reservoirs quick component ground water discharge (in case of Nash-cascades linear reservoirs) -	(Section 4.4.3)
n	N° of reservoirs slow component ground water discharge	(Section 4.4.3)
n	Pore content –	(Section 4.8.5)
n	actual hours of sunshine –	(App.1)
N	possible hours of sunshine (obtained from given table)	(App.1)
P	total precipitation	(mm/day)
$P_{N,open\_water,t}$	effective precipitation open water surface	(mm/day)
$P_{b,t}$	precipitation intensity	(mm/day)
$P_{perc,max}$	percolation to the saturated zone at pF = 0	(mm/day)
$P_{N,sur,t}$	effective precipitation surface runoff unpaved surface	(mm/day)
$P_{perc,t}$	percolation rate to saturated zone	(mm/day)
$q_{open\_water,t-1}$	specific discharge open water surface	(mm/day)
$q_{sewer,t-1}$	specific discharge, separated sewer system	(mm/day)
$q_{paved,t-1}$	specific discharge, other paved surface	(mm/day)
$q_{slow,i,t-1}$	specific slow component ground water discharge unpaved surface	(mm/day)
$q_{quick,i,t-1}$	specific quick component ground water discharge unpaved surface	(mm/day)
Q	direct runoff	(m^3/s)
$Q_{open\_water,t}$	discharge open water surface	(m^3/s)
$Q_{sewer,t}$	discharge separated system	(m^3/s)
$Q_{paved,t}$	discharge other paved surface	(m^3/s)
$Q_{slow,t}$	drainage slow component ground water discharge	(m^3/s)
$Q_{quick,t}$	drainage quick component ground water discharge	(m^3/s)
$Q_{seep,t}$	discharge seepage	(m^3/s)
$Q_{total,t}$	total discharge	(m^3/s)
$Q_{o,t}$, $Q_{c,t}$	observed responding computed runoff	(m^3/s)
$\bar{Q}_{o,t}$	average discharge	(m^3/s)
r	model correlation coefficient	
r_a	aerodynamic resistance	(s/m)
r_c	crop resistance	(s/m)
R_A	short wave radiation received at the outer limits of the at atmosphere expressed	(W/m)
R_N	net radiation at the earth's surface	(W/m^2)
R^2	model efficiency coefficient	
ρ_a	density of air (ρ_a = 1.2047 kg/m^3 at sea level)	
s	slope of the temperature-saturation vapour pressure curve	(kPa/K)
S	potential maximum retention or infiltration	(inch)
T_a	the 24 hour mean temperature of the air in °C	
σ	Stefan-Boltzmann constant	($\sigma = 5.6745\times10\text{-}8\ W/m^2/K^4$)
X_p, $X_{rep.}$	total annual rainfall of the design wet year and representative year	
x	exponent (-)	
y	exponent (-)	

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Water is the most abundant, but most vital, substance on the earth. It is the principal constituent of all living things and a major force that is constantly shaping the surface of the earth. It is also a key factor in air-conditioning the earth for human existence and in influencing the progress of civilization.

With the population increase world over, the pressure upon this vital resource is continually increasing and is expected to become much more severe in the coming two-three decades. Already there are areas where water is being used at a rate which is near the maximum available supply. On the other hand, with the rapid growth of urbanization in river valleys, the destructive effects of floods are also increasing. It is, therefore, becoming increasingly important that we strive to gain a better understanding of the occurrence and behavior of the water on the earth.

Now a days, freshwater is becoming an increasingly scarce and vulnerable resource in some places in the world, also in Vietnam, as population and economic growth are demanding a growing share of the country's water supplies. This development is particularly evident in the Dong Nai River basin, which houses the Vietnam's largest population center of Ho Chi Minh City as well as the largest concentration of industrial output. At the same time, this basin continues to diversify its agricultural sector with products ranging from basic staples like rice and maize to raw materials for the local industry, including cotton, rubber, and sugarcane, to high-valued crops, like coffee, fruit, grapes, pepper, tea, and vegetables. The highly productive basin economy depends on water supply for a variety of uses, including drinking water, industrial processes, hydropower production, irrigation, and to combat water pollution in the dry season. In this context, proper management of river basin is of paramount importance. Information, communication technology, and related knowledge in water related problems would help people in better management of river basins. Some of these technologies such as application of hydrological modeling and hydrodynamic and quality modeling can assist planners to contemplate and propose ever more comprehensive, complex, and ambitious plans for water resource systems.

Hydrological models provide a way of transferring knowledge from a measured or study area to areas where hydrological information is needed for objective decisions. With hydrodynamic and quality modeling, one can perform unsteady flow computations in networks of open water courses, simulating the transportation of substances in free surface flow and fairly complex water quality processes. The combination of models is a very useful tool to analyze and solve the problem of integrated water resources management.

1.2. PROBLEM DEFINITION

The Dong Nai river system is closely related to most developments in the basin. Specially the lower area is one of the focal economic development zones in Vietnam, including Ho Chi Minh city, Bien Hoa city, and Ba Ria Vung Tau as development centres. The rivers in the lower area are the main sources for municipal and industrial water supply.

Due to uneven spatial-temporal distribution of rainfall, and tidal intrusion from South China Sea, the basin faces problems of flood, drought, and salinity intrusion. Moreover, because of industrialization and rapidly increasing population that is becoming a big problem in this area. Surface water quality in Ho Chi Minh city and some other cities located along the Sai Gon and Dong Nai rivers is probably one of the most serious environmental issues, particularly in relation to public health and economic activities. In terms of water pollution, there are two sources releasing water directly to the city's drainage system: domestic sewage and industrial wastewater. Almost all sewage and wastewater is released by local drains to the rivers without treatment, deteriorating the water quality. Moreover, poor maintenance of drains and uncontrolled intrusion by squatters worsen the problem. Finally, as the result of uncontrolled release of domestic sewage and industrial wastewater to local drains and rivers, local groundwater is contaminated. Therefore various developments in the basin have suffered the problems of water resources and environment. In the lower part of the Dong Nai river basin, the main problems are:

(1) Inundation hampering living conditions (especially in Ho Chi Minh city), agricultural development, etc. during the rainy season.

(2) Water pollution causing problems to water supply for domestic, industrial, and agricultural uses in the dry season.

The flow regime at the upstream determines the above inundation and water quality, and the solution to the problems in the downstream part is strongly linked with the hydrology of the upper river system. The lack of availability of long-term data invokes to carry out a rainfall-runoff modeling study, as presented in this thesis work. Thus, long-term hydrological rainfall–runoff modeling was used with an aim to present a hydrological model for augmentation of data useful in integrated water resources planning and management.

1.3. SCOPE OF THE STUDY

As runoff data are missing or only available during short periods, they can be generated using rainfall – runoff relationships or long-term hydrological simulation models. It is realized that this analysis must be applied to the catchment as a whole. However, the total catchment is too large for such studies, the analysis is limited to a particular Be River sub-catchment of upper Dong Nai basin, which can be extrapolated over a more extended part of the catchment. The scope of the study is summarized as follows:

Rainfall – runoff modeling of the Be basin (upper Dong Nai catchment)

- Collection of relevant hydrometeorological data such as rainfall, sunshine hours, wind velocity, relative humidity, and temperature in Be river basin and surrounding areas.
- Generation of land use and crop pattern data
- Analysis of rainfall and evapotranspiration data in the Be river basin.
- Applying the available process-based rainfall-runoff (RAM) model and a simple Soil Conservation Service Curve Number (SCS-CN) rainfall runoff model to the data of Be river basin.
- Compare the results of the two models.

1.4. OUTLINE OF THE THESIS

This thesis consists of six chapters as described below:

Chapter 1 – introduces the problem in general and provides an outline of the work.

Chapter 2 – provides literature review of hydrological models.

Chapter 3 - describes the characteristics of the study area.

Chapter 4 - describes the application of RAM in the Be river basin.

Chapter 5 - introduces the SCS-CN-based long-term daily flow simulation model & its application.

Chapter 6 – presents the conclusions.

CHAPTER II : LITERATURE REVIEW

The long-term daily hydrologic simulation is useful in augmentation of hydrologic data, water resources planning (Maass et al., 1962; Chaturvedi and Srivastava, 1981), and watershed management (Mishra and Singh, 2003, 2004) and is efficacious in description of the performance of a water resource system under climatic variations of rainfall and other aspects (Kottegoda et al., 2000). This chapter presents the state-of-the art-of long term hydrologic simulation modeling. To this end, to present a brief overview of the popular physically based, conceptual, and empirical models, it is required that various processes actually involved in the runoff generation due to rainfall be described, which, in turn, leads to describing the hydrological cycle and its components.

2.1. HYDROLOGICAL CYCLE

The hydrological cycle is a continuous process in which water circulates from the oceans through the atmosphere and rivers back to the ocean. Figure 2.1 provides a simplified schematic view of the hydrologic cycle.

Water evaporates into the atmosphere and falls as precipitation on the land and the sea. The precipitation that falls on the land surface is stored temporarily on vegetation (interception), on objects, on the surface (depressions), in the soil (replenishment of soil moisture and ground water reservoir) and in open waters. The surplus precipitation, the precipitation that does not evaporate, will end up running off as ground water or surface water eventually.

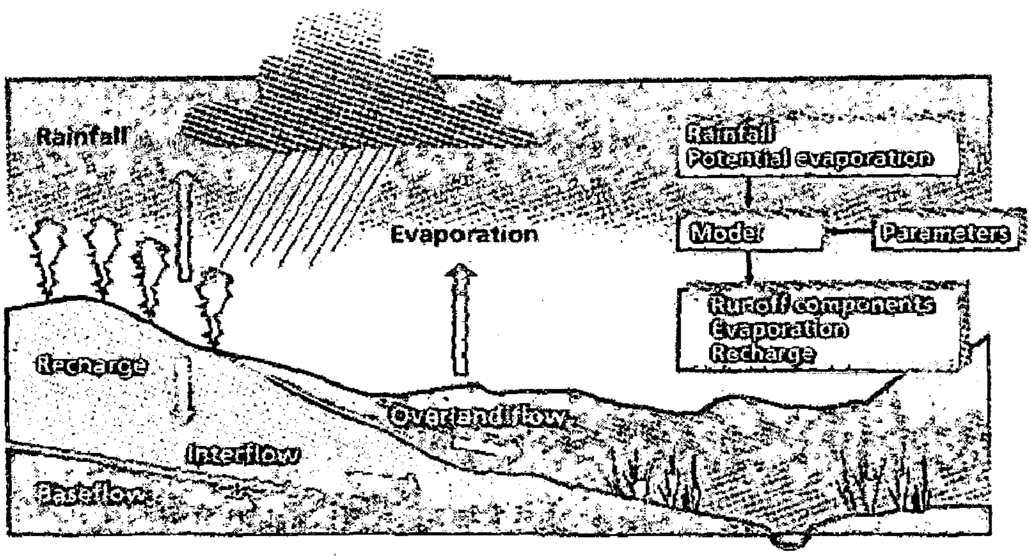


Figure 2.1 : Hydrology Cycle

2.2. RAINFALL – RUNOFF PROCESS

The precipitation that is drained during a time interval does not immediately flow to the river due to the buffer effect of the terrain, the subsoil and the drainage system. This buffer effect, which is the result of a number of reservoir effects of different nature and size leads to time shifts between the moments of precipitation, evaporation, and discharge. The larger a time interval is taken and, therefore, the smaller the storage effect, the more the discharge will approach the difference between precipitation and evaporation. The total storage effect is, however, important to the determination of a flood wave (relatively short period of time), due to quelling and slowing down of the precipitation surplus. The storage effects are less important to the total drainage during a longer period of time.

Many distinct decompositions of the rainfall-runoff process in a catchment are possible but the one represented in Fig. 2.2 has attracted more attention of the hydrologists, as it is helpful in finding relationship between the variables characterizing the input, i.e. rainfall, and the output, i.e. runoff. The systems approach is one of the most popular methods of forecasting flows resulting from known rainfall over a catchment, as the true mathematical representation of the natural process is very difficult, particularly in sparse data scenario.

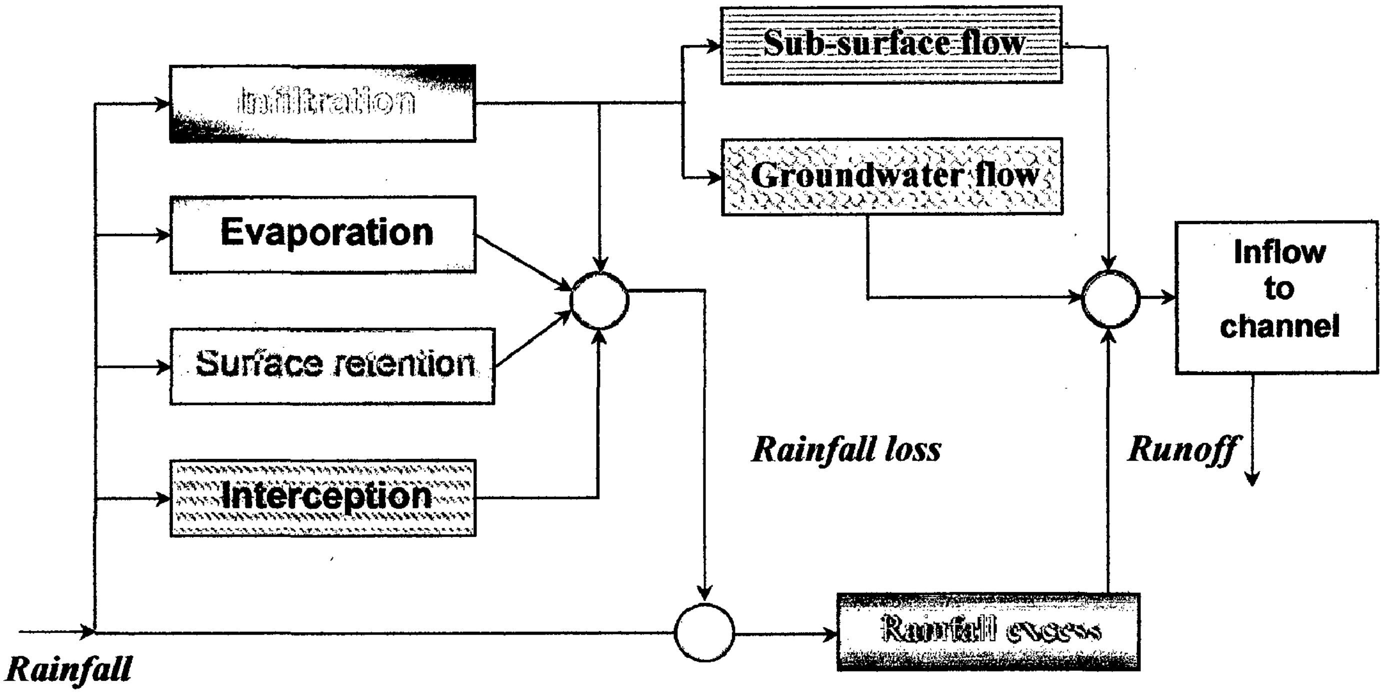


Figure 2.2 : The process of rainfall-runoff transformation over a catchment

2.2.1. General

Unlike the hydrologic cycle, which is a closed system, catchment is an open hydrologic system which, when applied with input in the form of rainfall, generates its response in the form of runoff. Precipitation – runoff processes are generally described at a catchment area level. Within a catchment area, the relevant parameters may vary substantially, like the soil type, slope, land use, etc. A detailed physical description of all the processes actually occurring is, therefore, difficult to provide. The physical process of transformation of rainfall into runoff over a catchment is a complex hydrologic phenomenon on account of underlying nonlinear sub-processes. A proper understanding of the rainfall-runoff relationship at the catchment scale is important for water management studies, safe yield computation, and design of flood control structures. When the rainfall occurs an area, the following process takes place (Fig. 2.2).

2.2.1.1. Interception

Interception is one part of rainfall, which is held, back on the leaves of plants and over the vegetation on ground and later evaporates into the atmosphere.

2.2.1.2. Surface retention

Another part of the rainfall that is stored in the depression on the earth surface or is retained under the vegetal cover is called as the surface retention. In due course of time, it infiltrates into the ground and/or evaporates into the atmosphere.

2.2.1.3. Overland flow

Overland flow is that portion of rainfall, which flows over the ground surface and meets the stream through gullies and rivulets.

2.2.1.4. Infiltration

Infiltration is the part of the rainfall that immediately enters the soil surface, a portion of which is transpired into the atmosphere through the deep-rooted plants. The infiltrated water follows various paths.

a) *Soil moisture*: a portion of the infiltrated water is retained in the upper layer of the soil. Later a part of this is evaporated and the remaining part is transpired into the atmosphere through the plants.
b) *Interflow*: another portion of the infiltrated water moves toward streams without reaching the ground water table and is called as the interflow.
c) *Base flow*: some part of the infiltrated water meets the groundwater table. A portion of this groundwater moves towards the stream and seeps into it through the banks and beds and thus it also becomes runoff under favorable conditions called as the base flow.

Each of these processes vary in space and time, which makes the process of rainfall-runoff transformation a complex one.

2.2.2. Categories of Models

A model represents the system by a set of relationships amongst parameters and variables contemplating the similarity of the prototype with the model, but without identity (Singh, 1988). The models developed in past to simulate the rainfall-runoff process can be broadly grouped under three categories, with increasing order of complexities involved as:

- Empirical or black box models
- Conceptual models
- Physically based distributed models

2.2.2.1. Empirical (Black Box) Models

The empirical models treat hydrologic system (e.g. a catchment) as a black box and try to find relationship between historical inputs and the outputs (Singh, 1988). In this approach, the continuity equation is expressed in a spatially lumped form without considering the physical laws operating within the catchment and instead a general but simple relationship is assumed between rainfall amount and the discharges at the outlet of the catchment. In operational hydrology many situations exist, which demand the use of such simple, system theoretic models.

The rational method was the first linear black box rainfall-runoff model. The rational method presents the concept of time of concentration and its relation to peak flow but it fails to give time development of discharge. The development of empirical models gained a boost with the proposition of unit graph theory by Sherman in 1932. He defined a unit graph or a unit hydrograph as: "*A direct runoff hydrograph (DRH) resulting from unit amount of excess rainfall generated uniformly over the catchment area at a constant rate for an effective duration.*"

A UH is a linear model that relates the excess rainfall (ER) to the direct runoff (DR), describing the response of catchment. The assumptions regarding spatial and temporal uniformity of rainfall, validity of the principles of proportionality and superposition, and time invariance are basic in the concept of the UH theory.

2.2.2.2. Conceptual Models

Conceptual models, on the other hand, attempt to represent the known physical process occurring in the rainfall-runoff transformation in a simplified manner by way of linear/nonlinear mathematical formulation. The total process is divided into sub-processes, which are conceptualized assuming quasi-physical relationships, with the model parameters representing the catchment characteristics. While conceptual models have proved their importance in understanding the hydrological processes, their implementation and calibration presents various difficulties. As a result the model prediction accuracy is found to be user dependent (Klemes, 1982).

Some of the limitations of the conceptual rainfall-runoff models are highlighted below:

- This type of models require significant amount of data.
- The unique optimal values for their parameters are difficult to obtain.
- It is difficult to determine the sensitivity of the parameters and hence the sensitivity of model forecasts to factors such as errors in input and output data, model error, objective function used *etc.*
- The nonlinear structural characteristic of conceptual rainfall-runoff models lead to the existence off multiple optima *i.e.* more than one solution.

- These models also face problems like parameter interaction, non-convexity of response surface, and discontinuous derivatives.
- The model prediction accuracy is found to be user dependent as its use requires some degree of expertise and experience with the model.
- Very often the users are tempted to fit the model without seriously considering the parameter values, resulting in poor model performance during verification phase.

Although, conceptual models provide results with reasonable accuracy, their use is restricted due to the above mentioned difficulties experienced in their calibration and implementation. A brief review of these models follows:

The computer-based lumped, conceptual rainfall-runoff models have been widely applied in hydrological modeling since they were first introduced in the late 1960's and early 1970's (Henrik et al., 2002). Among a multitude of models, a few well known and some recent storage concept-based models worth citing are: Stanford Watershed Model IV (SWM IV) (Marco and Michele, 1991; Singh, 1989), Boughton model (Johnston and Pilgrim, 1976; Mein and Brown, 1978), Kentucky Watershed model (Moore et al., 1983; James, 1972), Institute of Hydrology model (Blackie and Eles, 1985), MODHYDROLOG Model (Chiew et al., 1993), and Hydrology and River Hydraulics at University of Tokushima (HRUT) Model (Yao et al., 1996). Using the storage concept, the Soil Conservation Service Curve Number (SCS-CN) model has also been widely employed in the past for long term hydrologic simulation (Mishra et al., 1998; Mishra and Singh, 2003, 2004). These models can also be applied for data generation from synthetically generated precipitation (Kraeger, 1971; Obeysekera, 1978).

The above rainfall-runoff models considered as important tools in operational hydrology differ from each other in terms of the mathematical representation of various governing processes, spatial discretization of the catchment, and data requirement. These models attempt to represent the reality when properly fitted to real observations (James and Luk, 1998). Because of intricate spatial and temporal variability, natural processes are however too involved to model by physical means, leading to simplifications to reduce the degree of complexity, and consequently, to the development and use of conceptual, lumped models (Ibbit, 1972) which require minimal amount of data related to physical characteristics of the watershed (Donnelly-Makoweeki and Moore, 1999). Though simple and easy to understand and apply (Basha, 2000), such models need long meteorological and hydrological records for calibration. Singh and Woolhiser (2002) reviewed various mathematical models of watershed hydrology and found them to be efficacious in simulation of not only water quantity but also quality.

The current version of the Institute of Hydrology model consists of 4 stores of moisture representing interception, surface runoff, soil moisture, and groundwater, and has 15 model parameters determined either from field survey or optimization. It has been applied in UK and East Africa for watersheds ranging from 37 ha to 1600 sq. km with their annual rainfall varying from 500 to 2500 mm (Blackie and Eles, 1985). The MODHYDROLOG model (Chiew and McMohan, 1991) has 19 parameters; includes the surface runoff, interflow, and base flow, and a non-linear routing mechanism; uses daily rainfall and potential evapotranspiration data as input; and simulates daily, monthly, and annual flows (Chiew et al., 1993; Chiew and McMahon, 1994). Its application to 28 catchments in Australia exhibited difficulty in simulation of long periods of zero flows followed by peak flows (Chiew and McMahon, 1994). The 37-parameter HRUT model including four runoff components, viz., surface flow, rapid top-soil through flow, delayed root-soil through flow, and base flow, requires air temperature, relative humidity, net radiation, wind speed, rainfall, and soil water as input. It was tested on an experimental site of the laboratory of Hydrology and River Hydraulics at University of Tokushima.

Despite their workability to test sites, the process-based (described subsequently) models are complex for they contain too many parameters and their real-world application is generally involved (Marco and Michele, 1991). For example, the most widely accepted SWM IV model (Singh, 1989) contains 25 parameters (if snow component is excluded) to simulate direct runoff, surface runoff, sub-surface runoff, and base flow using hourly or daily precipitation, daily temperature, radiation, wind, and monthly or daily evaporation data. The 13-parameter modified Boughton model (Moore and Mein, 1976) computes daily evapotranspiration from upper and lower soil stores, daily infiltration from the drainage store to the lower soil store, and runoff. Requiring only daily rainfall and evaporation data, its application is reported to only 4 Australian watersheds (Mein and Brown, 1978). The optimization-based 22-parameter Kentucky watershed model (Liou, 1970) has been used by James (1970, 1972). Moore et al. (1983) developed a 14-parameter model, which performed well when applied to daily data of River Millseat watershed in Kentucky. Similar to Kentucky Watershed model (Moore et al., 1983), Putty and Prasad (1993) proposed a model for Sahyadri ranges of Western Ghats, India, containing 11 parameters, out of which some were determinable from soil and land use characteristics, and the others by optimization. Making use of the source area concept (Betson and Maurius, 1969; Dunne and Black, 1970a,b; Dunne, 1978; Selby, 1982; Ward, 1984; Anderson and Burt, 1990), Mishra et al. (In Press) proposed a lumped, storage- and source area-based daily rainfall-runoff model incorporating the processes of initial abstraction, evaporation transpiration, infiltration, drainage, percolation, deep seepage, source area runoff, throughflow, and base flow.

2.2.2.3. Physical Process Based Models

The process- or physically based models are too complex, data intensive, and cumbersome to use. Typically they involve solutions of a system of partial differential equations that represent the flow processes within the catchment (Beven, 1985; Loague and Freeze, 1985). The kind of data required for use of the physically based distributed models is rarely available, even in heavily instrumented research catchments. Even by using current advanced computing capabilities the representation of a catchment in the physically based model is, at best, an approximation (Beven, 1987, 1989). Despite these limitations, the physically based models exhibit usefulness in solution to many hydrologic problems when utilized appropriately. The major limitations of the process-based models are listed below:

- Data intensive: proper application of the physically based model requires use of vast amount of data, which may not be available for many catchments particularly for large catchments in developing countries.

- Lumping at small scale: the application of distributed model over a catchments involves division of catchments into sub-areas, and lumping of the model parameters at this scale. Such a model is viewed as a lumped conceptual model rather than a distributed model.
- Difficulty in calibration: as many parameters are involved, these interact with each other posing tremendous difficulties in model calibration.
- Unknown boundary conditions: the initial and boundary conditions particularly those related to soil moisture conditions are not known correctly and are also difficult to ascertain.
- Expensive to run: short time steps may be necessary to maintain stable solution, and as the solution is found at each computational node at each time step, the number of calculations required can be very large. These models also require considerable expenditure in terms of programming, data preparation, and field experimentation.
- The limitations outlined above make the physically based models presently unsuitable for practical applications. Successful application of the physically based models in the field is also hampered due to the scale problems associated with the immeasurable spatial variability of rainfall and hydraulic property of the soil.

The hydrologic models vary in description of the components of the hydrologic cycle, model architecture and structure, degree of complexity of inputs, number of parameters to be determined, time interval used in simulation, error and risk analyses, and output generated. Most of the models, such as the Hydrologic Simulation Package Fortran (HSPF), USDAHL (Holtan and Lopez, 1971) and its variants, Systeme Hydrologique Europeen (SHE) (Abbott et al., 1986a, b), Hydrologic Engineering Centre Hydrologic Modeling System (HEC-HMS) (HEC, 2000), etc., have a number of parameters, usually use a short time interval, produce hydrographs as well as water yield, and provide continuous simulation. In 1991, the U. S. Bureau of Reclamation prepared an inventory of 64 watershed models into four categories and the inventory is being currently updated. Burton (1993) compiled Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 1990's, which contain several important watershed hydrology models. Singh (1995) edited a book that summarized 26 popular models from around the globe. The Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data (1998) published proceedings of the First Federal Interagency Hydrologic Modeling Conference which contains many popular watershed hydrology models developed by federal agencies in the United States. Wurbs (1998) listed a number of generalized water resources simulation models in seven categories and discussed their dissemination. A revised summary of models is given in the table 2.1 complied by Singh (2002).

Despite their comprehensive structure, many of these models have not yet become standard tools in hydrologic practice in developing countries, such as India, Pakistan, Nepal, and other countries of Asia as well as African countries. The reason is twofold. First, most basins in these countries are ungauged and there is little hydrologic data available. Second, these models contain too many parameters, which are difficult to estimate in practice and vary from basin to basin. Although some of these models have been applied to ungauged basins, the fact is that they are not easy for practical applications. Furthermore, when these models are compared on the same basin, they are found widely varying in their performance (Woodward and Gburek, 1992). Thus, what is needed in developing countries is simple models which can provide reasonable simulations and need little data.

The Soil Conservation Service curve number (SCS-CN)-based models seem to satisfy the requirements of developing countries and it is no surprise that they have become popular, despite their lack of sophistication. Theoretically, the SCS-CN method is applicable to any watershed of any size as long as the measured runoff corresponds to the observed rainfall amount. However, Ponce and Hawkins (1996) have discussed its limitations to watersheds of less than 250 sq. km. Using theoretical arguments, it is possible to apply the SCS-CN method to any basin for long-term hydrologic simulation. In large watersheds, routing plays an important role in converting the rainfall-excess to the surface runoff hydrograph produced at the basin outlet. On the other hand, small watersheds require minimal routing in long-term hydrologic simulation when utilizing a time interval of 1-d or larger. Consequently, the SCS-CN method has been used on small basins for long-term hydrologic simulation and several models have been developed in the past two decades. The models of Williams and LaSeur (1976), Huber et al. (1976), Hawkins (1978), Knisel (1980), Soni and Mishra (1985), and Mishra et al. (1998) are notable.

Table 2.1. **SAMPLE OF POPULAR HYDROLOGIC MODELS**

Nº	Model name	Author	Year	Remark
1	Agricultural Transport Model (ACTMO)	Frere et al.	1975	Lumped, Conceptural, event based Runoff and water quality simulation model
2	Agriculture Non-point Source Model (AGNPS)	Young et al.	1989, 95	Distributed parameter, event based , water quantity & quality simulation model
3	Agriculture Runoff Model (ARM)	Donigian et al.	1977	Process-oriented , Lumped Runoff simulation model
4	Antecedent Precipitation Index Model (API)	Sittner et al.	1969	Lumped, river flow forecast model
5	Areal Non-point Source Watershed Environment Response Simulation (ANSWERS)	Beasley et al Bouraoui et al.	1977 2002	Event-based or continuous, Lumped parameter Runoff & water quality mod
6	ARNO (Arno River) Model	Todini	1988, 96	Semidistributed, continuous Rainfall-Runoff simulation model
7	Cascade two dimensional Model (CASC2D)	Julien and Saghafian	1991	Physical based, distributed, event based Runoff simulation model
8	Catchment Model (CM)	Dawdy and O'Donnell	1965	Lumped, event runoff model
9	Chemicals, Runoff and Erosion from Agricultural Management System (CREAMS)	USDA	1980	Process-oriented, Lumped parameter, AgriculturalRunoffWaterQualityModel
10	Constrained Linear Simulation (CLS)	Natale and Todini	1976,77	Lumped parameter, event based or continuous Runoff simulation model
11	Daily Conceptual Rainfall-Runoff Model (HYDROLOG) – Monash Model	Potter and McMahon Chiew and McMahon	1976 1994	Lumped,Conceptual Rainfall-Runoff Model
12	Distributed Hydrological Model (HYDROTEL)	Fortin et al.	2001	Physical based, distributed, continuous Hydrologic simulation model
13	Distributed Hydrology Soil Vegetation Model (DHSVM)	Wigmosta et al.	1994	Distributed, Physical based, continuous Hydrologic simulation model
14	DUFLOW	IHE, TU Delf and MPW	1988 2000	Rainfall-Runoff Module, Water Quantity and Quality Model, simulated interaction groundwater and surfacewater

15	Dynamic Watershed Simulation Model (DWSM)	Borah and Bera	2000	Process-oriented, event based, Runoff and water quality simulation model
16	Erosion Productivity Impact Calculator Model (EPIC)	Williams et al. Williams	1984 1995	Process-oriented, Lumped parameter Continuous water quantity & quality simulation model
17	G Lakes Environmental Research Laboratory (GLERL)	Croley	1982,83	Physical based, Semidistributed continuous simulation model
18	Gemorphology-based Hydrologic simulation model (GBHM)	Yang et al.	1998	Physical based, distributed, continuous Hydrologic simulation model
19	Generalized River Modeling Package – System Hydrological European (MIKE-SHE)	Refsgaard and Storm	1995	Physical based, distributed, continuous hydrologic and hydraulic simulation model
20	Global Hydrologic Soil Vegetation Model (GHM)	Anderson and Kavas	2002	Process-oriented, Semidistributed, large scale hydrologic simulation model
21	Groundwater Loading Effects of Agriculture Management System (GLEAMS)	Knisel et al. Knise and Williams	1993 1995	Process-oriented, Lumped parameter, event based water quantity & quality simulation model
22	Hydrologic Engineering Center- Hydrologic Modeling System (HEC-HMS)	Feldman HEC	1981 2000	Physically based, Semidistributed, event based, runoff model
23	Hydrologic Modeling system (HMS)	Yu and Schwartz Yu et al.	1996,98, 1999	Physical based, distributed, continuous simulation system
24	Hydrological Model (CEQUEAU)	Morin et al.	1995 1998	Distributed, Process-oriented, continuous Runoff simulation model
25	Hydrological Modeling system (ARC/EGMO)	Becker and Pfuzner Lahmer et al.	1987 1999	Process-oriented, distributed, continuous simulation system
26	Hydrological Simulation Model (HBV)	Bergstorm	1976,92,95	Process-oriented,Lumped, continuous streamflow simulation model
27	Institute of Hydrology Distributed Mod (IHDM)	Beven et al. Calver and Wood	1987 1995	Physical based, distributed, continuous Rainfall-Runoff Modeling system
28	Integrated Hydrometeological forecasting system (IHFS)	Geogakakos et al.	1999	Process-oriented, distributed, Rainfall and flow forecasting system

29	Kinematic Runoff and Erosion Model (KINEROS)	Woolhise ed al. Smith et al.	1990 1995	Physical based, Semidistributed, event based, Runoff and water quality simulation
30	Large Scale Catchment Model (LASCAM)	Sivapalan et al.	1996	Conceptual, Semidistributed , large scale, continuous, Runoff and water quality simulation model
31	Macroscale Hydrological Model – Land surface Scheme (MODCOU-ISBA)	Ledoux et al. Noilhan and Mahfouf	1989 1996	Macroscale, Physical based, distributed continuous simulation system
32	Mathematical Model of Rainfall-Runoff Transformation System (WITSTOO)	Ozga-Zielinska and Brzezinski	1994	Process-oriented, Semidistributed, event based or continuous simulation model
33	Modular Kinematic Model for Runoff simulation	Stephenson Stephenson and Randell	1989 1999	Physical based, Lumped parameter, event based Runoff simulation model
34	National Hydrology Research Institute Model (NHRI)	Vandenberg	1989	Physical based, Lumped parameter, ContinuousHydrologicSimulation mod
35	National Weather service – River Forecast System (NWS-RFS)	Burnash et al. Burnash	1973 1975	Lumped, continuous river forecast system
36	Package-FortranIV (HSPF)	Bicknell et al.	1993	Continuous, dynamic event or steady state simulator or hydrologic and hydraulic and water quality process
37	Pennsylvania State University – Urban Runoff Model (PSU-URM)	Aron and Lakatos	1980	Lumped, event based urban Runoff model
38	Physically based Runoff Production Model (TOPMODEL)	Beven and Kirkby Beven	1976,79 1995	Physical based, distributed, continuous Hydrologic simulation Model
39	Predicting Arable Resource Capture in Hostile Environments – The Harvesting of Incident Rainfall in Semi-arid Tropics (PARCHED-THIRST)	Young and Gowing Wysere et al.	1996 2002	Process-oriented, Lumped parameter, event based agro-hydrologic model
40	Purdue Model	Huddins and Monke	1970	Process-oriented, physically based, event runoff model
41	Rainfall-Runoff Model (R-R)	Kokkonen et al.	1999	Semidistributed, Process-oriented, continuous streamflow simulation model
42	Regional-Scale Hydroclimatic Model (RSHM)	Kavas et al.	1998	Process-oriented, regional scale, continuous

				Hydrologic simulation model
43	Runoff Routing Model (RORB)	Laurenson Laurenson and Mein	1964 1995	Lumped, event runoff simulation model
44	Simple Lumped Reservoir Parameter Model (SLURP)	Kite	1995	Process-oriented, distributed , continuous simulation model
45	Simplified Hydrologic Model (SIMHYD)	Chiew et al.	2002	Conceptual, daily, Lumped parameter, monthly Runoff simulation model
46	Simulation for Water Resources in Rural basins (SWRRB)	Williams et al. Williams	1985 1995	Event-based or continuous, Lumped parameter Runoff & sediment yield simulation model
47	Simulation of Production and Utilization of Rangelands (SPUR)	Wight and Skiles Carlson and Thurow et al.	1987 1992, 95	Physical based, Lumped parameter ecosystem simulation model
48	Snowmelt Runoff Model (SRM)	Rango	1995	Lumped, continuous snowmelt-Runoff simulation model
49	Soil Conservation Service Curve Number (SCS-CN)	Mishra S.K. and Singh V.P.	2003	Lumped, continuous simulation model
50	Soil Water Assessment Tool (SEAT)	Arnold et al.	1998	Distributed, conceptural, continuous simulation model
51	Soil-Vegetation-Atmosphere Transfer Model (SVAT)	Ma et al. Ma and Cheng	1999 1998	Macroscale, Lumped parameter, streamflow simulation system
52	Stanford watershed Model (SWM) / Hydrologic Simulation	Crawford & Linsley	1966	Continuous, dynamic event or steady state simulator or hydrologic and hydraulic and water quality process
53	Stochastic Event Flood Model (SEFM)	Scaefer and Barker	1999	Process-oriented, Physical based event based, flood simulation model
54	Storm Water Management Model (SWMM)	Metcalf and Eddy et al. Huber and Dickinson Huber	1971 1988 1995	Process-oriented , Semidistributed continuous stormflow model
55	Surface Runoff, Infiltration River Discharge and Groundwater Flow (SIRG)	Yoo	2002	Physical based, Lumped parameter, event based streamflow simulation model
56	System Hydrologic European Transport (SHETRAN)	Ewen et al.	2000	Physical based, distributed, water quantity & quality simulation model

57	System Hydrological European / System European Sediment (SHE/SHESED)	Abbott et al. Bathurst et al.	1986 1995	Physical based, distributed, continuous streamflow and sediment simulation
58	Tank Model	Sugawara et al. Sugawara	1974 1995	Process-oriented , Semidistributed or Lumped continuous simulation model
59	Tank Model	Sugawara et al. Sugawara	1974 1995	Process-oriented , Semidistributed or Lumped continuous simulation model
60	Tennessee valley Aythority Model (TVA)	Tenn, Valley	1972	Lumped, event runoff model
61	THALET	Grayson et al	1995	Process-oriented, distributed parameter, terrain analysis-based, event based Runoff simulation model
62	The water and snow balance model system (WSMOD)	Xu	1999	Conceptual, Lumped, continuous Hydrologic model
63	Topgraphic Kinematic Approximation and Integration Model (TOPIKAPI)	Todini	1995	Distributed, Physical based , continuous Rainfall-Runoff simulation model
64	Two parameter Monthly water balance model (TPMWBM)	Guo and Wang	1994	Process-oriented, Lumped parameter, monthly Runoff simulation model
65	University of British Columbia Model (UBC)	Quick and Pipes Quick	1977 1995	Process-oriented, Lumped parameter, continuous simulation model
66	US Department of Agriculture Hydrograph Laboratory (USDAHL)	Holtan and Lopez	1971	Event-based, process-oriented, lumped hydrograph model
67	US Geological Survey Model (USGS)	Holtan et al.	1974	
68	Utah State University Model (USU)	Andrews et al.	1978	Process-oriented, event /continuous streamflow model
69	Waterloo Flood System (WATFLOOD)	Kouwen et al. Kouwen	1993 2000	Process-oriented, Semidistributed continuous flow simulation model
70	Watershed Bounded Network Model (WBNM)	Boyd et al. Rigby et al.	1979, 96 1991	Gemorphology-based, Lumped parameter, event based flood simulation model
71	Xinanjiang Model	Zhao et al. Zhao and Liu	1980 1995	Process-oriented , Lumped continuous simulation model

CHAPTER III

DESCRIPTION OF THE STUDY AREA

In this thesis work, the data of Be river basin (Vietnam) are used for development and evaluation of model performance. This chapter is aimed at to describe the geographical, geophysical, and climatological features of the study area as follows.

3.1. GEOGRAPHICAL FEATURES

The Be river basin (Fig. 3.1) is one of the subcatchments of the Dong Nai basin (Fi.g. 3.2) in Vietnam. It is located between 106°36'E to 107°30' longitude and 10°19'N to 12°20'N latitude. The basin consists of the Be province and a part of the provinces of Dac Lac, Dong Nai and Tay Ninh. The total catchment area is 7,201 km^2. The following text describes first the whole Dong Nai basin and then the Be River system studied in this thesis work.

3.1.1 Dong Nai Basin

The major features of the whole Dong Nai basin can be described as follows:

- The main stem of the Dong Nai river originates from high hills (El. 1,000 to 2,000 m) lying in the northern end of Lam Dong province, initially taking the southwestward direction in its flow course (Figure 3.1). After the joining of the Da Dung river from east, the Dong Nai river turns its flow direction to the west, making the border line between Lam Dong and Dac Lac provinces.

- After passing counter-clockwise along the border lines between Dac Lac and Lam Dong provinces and between Lam Dong and Song Be provinces, the Dong Nai river heads to the south-east. After joining the Da Te river from the north-east, the Dong Nai river changes its flow direction, and crosses Dong Nai province. Meandering east of Ho Chi Minh city, the Dong Nai river finally debouches in the South China Sea with a catchment area of 40,683 km^2 at the estuary including its tributaries.

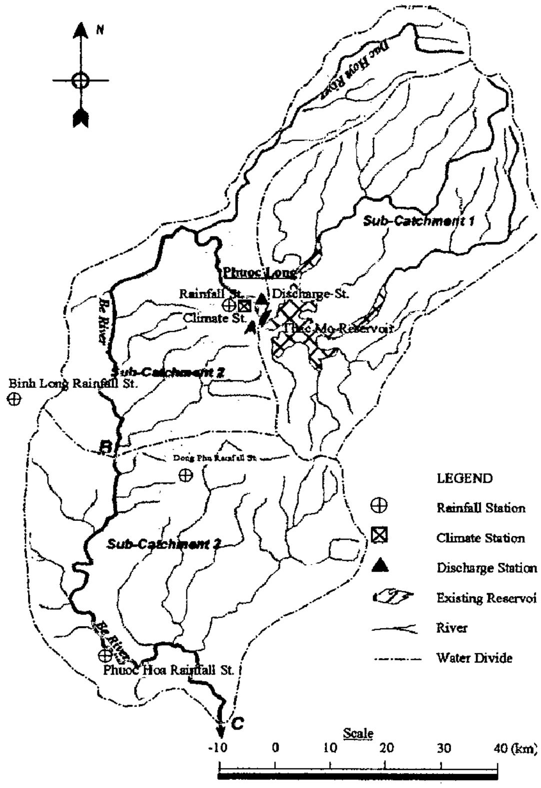


Figure 3.1 : The Be river basin

<u>Table 3.1</u> : Average Monthly Meteorological Characteristics In Be River Basin

Month	Air T°	Relative Humidity	Sunshine Hour	Wind Velocity
	°C	%	h/day	m/s
Jan	25.4	71.5	8.2	2.0
Feb	26.1	70.0	8.7	2.2
March	27.6	70.0	8.7	2.3
Apr	28.5	73.2	8.1	2.2
May	28.1	79.0	6.9	2.0
June	27.1	84.0	5.9	2.0
July	26.6	85.2	5.7	2.1
Aug	26.5	85.9	5.3	2.0
Sept	26.3	86.7	4.9	1.8
Oct	26.1	85.4	5.6	1.6
Nov	25.8	80.2	6.5	1.8
Dec	25.0	74.6	7.3	2.0
Mean	**26.6**	**78.8**	**6.8**	**2.0**

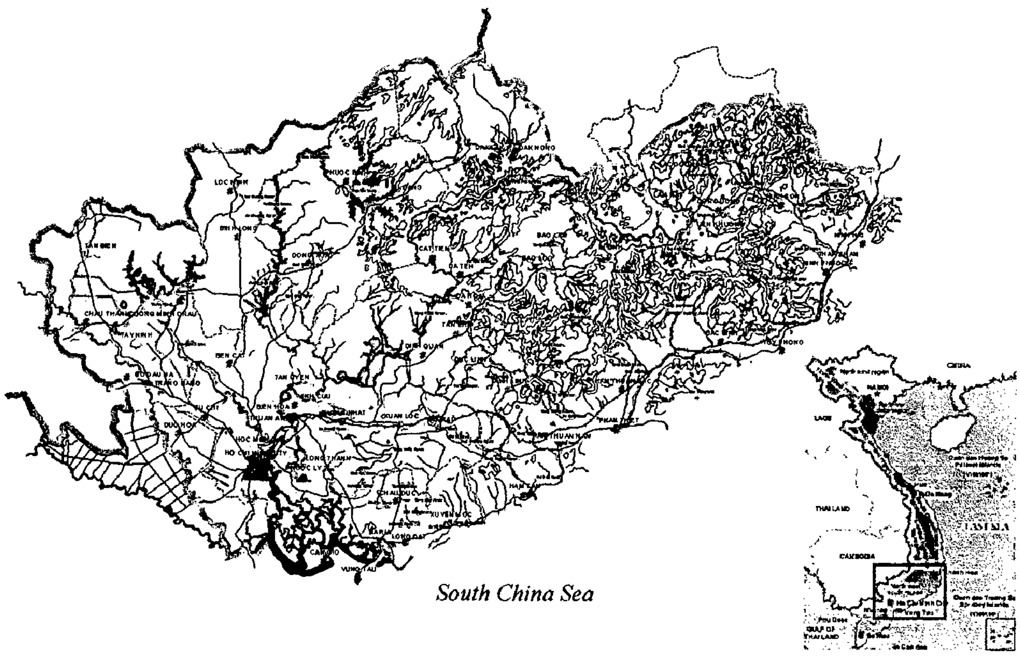


Figure 3.2 The Dong Nai River Basin

- Besides the Sai Gon and Vam Co rivers there are two main tributaries, the La Nga and Be rivers, to the Dong Nai river. Sai Gon river meets the Dong Nai about 30 km upstream of the estuary and the Vam Co river merging into it almost at the estuary. The La Nga river originates from the south-west flank of Mt. Pantar (MSL+ 1,654 m) in Lam Dong province in the south of the Dong Nai river basin. Meandering westward, the La Nga river merges into the Dong Nai river at Thanh Son.
- The origin of the Be river lies in the Tuy Duc standing on the international border between Vietnam and Cambodia in Dac Lac province, and its main tributary, the Dac Hoyt river which runs south-westward forming the international boundary between the two countries. The Be river meets the Dong Nai main stream downstream of the Tri An dam-site after passing the wide valley extending in the centre of Song Be province.

- The Sai Gon river, which originates from the southern flank of the hills (MSL+ 100 to 200 m) bordering with Cambodia in Tay Ninh province, has a characteristic gentle and meandering slope. Five kilometer upstream of the confluence with the Dong Nai is the Saigon island port, which is the pivot of navigation to support the economic activities in Ho Chi Minh city and the Mekong Delta.

- West of the Sai Gon river, there is Vam Co river, which has two main tributaries, the East and West Vam Co rivers. Both of them originate in low hill area in Cambodia and gently flow down south-eastward through the wide plain in the Long An province, finally merging into Dong Nai river near the estuary.

The basin includes part or all of 11 provinces in southern Vietnam. About 13.6 million people- 18% of the national total – live in the basin. In 1998, the Dong Nai basin accounted for 15% of the national gross agricultural output, 51% of total industrial output, and contributed 39% to the country's service sector (Claudia et al., 2001). Economic growth is expected to continue at 7-10% per year. The industrial engine is mainly the Ho Chi Minh City-Bien Hoa-Ba Ria Vung Tau- Binh Duong economic zone. Total runoff amounts to 37.4 billion cubic meters (BCM). Precipitation averages 2,000 mm, and evaporation 1,200 mm. The basin exhibits a marked seasonal variation in flow with 80% to 90% of total precipitation concentrated during the rainy months of May-October.

The Dong Nai basin has two main distinct hydro-geological regions. The upper basin is located in the Central Highland areas with elevation ranging from 50 m up to 1,600 m. This area has a high potential for hydropower development and retaining reservoirs for irrigation as well as flood control. At present, besides various small reservoirs created in the small upstream reaches for irrigation, there are three large reservoirs located in the upstream part:

- The Tri An reservoir in the Dong Nai River with a total storage capacity of 2.75 billion m^3 for mainly hydropower production, which was completed in 1988. The mean yearly inflow at the Tri An reservoir is $505.91 m^3/s$. The hydropower plant has an installed capacity of 400 MW. The mean annual power production is about 1.7 billion KWH.
- The Thac Mo reservoir in the upper part of the Be River with the main purpose of hydropower production has a total storage capacity of 1.37 billion

m^3, which was completed in 1994. The installed capacity of the hydropower plant is 150 MW. The average annual power production is about 0.6 billion KWH.

- The Dau Tieng reservoir in the Sai Gon river with a total storage capacity of 1.72 billion m^3, which has started its operation in 1985 for irrigation purposes. The mean annual flow at the reservoir site is 53.4 m^3/s.

Apart from their main purposes, these reservoirs also function for flood reduction and water supply in the dry season.

The lower basin is the low-lying area with a complex river network connecting Dong Nai, Sai Gon and Vam Co rivers via many canals including Chiec, Cay Kho, Can Giuoc, Cho Dem-Ben Luc, Rach Tra-Thay Cai, Rach Tra-Cau An Ha, etc. The lower basin is subject to tidal influences, particularly during the dry season. Low flow upstream increases river pollution by industrial zones and cities located along the river. In the rainy season, this lower part suffers from the inundation due to high flows from the upstream catchment, tidal intrusion from the sea as well as local rainfall. This area is the main part of the Southern Focal Economic Area which acts as a locomotive of economic development in the nation along with the Ha Noi-Hai Phong and Da Nang areas. It covers the whole of Ho Chi Minh City, the Dong Nai, Ba Ria-Vung Tau provinces and a part of Binh Duong, Tay Ninh and Long An provinces. These are the most developing cities and provinces in the South of Vietnam. At present, some intakes extract water for domestic and industrial uses in the lower part. The Hoa An intake located in the Dong Nai river at Bien Hoa has an extraction capacity of about 50.3 million m^3/month. Extraction of about 95.38 million m^3/s is projected by the year 2010, which serves about 7 million people and industries in the focal economic zone. The Binh Duong intake is located in the Sai Gon River, extracting water for municipal and industrial uses of Thu Dau Mot town of Binh Duong province. The Ben Than intake will be located in the Sai Gon River with an extraction capacity of about 28.25 millions m^3/month. In addition, there are some irrigation projects in the riparian areas of the Dong Nai River and the Sai Gon River, which extract water from these rivers.

3.1.2 Be River Basin

The basin drainage system exhibits a branched tree pattern with the River Be as the main stem. The origin of the Be river lies in the Tuy Duc on the international border between Vietnam and Cambodia in Dac Lac provinces, and its main tributary, the Dac Hoyt river, runs south-west forming the international boundary between the two countries. The Be river meets the Dong Nai main stem downstream of the Tri An dam-site after passing the wide valley in the centre of Song Be province.

There exists four rain gauges in the Be river basin with observed data for a period of 24 years (1977 – 2000). At the Phuoc Long meteorological station, located in the middle of the basin,. and the Tan Son Nhat Airport station, the data of air temperature, relative humidity, wind direction and velocity, evaporation and sunshine hours are observed and recorded on monthly basis. There is a gauge-discharge station at Phuoc Long. Figure 3.1 shows the river system and location of hydrolometeorological stations in the Be river basin and surrounding area.

3.2. METEOROLOGICAL FEATURES

3.2.1. Climate

The study area falls in the tropical monsoon zone of the country. From May to October, a high prevailing pressure in central Asia forms the South-West monsoon, bringing humid air from the Thai Gulf to the Dong Nai River basin and causing rains in the area. The North-East monsoon brings northern dry wind from the Asian Continent during the period November-April when the southern hemisphere is in summer. This dry wind creates little precipitation in the study area and, and thus, the season is dry for its most part.

3.2.2. Air Temperature

Air temperature in the study area is lowest in winter (December and January), increases in spring, and reaches its highest during the summer in April-May. It is observed that there is no significant difference in air temperature throughout a year. In Tan Son Nhat (El. 9 m) and Phuoc Long (El. 45 m), the mean annual air temperatures are of the order of 27.6 ^{o}C and 25.6 ^{o}C, respectively. The air temperature difference is reported to be of the order of 7 to 8 ^{o}C.

3.2.3. Relative Humidity

The mean annual relative humidity in the study area varies from 77.4 % at Tan Son Nhat to 80.1% at Phuoc Long climate station. Relative humidity is high in the rainy season (June to October), reaching 85.8 % (Table 3.1).

3.2.4. Sunshine Hours

In the study area, the mean monthly sunshine hours vary from 4.9 hours/day in September to 8.7 hours/day in February/March with an average of 6.8 hours/day (Table 3.1).

3.2.5. Wind Velocity and Direction

The data obtained for the wind velocity and direction in the study area (Table 3.1) show that the prevailing wind runs from the South - West throughout the rainy season (May to October) and is formed by the high pressure in Central Asia as noted previously. The North -East monsoon brings northern wind during the dry season from Nov to Apr.

3.3. EVAPOTRANSPIRATION

In the Dong Nai river basin some meteorological stations provide directly the observed the Piche and pan evaporation data. However, the observed Piche data at these stations show some erroneous results which are difficult to explain (Anh, 1995), and the pan evaporation method is not considered accurate (De Laat, 1996). For this thesis, use is made of the available meteorological data at Phuoc Long and Tan Son Nhat Airport station. Evapotranspiration is calculated by the FAO Penman-Monteith and Radiation method, described in Appendix I.

3.4. RAINFALL

In the Be river basin the four rainfall stations with an observation period from 1977 to 2000 were used in this study. Table 3.2 shows the details of the stations and availability of data.

Table 3.2. Inventory of Rainfall Gauges

Rainfall Station	Location	Altitude	Years
Binh Long	106°36 E 11°38 N	MSL +40 m	24 years
Phuoc Hoa	106°46 E 11°14 N	MSL +30 m	24 years
Dong Phu	106°54 E 11°32 N	MSL +40 m	24 years
Phuoc Long	106°59 E 11°50 N	MSL +45 m	24 years

In general, the rainfall in Be river basin is fairly high. The average annual rainfall ranges from 2000 mm (Binh Long station) to 2500 mm (Dong Phu station). The rainfall varies strongly in time, with the rainy season accounting for 80 to 90% of the total annual. Peak rainfall occurs in August and September, often resulting in floods. January to March are the months of lowest rainfall, when flow in the rivers is predominantly the base flow from groundwater seepage

Applying the normal distribution, the analysis of annual areal rainfall in the Be river basin is presented in Table 3.3.

Table 3.3. Application of normal distribution for the areal rainfall in Be river basin

Year	Rainfall X (mm)	Rank	X sorted (mm)	P	St.Variate y	X cal. (mm)	Lower CL	Upper CL
1977	2104.6	1	1958.0	0.026	-1.90	1937.7	1768.8	2106.5
1978	2589.1	2	2086.1	0.067	-1.50	2031.8	1885.2	2178.4
1979	2568.0	3	2092.9	0.108	-1.20	2102.4	1970.8	2234.0
1980	2507.5	4	2094.3	0.149	-1.00	2149.5	2026.8	2272.2
1981	2086.1	5	2104.6	0.191	-0.88	2177.7	2059.9	2295.6
1982	2389.9	6	2240.8	0.232	-0.74	2210.7	2097.9	2323.4
1983	2092.9	7	2260.3	0.273	-0.60	2243.6	2135.2	2352.0
1984	2260.3	8	2261.7	0.314	-0.48	2271.9	2166.6	2377.1
1985	2284.1	9	2274.6	0.356	-0.37	2297.8	2194.8	2400.7
1986	2784.6	10	2284.1	0.397	-0.26	2323.7	2222.5	2424.8
1987	2240.8	11	2292.2	0.438	-0.16	2347.2	2247.1	2447.3
1988	1958.0	12	2364.4	0.479	-0.05	2373.1	2273.6	2472.6
1989	2543.6	13	2389.9	0.521	0.05	2396.6	2297.1	2496.1
1990	2681.8	14	2410.6	0.562	0.16	2422.5	2322.4	2522.6
1991	2274.6	15	2411.9	0.603	0.26	2446.0	2344.9	2547.2
1992	2411.9	16	2501.1	0.644	0.37	2471.9	2369.0	2574.9
1993	2261.7	17	2507.5	0.686	0.48	2497.8	2392.6	2603.1
1994	2790.0	18	2543.6	0.727	0.60	2526.1	2417.7	2634.4
1995	2094.3	19	2568.0	0.768	0.74	2559.0	2446.2	2671.8
1996	2744.1	20	2589.1	0.809	0.88	2592.0	2474.1	2709.8
1997	2292.2	21	2681.8	0.851	1.00	2620.2	2497.5	2742.9
1998	2364.4	22	2744.1	0.892	1.20	2667.3	2535.7	2798.9
1999	2410.6	23	2784.6	0.933	1.50	2737.9	2591.3	2884.5
2000	2501.1	24	2790.0	0.974	1.90	2832.0	2663.2	3000.9
Ave. =	2384.8		Std. =	235.4		$t_{97.5,23}$ =	(-2.07	, 2.07)

Daily rainfall distribution for representative years

Determination of the daily rainfall distribution depends upon the observed data during such a so-called representative year. For instance, engineering design conditions for flood protection measures require a hydrological year where high rainfall and heavy storm can be combined. An analysis, useful for future works, for wet and dry years is provided in Appendix-II.

3.5. SOIL TYPE AND LAND USE

The Dong Nai basin is endowed with several natural advantages. Unlike some other basins, typhoons are rare. Thus, flooding is not as severe as in other basins, except some inundation that occurs near the costal zones during the rainy season due to inadequate drainage capacity. The temperature, humidity and sunlight conditions are favorable to agriculture.

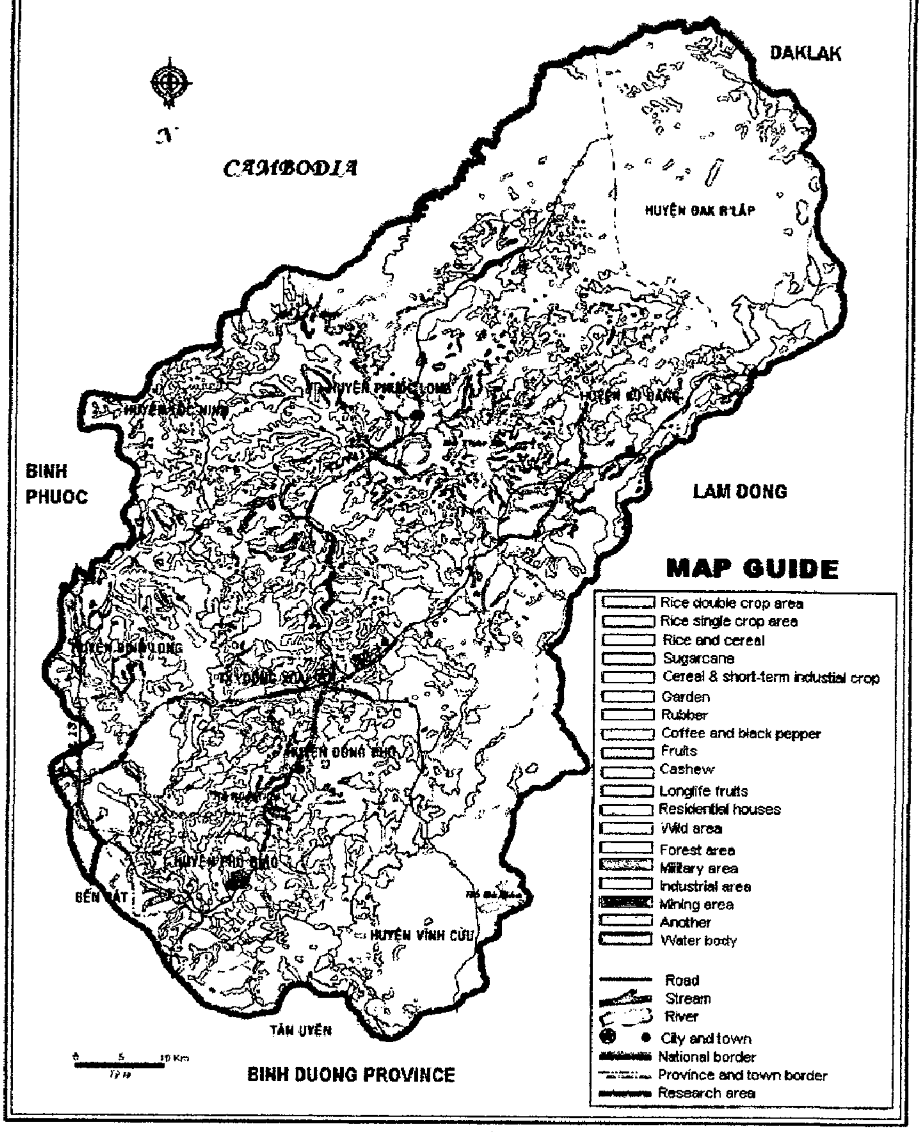
The amount of arable land is estimated as 1.2 million ha, forms about 30% of the basin area. Most agricultural activities are concentrated in the narrow valleys. The rugged topography in the highland area is occupied by tree crops. Altogether, agricultural production accounts for 20% of the basins total output. Total production is about 2 million tones per year in paddy equivalent. The intensity of cultivation is low, approximately equal to 1.2. This level of production, about 200kg per capita, is still insufficient to meet the consumption needs of the basin's inhabitants, who need to import rice from the neighboring Mekong Delta.

The Dong Nai basin is called the "home of rubber trees" and agriculture in Dong Nai is referred to as "rubber agriculture". Most of the land in the basin consists of basaltic and gray soils, which can support the cultivation of several important commercial crops, such as rubber, pepper, coffee, tobacco, and cotton. Nearly one third of the country's land area ascribed to tree crops and other perennials is located in the basin. Rubber dominates, with the Dong Nai basin accounting for 90% of Vietnam's total production. Rice cultivation is the other major agricultural activity, concentrated almost entirely in Long An province. The extensive forest in the Dong Nai is mostly natural.

In the Be river basin area of 7,201 km^2, about 10% is covered by open water and 90% unpaved surface. In the upper part of the Be river is the existing Thac Mo reservoir with a catchment area of 2,215 km^2. This reservoir was completed in 1994 with the main purpose of hydropower production. Figure 3.2. shows the land use of the Be River Basin, which can be quantified as follows:

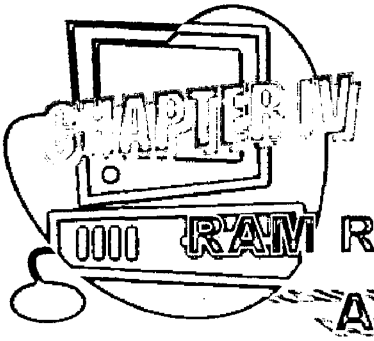
Forest area = 31%
Wild area = 2.8%
Rubber area = 12.8%
Fruit trees area = 10%

FIGURE 3.3 : LAND USE MAP IN THE BE RIVER BASIN - VIET NAM



3.5. DISCHARGE MEASUREMENT AND DATA AVAILABILITY

Discharge data are recorded at the Phuoc Long gauging station located downstream of the dam site. These flows were completely virgin flow until 1994, and afterwards, the flows at the gauging site are affected by the regulation of the reservoir. Here, it is noted that virgin flows of the period 1986-1990 were used in the modeling study. The flows are however may be affected by the tides from the South China Sea. This effect is not taken into consideration in the present study.



RAINFALL RUNOFF MODEL AND ITS APPLICATION

4.1. INTRODUCTION

The long-term daily hydrologic simulation is useful in augmentation of hydrologic data, water resources planning, and watershed management and is efficacious in description of the performance of a water resource system under climatic variations of rainfall and other aspects. As described in Chapter 2, the literature review suggests that a wide variety of models ranging from simple black-box type to the complex physically based distributed ones are available. Precipitation – runoff processes are generally described at a catchment area level. Within a catchment area, the relevant parameters may vary substantially, like the soil type, slope, land use, etc. A detailed physical description of the occurring processes is, therefore, difficult to give. In this chapter, the available rainfall-runoff RAM model available at Southern Institute of Water Resources Research, Ho Chi Minh City, Vietnam, is described and apllied to the Be River data (Chapter 3). In RAM a division into types of surfaces is made in view of the differences in precipitation runoff processes:

- Open water surface
- Paved surface
- Unpaved surface

In case of open water surface, the rainfall-excess will reach the outlet without any delay and the paved surface will exhibit a quick runoff process whereas an unpaved surface will include a slow (baseflow) component. In addition, the storage of moisture in the unsaturated zone of an unpaved surface are taken into account in terms of the following hydrological processes:

- Infiltration into the soil moisture (unsaturated zone)
- Percolation into the ground water (saturated zone)
- Ground water discharge into the drainage system

Distinguishing between types of surface and between hydrological sub-processes, the framework of the rainfall-runoff model is given in Figure 4.1 and the mathematical modeling of these processes is explained in the subsequent text. Here, it is worth noting that the term precipitation is used to represent rainfall only and does not include the precipitation due to snowfall, frost, dews etc.

4.2. OPEN WATER

The effective precipitation for open water is easy to determine. The losses are equal to the open water evaporation. The effective precipitation per time interval amounts to:

$$P_{N,open\_water,\,t} = P_{b,t} - f_0 E_{r,t} \tag{4.1}$$

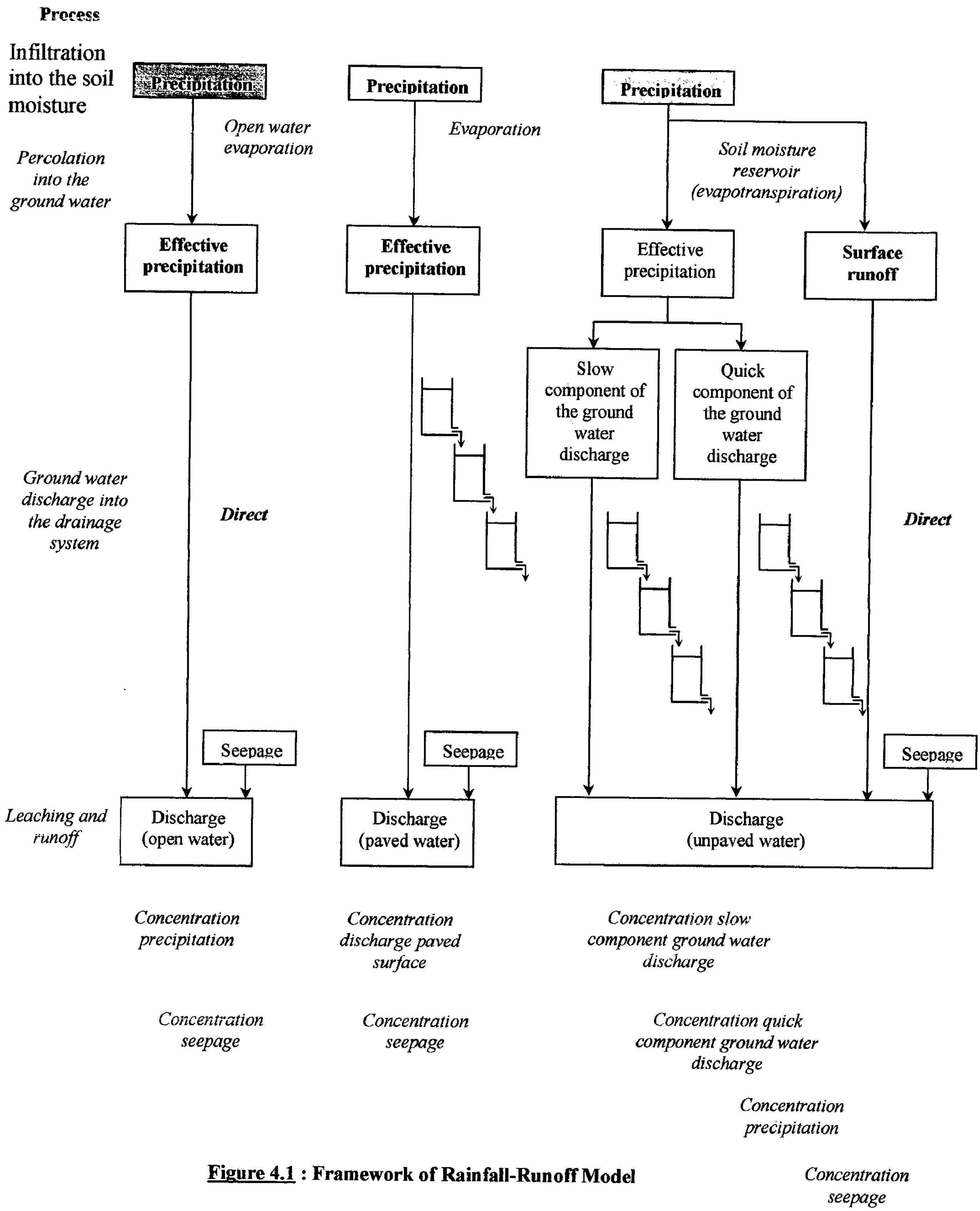


Figure 4.1 : Framework of Rainfall-Runoff Model

Where	$P_{N,open\_water,t}$	effective precipitation open water surface (mm/day)
	$P_{b,t}$	precipitation intensity (mm/day)
	$E_{r,t}$	reference crop evaporation Makkink (mm/day)
	f_0	Makkink factor for open water

During the dry period, the open water evaporation is larger than the precipitation intensity. In this case, a negative effective precipitation is calculated, which equals the precipitation shortage in simulating evaporation out of surface water in the drainage system.

The hydrograph is described by means of a single linear reservoir by describing the effect of delay due to the surface water itself.

$$q_{open\_water,t} = q_{open\_water,t-1}e^{-\Delta t/k_0} + P_{N,open\_water,t}(1-e^{-\Delta t/k_0}) \quad (4.2)$$

$$Q_{open\_water,t} = aA_{open\_water}q_{open\_water,t} \quad (4.3)$$

where

$q_{open\_water,t-1}$	specific discharge open water surface (mm/day)
$Q_{open\_water,t}$	discharge open water surface (m^3/s)
A_{open_water}	open water surface (ha)
k_0	time constant reservoir open water surface (day)
Δt	time step (day)
a	conversion factor unit (a = 10/(24*3600))

4.3. PAVED SURFACE

For all surface types, viz., closed paved surfaces, rural areas, urban areas, greenhouse areas, etc., the same principle is used for modeling the precipitation loss. The precipitation is collected in a reservoir, which is the storage of the surface, from which evaporation and infiltration take place. The precipitation which cannot be stored, infiltrated or evaporated is discharged as surface runoff and forms the input for the discharge retardation model.

Because of the difference of storage and infiltration depending on the type of paved surface, a distinction is made between open paved surface and closed paved surface. For each type surface, the evaporation is set equal to the open water evaporation. In general,

$$P_{N,paved,t} = P_{b,t} - f_0E_{r,t} \quad \text{if} \quad P_{b,t} \geq f_0E_{r,t} \quad (4.4)$$

$$P_{N,paved,t} = 0 \quad \text{if} \quad P_{b,t} < f_0E_{r,t} \quad (4.5)$$

The discharge from the paved surface is divided into sub-flows as:

- Paved surface discharging directly through the drainage system;
- Paved surface discharging though a separated sewer system.

The runoff of both subflows is determined using the single linear reservoir concept. A single reservoir was chosen because of the relatively short reaction time.

$$q_{sewer,t} = q_{sewer,t-1}e^{-\Delta t/k_{sewer}} + P_{N,paved,t}(1 - e^{-\Delta t/k_{sewer}}) \tag{4.6}$$

$$Q_{sewer,t} = aA_{sewer}q_{sewer,t} \tag{4.7}$$

$$q_{paved,t} = q_{paved,t-1}e^{-\Delta t/k_p} + P_{N,paved,t}(1 - e^{-\Delta t/k_p}) \tag{4.8}$$

$$Q_{paved,t} = aA_{paved}q_{paved,t} \tag{4.9}$$

where

$q_{sewer,t-1}$	specific discharge, separated sewer system (mm/day)
$q_{paved,t-1}$	specific discharge, other paved surface (mm/day)
$Q_{sewer,t}$	discharge separated system (m^3/s)
$Q_{paved,t}$	discharge other paved surface (m^3/s)
A_{sewer}	sewer paved surface (ha)
A_{paved}	other paved surface (ha)
k_{sewer}	time constant reservoir separated sewer system (day)
k_p	time constant reservoir other paved surface (day)
Δt	time step (day)
a	conversion factor unit (a = 10/(24*3600))

4.4. UNPAVED SURFACE

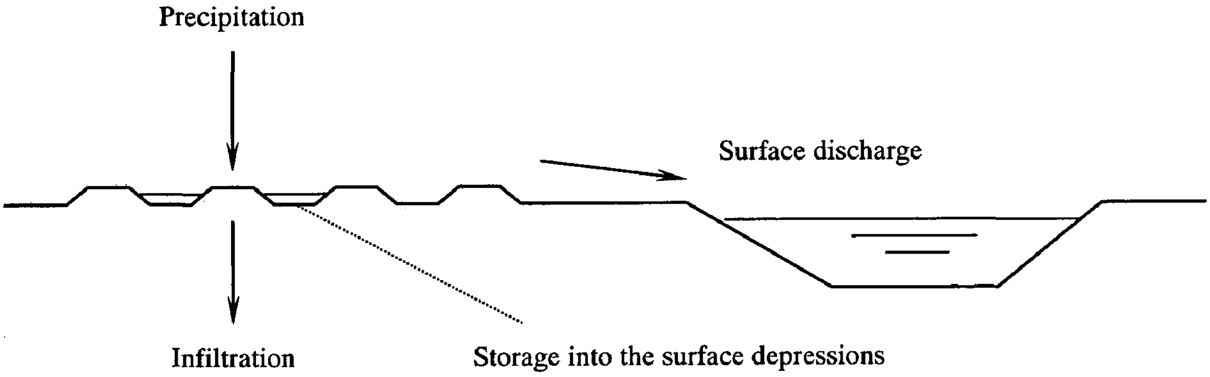
The runoff processes on an unpaved surface, the above three processes are distinguished in the precipitation – runoff model, as shown in Fig.4.2, the details of which are given below.

4.4.1. Infiltration into Soil Moisture (Unsaturated Zone)

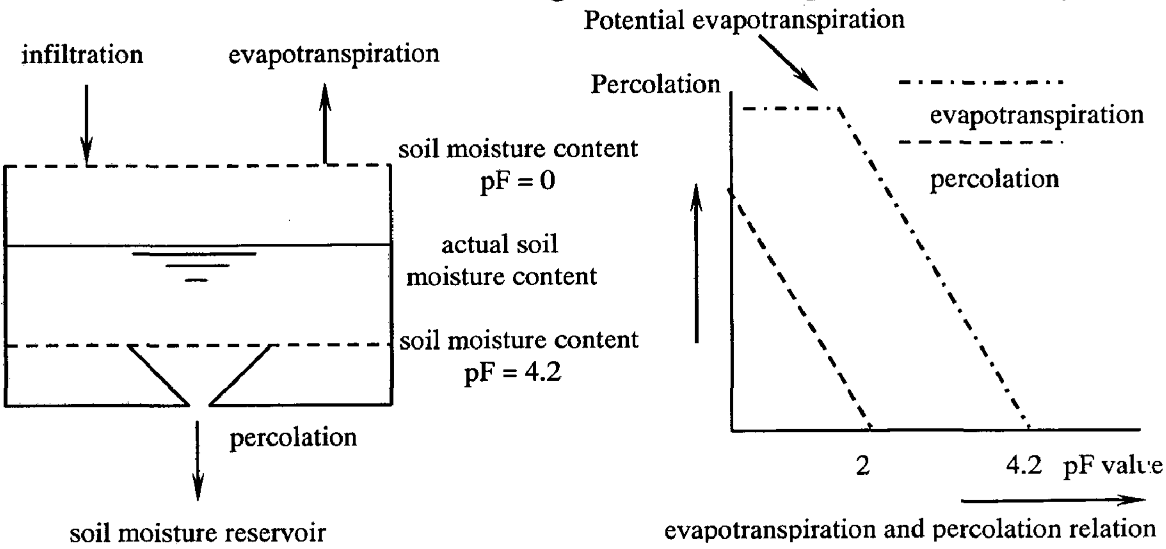
The infiltration into the unsaturated zone is determined along with the determination of the storage in the surface depressions and possibly occurring surface runoff. These aspects are addressed point by point below:

- Infiltration.
- Storage in surface depressions.
- Surface runoff.

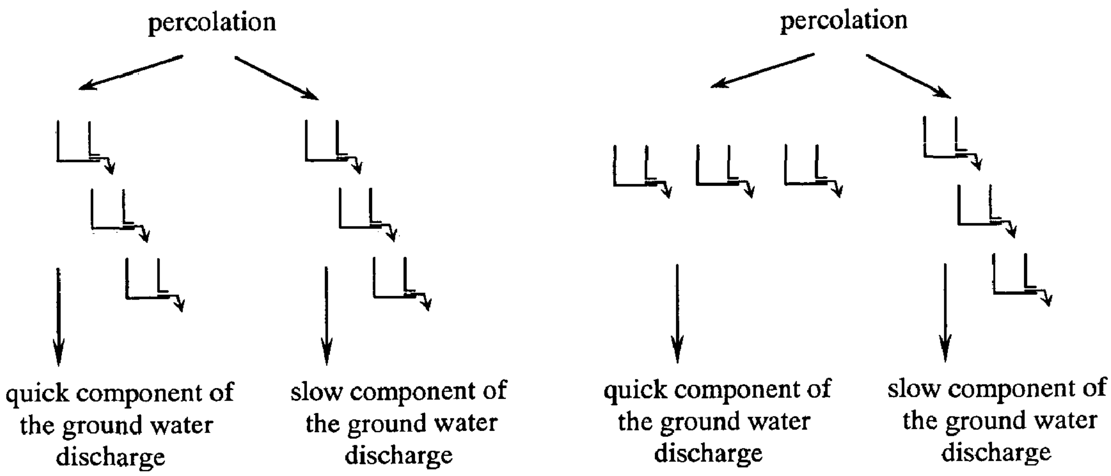
Process A. Infiltration into the soil moisture (adapted from RAM manual)



Process B. Percolation into the ground water (adapted RAM manual)



Process C. Ground water discharge into the drainage system



Option 1: two parallel Nash-cascades
Option 2: combination Nash-cascade-Krayenhoff

Figure 4.2. : Set-up runoff processes unpaved surface

The amount of precipitation that infiltrates is determined by the infiltration capacity of the soil. If the precipitation intensity surpasses the infiltration capacity, the remaining part of the precipitation will be stored in surface depressions. If the maximum storage in the surface depression is surpassed, the extra precipitation will runoff over the surface (surface runoff). The following formulae describe the three aspects in different phases.

➢ ***Infiltration***

$$I_t = P_{b,t} + \frac{B_{t-1}}{\Delta t} \qquad \text{if} \quad P_{b,t} + \frac{B_{t-1}}{\Delta t} \leq I_{\max} \qquad (4.10)$$

$$I_t = I_{max} \qquad \text{if} \quad P_{b,t} + \frac{B_{t-1}}{\Delta t} > I_{max} \qquad (4.11)$$

$$I_t = \Phi_{pF=0} - \Phi_{t-1} + P_{perc,\max} \quad \text{if} \quad \Phi_{t-1} + I_t - P_{perc,\max} > \Phi_{pF=0} \qquad (4.12)$$

where

P_{bt}	precipitation intensity (mm/day)
B_{t-1}	storage in surface depressions (mm)
I_{t-1}	infiltration intensity (mm/day)
Φ_{t-1}	actual moisture storage (mm)
I_{max}	infiltration capacity (mm/day)
Δt	time step (day)
$P_{perc,max}$	percolation to the saturated zone at pF = 0 (mm)
$\Phi_{pF=0}$	moisture storage if pF = 0 (mm)

➢ ***Storage in the surface depressions***

$$B_t = 0 \qquad \text{if} \quad P_{b,t} + \frac{B_{t-1}}{\Delta t} \leq I_{\max} \qquad (4.13)$$

$$B_t = (P_{b,t} - I_t)\Delta t + B_{t-1} \qquad \text{if} \quad P_{b,t} + \frac{B_{t-1}}{\Delta t} > I_{\max} \text{ and}$$
$$\text{if} \quad (P_{b,t} - I_t)\Delta t + B_{t-1} \leq B_{\max} \qquad (4.14)$$

$$B_t = B_{\max} \qquad \text{if} \quad P_{b,t} + \frac{B_{t-1}}{\Delta t} > I_{\max} \text{ and}$$
$$\text{if} \quad (P_{b,t} - I_t)\Delta t + B_{t-1} > B_{\max} \qquad (4.15)$$

where

P_{bt}	precipitation intensity (mm/day)
B_{t-1}	storage in surface depressions (mm)
I_{t-1}	infiltration intensity (mm/day)
I_{max}	infiltration capacity (mm/day)
Δt	time step (day)
B_{max}	maximum storage in surface depressions (mm)

➤ ***Surface runoff***

$$P_{N,sur,t} = P_{b,t} + \frac{B_t}{\Delta t} - I_t - \frac{B_{\max}}{\Delta t} \quad \text{if} \quad (P_{b,t} - I_t)\Delta t + B_{t-1} > B_{\max} \qquad (4.16)$$

$$P_{N,sur,t} = 0 \quad \text{if} \quad (P_{b,t} - I_t)\Delta t + B_{t-1} \le B_{\max} \qquad (4.17)$$

where

P_{bt}	precipitation intensity (mm/day)
B_{t-1}	storage in surface depressions (mm)
I_t	infiltration intensity (mm/day)
I_{max}	infiltration capacity (mm/day)
Δt	time step (day)
B_{max}	maximum storage in surface depressions (mm)
$P_{N,sur,t}$	effective precipitation surface runoff unpaved surface (mm/d).

4.4.2. Percolation into Groundwater (Saturated Zone)

The percolation into the groundwater is described by means of a soil moisture reservoir. A water balance of the amount of moisture in the unsaturated zone is maintained in the soil moisture reservoir. The replenishment of soil moisture in the unsaturated zone or the inflow of the soil moisture reservoir is the infiltration calculated by the model. The outflows are the evapotranspiration and the effective precipitation (the precipitation that runs off through drains or groundwater). The principle of the soil moisture reservoir is reflected in Figure 4.2.

In the precipitation-runoff model, capillary rise from the ground water to the unsaturated zone has not been included. Furthermore, it has been assumed that the infiltration immediately results in percolation, thus retardation is ignored. This may lead to errors in the calculated evapotranspiration and the percolation.

4.4.2.1. Evapotranspiration

The potential evapotranspiration is determined based on the reference crop evapotranspiration and crop factor. The crop factor is a measure for the transpiration of the crop and depends on the type of crop and the growth stage (function of time). If the crop is not supplied with water in an optimum way, the actual evapotranspiration is smaller than the potential evapotranspiration. A single relation between the actual evapotranspiration and actual moisture storage is included (evapotranspiration relation). It is assumed that if the soil moisture content is larger than the field capacity, the actual evapotranspiration is equal to the potential evapotranspiration. Between the moisture storage at field capacity and the wilting point, the actual evapotranspiration decreases linearly from the potential evapotranspiration at field capacity to zero at the wilting point. It has been assumed that no moisture is available to the vegetation at the wilting point.

The relation between moisture content and the evapotranspiration can be defined according to the following possibilities:

- The exponent in the moisture content ratio
- The definition of fixed points (markers) in the evapotranspiration function.

The following formulas define the actual evaporation according to the exponent in the moisture content ratio:

$$E_{a,t} = fE_{r,t} \qquad \text{if} \quad \Phi_{pF=0} \geq \Phi_{t-1} > \Phi_{pF=2} \qquad (4.18)$$

$$E_{a,t} = \left(\frac{\Phi_{t-1} - \Phi_{pF=4.2}}{\Phi_{pF=2} - \Phi_{pF=4.2}}\right)^{x} fE_{r,t} \qquad \text{if} \quad \Phi_{pF=2} \geq \Phi_{t-1} > \Phi_{pF=4.2} \qquad (4.19)$$

$$E_{a,t} = 0 \qquad \text{if} \quad \Phi_{t-1} < \Phi_{pF=4.2} \qquad (4.20)$$

where

Φ_{t-1}	actual moisture storage	(mm)
$\Phi_{pF=0}$	moisture storage at pF = 0	(mm)
$\Phi_{pF=2}$	moisture storage at pF = 2	(mm)
$\Phi_{pF=4.2}$	moisture storage at pF = 4.2	(mm)
f	crop factor Makkink	
$E_{r,t}$	reference crop evaporation Makkink	(mm/day)
x	exponent (-)	
$E_{a,t}$	actual evapotranspiration	(mm/day)

4.4.2.2. Percolation

The percolation to the groundwater depends on the water content in the unsaturated zone. In the precipitation-runoff model, a single relation between percolation and actual moisture storage, referred as the percolation relation, has been included. It has been assumed that in the case of saturation, the percolation is equal to the maximum percolation. Between the moisture storage saturation and at field capacity, the percolation decreases linearly from the maximum percolation at the saturation to zero at field capacity. It has been assumed that no moisture is available for percolation at the wilting point.

Here, it is possible to make the percolation relation more flexible by incorporating an exponent of the moisture storage ratio as:

$$P_{perc,t} = \left(\frac{\Phi_{t-1} - \Phi_{pF=2}}{\Phi_{pF=0} - \Phi_{pF=2}}\right)^{y} P_{perc,\max} \qquad \text{if} \quad \Phi_{pF=0} \geq \Phi_{t-1} > \Phi_{pF=2} \qquad (4.21)$$

$$P_{perc,t} = 0 \qquad \text{if} \ \Phi_{t-1} < \Phi_{pF=2} \qquad (4.22)$$

where

Φ_{t-1}	actual moisture storage	(mm)
$\Phi_{pF=0}$	moisture storage at pF = 0	(mm)
$\Phi_{pF=2}$	moisture storage at pF = 2	(mm)
$\Phi_{pF=4.2}$	moisture storage at pF = 4.2	(mm)
$P_{perc,max}$	maximum percolation rate to saturated zone	(mm/day)
y	exponent (-)	
$P_{perc,t}$	percolation rate to saturated zone	(mm/day)

4.4.3. Groundwater Discharge into Drainage System

The discharge from unpaved surface is coupled with various processes. Here, it is worth emphasizing that the interflow and drainage have not been described separately, but they jointly form the quick groundwater runoff. However, the following aspects are distinguished:

- Surface runoff
- Quick component of ground water discharge
- Slow component of ground water discharge

4.4.3.1. Surface Runoff

This discharge is described with one linear reservoir, similar to the description for the discharge of open water (the discharge of the water across the surface to open water takes place relatively quickly).

4.4.3.2. Quick and Slow Component of Ground Water Discharge

During the discharge through the saturated zone, a significant slowing down effect occurs because of resistances in the soil. This process is described by a configuration of linear reservoirs. The quick and slow components of the ground water discharge are described by separate linear reservoirs, of which two possibilities are taken up:

- Two parallel Nash-cascades
- Combination of Nash-cascades and Krayenhoff van de Leur J-model

(a) Two parallel Nash-cascades

In this option, the discharge is divided into a quick and slow component groundwater runoff by means of a distribution code. The percolation calculated will be partly runoff through a slow component (βP_{perc}) and partly through a quick component, $[1-\beta]$ P_{perc}. The hydrographs of both the quick and slow ground water discharge are described by a series of linear reservoirs (Figure 4.2). By entering the time constant and the number of reservoirs, the user may enter the properties of the discharge process.

The quick and slow ground water discharges are described by the following formulas:

For the 1st reservoir:

$$q_{quick,1,t} = q_{qick,1,t-1} e^{-\Delta t / k_q} + (1-\beta) P_{perc,t} (1 - e^{-\Delta t / k_q}) \qquad (4.23)$$

For i is the 2nd up to and including the mth reservoir:

$$q_{quick,i,t} = q_{qick,i,t-1} e^{-\Delta t / k_q} + q_{quick,i-1,t} (1 - e^{-\Delta t / k_q}) \tag{4.24}$$

For the 1st reservoir:

$$q_{slow,1,t} = q_{slow,1,t-1} e^{-\Delta t / k_s} + \beta P_{perc,t} (1 - e^{-\Delta t / k_s}) \tag{4.25}$$

For i is the 2nd up to and including the nth reservoir:

$$q_{slow,i,t} = q_{slow,i,t-1} e^{-\Delta t / k_s} + q_{slow,i-1,t} (1 - e^{-\Delta t / k_s}) \tag{4.26}$$

The resulting flows are described as:

$$Q_{quick,t} = aA_{unpaved} q_{quick,m,t} \tag{4.27}$$

$$Q_{slow,t} = aA_{unpaved} q_{slow,n,t} \tag{4.28}$$

(b) Combination of Nash-cascades and Krayenhoff van de Leur J-model

In this option, the discharge is divided into a quick and slow component groundwater discharge. The hydrograph of the quick ground water discharge is described in this option by a number of parallel linear reservoirs (Krayenhoff van de Leur J-model). The slow ground water runoff is described by series of linear reservoirs (Figure 4.2.).

The quick and slow component of the ground water discharge is described by the following formulas:

For i is the 1st up to and including the dth reservoir:

$$q_{quick,i,t} = (1-\beta)\{\frac{1}{(\sum_{J=1,3,5...}^{(2d-1)} \frac{1}{j^2})} P_{perc,t} \frac{1}{(2i-1)^2}(1 - e^{\frac{-\Delta t (2i-1)^2}{k_q}})\} + q_{quick,i,t-1} e^{\frac{-\Delta t (2i-1)^2}{k_q}} \tag{4.29}$$

For the 1st reservoir:

$$q_{slow,1,t} = q_{slow,1,t-1} e^{-\Delta t / k_s} + \beta P_{perc,t} (1 - e^{-\Delta t / k_s}) \tag{4.30}$$

For i is the 2nd up to and including the nth reservoir:

$$q_{slow,i,t} = q_{slow,i,t-1} e^{-\Delta t / k_s} + q_{slow,i-1,t} (1 - e^{-\Delta t / k_s}) \tag{4.31}$$

The resulting flows are described as:

$$Q_{quick,t} = aA_{unpaved}(\sum_{i=1}^{d} q_{quick,i,t}) \quad (4.32)$$

$$Q_{slow,t} = aA_{unpaved}q_{slow,n,t} \quad (4.33)$$

where

$P_{perc,t}$	percolation into the saturated zone (mm/day)
$q_{slow,i,t-1}$	specific slow component ground water discharge unpaved surface (mm/day)
$q_{quick,i,t-1}$	specific quick component ground water discharge unpaved surface (mm/day)
$A_{unpaved}$	unpaved surface (ha)
β	distribution code quick and slow components ground water discharge
k_s	time constant reservoir slow component ground water discharge (day)
k_q	time constant reservoir quick component ground water discharge (day)
m	number of reservoirs quick component ground water discharge (in case of Nash-cascades linear reservoirs)
Δt	time step (day)
d	number of reservoirs quick component ground water discharge (in case of Krayenhoff van de Leur parallel linear reservoirs)
n	number of reservoirs slow component ground water discharge
a	conversion factor unit (a = 10/(24×3600))
$Q_{slow,t}$	drainage slow component ground water discharge (m^3/s)
$Q_{quick,t}$	drainage quick component ground water discharge (m^3/s)

4.5. SEEPAGE

In addition to the discharges that are calculated for open water, paved surface, and unpaved surface, the seepage is computed as:

$$q_{seep,t} = \frac{\Delta h}{c} \quad (4.34)$$

$$Q_{seep,t} = bA_{total}q_{seep,t} \quad (4.35)$$

where

Δh	hydraulic head difference	(m)
c	vertical hydraulic resistance	(day)
b	conversion factor unit (b = 10000/(24*3600))	
A_{total}	total surface	(ha)
$Q_{seep,t}$	discharge seepage	(m^3/s)

4.6. TOTAL DISCHARGE

The total runoff of a catchment area consists of the discharge from the three types of surface and the seepage:

- Open water - $Q_{open\ water}$
- Paved surface - Q_{paved}
- Unpaved surface - $Q_{unpaved}$
- Seepage - Q_{seep}

The drainage of unpaved surface consists of the runoff of the subflows:

- Surface runoff (Q_{sur}).
- Quick component ground water (Q_{quick}).
- Slow component ground water (Q_{slow}).

$$Q_{unpaved,t} = Q_{sur,t} + Q_{quick,t} + Q_{slow,t} \tag{4.36}$$

$$Q_{total,t} = Q_{openwater,t} + Q_{paved,t} + Q_{unpaved,t} + Q_{seep,t} \tag{4.37}$$

where, $Q_{total,t}$ (m^3/s) is total discharge, other components have been defined earlier.

4.7. COMPUTATONAL PROCEDURE

4.7.1. The Inputs and Outputs of RAM

The inputs of RAM include hydrological, climatalogical, and geographical data. Hydrological data consist of rainfall, potential evapotranspiration, and observed discharge. Geographical data include catchment area, land use, soil types, etc. The output of RAM model may include total flow of catchment outlet, flows of different land surfaces, and water quality component as well. Table 4.1 shows the computational procedure in a simple manner.

4.7.2. RAM Parameters

The parameters of RAM include soil moisture storage at pF = 0, pF = 2, pF = 4.2, the crop factor f, time constants of reservoir for open water (k_o), quick (k_q) and slow (k_s) components, infiltration capacity, maximum percolation value at pF = 0, distribution coefficient (β) for slow runoff component, different routing models and so on.

Figures 4.3 to 4.7 show the flow charts for quick and slow components of ground water discharge, discharge from open water body, discharge from paved surface and discharge from unpaved surface, respectively.

Table 4.1: COMPUTATIONAL PROCEDURE

INPUT - Climatic Data	COMPUTATION
Open Water Surface $P_{b,t}$: Precipitation intensity (mm/day) $E_{r,t}$: Reference crop evapotranspiration of grass (mm/day) f_o : Makkink factor for open water K_o : time constant reservoir open water surface (day) Δt : time step (day) A_o : Open Water Surface area (ha) a : conversion factor unit $a = 10/(24\times3600)$	$P_{N,\text{open water},t} = P_{b,t} - f_o \, . \, E_{r,t}$ $P_{N,\text{openwater},t}$: Effective rainfall on open water surface (mm/day) $q_{\text{Open water},t} = q_{0,t-1} . e^{-\frac{\Delta t}{K_o}} + P_{N,0,t}\,(1 - e^{-\frac{\Delta t}{K_o}})$ $Q_{\text{Open water},t} = a \, . \, Ao \, . \, q_{0,t}$ $q_{\text{Open water},t}$: specific discharge open water surface (mm/day) $Q_{\text{Open water},t}$: discharge open water surface (m^3/sec)
Paved Surface $P_{b,t}$: Precipitation intensity (mm/day) $E_{r,t}$: Reference crop evapotranspiration of grass (mm/day) f_o : Makkink factor for open water K_s : time constant reservoir separated system (day) K_p : time constant reservoir other paved surface (day) A_s : Sewer Surface area (ha) A_p : Other Surface area (ha) Δt : time step (day) a : conversion factor unit $a = 10/(24\times3600)$	$P_{N,\text{paved},t} = \begin{cases} P_{b,t} - f_o \, . \, E_{r,t} & \text{if } P_{b,t} \; . \; f_o.E_{r,t} \\ 0 & \text{if } P_{b,t} < f_o.E_{r,t} \end{cases}$ $P_{N,\text{paved},t}$: Effective rainfall on paved surface (mm/day) $q_{\text{sewer},t} = q_{sewer,t-1} . e^{-\frac{\Delta t}{K_s}} + P_{N,sewer,t}\,(1 - e^{-\frac{\Delta t}{K_s}})$ $Q_{\text{sewer},t} = a \, . \, A_s \, . \, q_{\text{sewer},t}$ $q_{\text{sewer},t}$: Specific discharge, separated sewer system (mm/day) $Q_{\text{paved},t}$: Discharge, separated sewer system (m^3/sec) $q_{\text{paved},t} = q_{paved,t-1} . e^{-\frac{\Delta t}{K_p}} + P_{N,paved,t}\,(1 - e^{-\frac{\Delta t}{K_p}})$ $Q_{\text{paved},t} = a \, . \, A_p \, . \, q_{\text{paved},t}$ $q_{\text{paved},t}$: Specific discharge, other paved surface (mm/day) $Q_{\text{paved},t}$: Discharge, other paved surface (m^3/sec)
Unpaved Surface *Infiltration* $P_{b,t}$; Δt : as defined above I_t : Infiltration intensity (mm/day) I_{max} : Infiltration capacity (mm/day)	$I_t = \begin{cases} P_{b,t} + \frac{B_{t-1}}{\Delta t} & \text{if } P_{b,t} + \frac{B_{t-1}}{\Delta t} \leq I_{max} \\ I_{max} & \text{if } P_{b,t} + \frac{B_{t-1}}{\Delta t} > I_{max} \\ \Phi_{pF=0} - \Phi_{t-1} + P_{perc,max} & \text{if } I_t > \Phi_{pF=0} \end{cases}$

Storage in surface depression

B_{t-1} : Storage in surface depression (mm)

B_{max} : max storage in surface depression

Φ_{t-1} : Actual moisture storage (mm)

$$B_t = \begin{cases} 0 & \text{if } P_{b,t} + \dfrac{B_{t-1}}{\Delta t} \leq I_{max} \\ (P_{b,t} - I_t)\,\Delta t + B_{t-1} & \text{if } P_{b,t} + \dfrac{B_{t-1}}{\Delta t} > I_{max} \\ & \text{and if } (P_{b,t} - I_t)\,\Delta t + B_{t-1} \leq B_{max} \\ B_{max} & \text{if } P_{b,t} + \dfrac{B_{t-1}}{\Delta t} > I_{max} \\ & \text{and if } (P_{b,t} - I_t)\,\Delta t + B_{t-1} > B_{max} \end{cases}$$

Eff. Precipitaion Surface runoff

$P_{perc,max}$: Percolation to the saturate zone at pH=0 (mm)

$$P_{N,s,t} = \begin{cases} P_{b,t} + \dfrac{B_t}{\Delta t} - I_t - \dfrac{B_{max}}{\Delta t} & \text{if} (P_{b,t} - I_t)\Delta t + B_{t-1} > B_{max} \\ 0 & \text{if } (P_{b,t} - I_t)\,\Delta t + B_{t-1} \leq B_{max} \end{cases}$$

$P_{N,s,t}$: Effective precipitation surface runoff unpaved surface (mm/day)

Atual evapotranspiration

For t = 1, Φ_o actual moisture storage (mm)

$\Phi_{pF=0}$ moisture storage at pH = 0 (mm)

$\Phi_{pF=2}$ moisture storage at pH = 2 (mm)

$\Phi_{pF=4.2}$ moisture storage at pH = 4.2 (mm)

x : exponent

$$E_{a,t} = \begin{cases} f\,.\,E_{r,t} & \text{if } \Phi_{pF=0}\,.\ \Phi_{t-1} > \Phi_{pF=2} \\ \left(\dfrac{\Phi_{t-1} - \Phi_{pF=4.2}}{\Phi_{pF=2} - \Phi_{pF=4.2}}\right)^x f E_{r,t} & \text{if } \Phi_{pF=2}\,.\ \Phi_{t-1} > \Phi_{pF=4.2} \\ 0 & \text{if } \Phi_{t-1} < \Phi_{pF=4.2} \end{cases}$$

$E_{a,t}$: Actual evapotranspiration (mm/day)

Percolation rate to saturated zone

$$P_{perc,t} = \begin{cases} \left(\dfrac{\Phi_{t-1} - \Phi_{pF=2}}{\Phi_{pF=0} - \Phi_{pF=2}}\right)^y \times P_{perc,max} & \text{if } \Phi_{pF=0}\,.\ \Phi_{t-1} > \Phi_{pF=2} \\ 0 & \text{if } \Phi_{t-1} < \Phi_{pF=2} \end{cases}$$

$P_{perc,t}$:Percolation rate to saturated zone (mm/day)

Discharge Seepage

Δh : hydraulic head difference (m)

c : vertical hydraulic resistance (day)

A_{total} : total surface (ha)

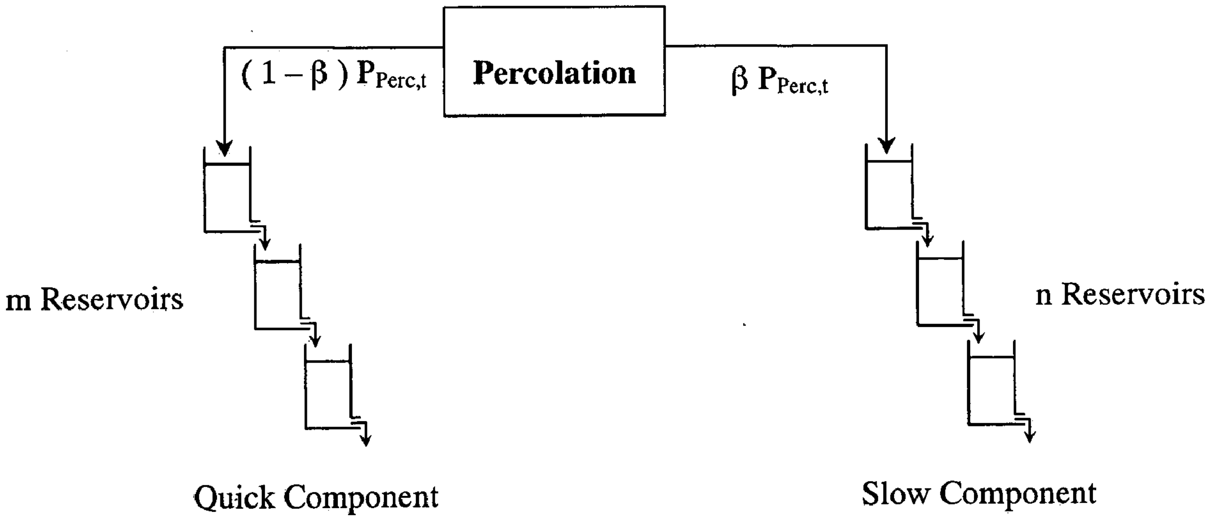
$$q_{seep,t} = \frac{\Delta h}{c}$$

$$Q_{seep,t} = b\,.\,A_{total}\,.\,q_{seep,t}$$

$Q_{seep,t}$: discharge seepage (m^3/s)

Total Discharge	$Q_{unpaved,t} = Q_{sur,t} + Q_{quick,t} + Q_{slow,t}$ $Q_{total,t} = Q_{openwater,t} + Q_{paved,t} + Q_{unpaved,t} + Q_{seep,t}$ $Q_{total,t}$: total discharge (m^3/s)

<u>Figure 4.3</u> : QUICK AND SLOW COMPONENTS OF GROUND WATER DISCHARGE



$$q_{q,1,t} = q_{q,1,t-1} \cdot e^{-\frac{\Delta t}{K_q}} + (1-\beta)\,P_{perc,t}\,(1 - e^{-\frac{\Delta t}{K_q}})$$

$$q_{sl,1,t} = q_{sl,1,t-1} \cdot e^{-\frac{\Delta t}{K_{sl}}} + \beta\,P_{perc,t}(1 - e^{-\frac{\Delta t}{K_{sl}}})$$

$$q_{q,i,t} = q_{q,i,t-1} \cdot e^{-\frac{\Delta t}{K_q}} + q_{q,i-1,t}(1 - e^{-\frac{\Delta t}{K_q}})$$

$$q_{sl,i,t} = q_{sl,i,t-1} \cdot e^{-\frac{\Delta t}{K_{sl}}} + \beta\,q_{sl,i-1,t}\,(1 - e^{-\frac{\Delta t}{K_{sl}}})$$

$$Q_{quick,t} = a.\,A_{unpaved} \cdot q_{quick,m,t}$$

$$Q_{slow,t} = a.\,A_{unpaved} \cdot q_{slow,n,t}$$

Figure 4.4 : **QUICK AND SLOW COMPONENTS OF GROUND WATER DISCHARGE**

Initial Values β , K_s, K_q, Q, n, d, Δt

Input

$A_{unpaved}$, β , K_s, K_q, m, n, d, Δt, a

↓

$$q_{quick,i,t} = (1-\beta)\left\{ \frac{1}{\sum_{j=1,3,5,...}^{(2d-1)} \frac{1}{j^2}} P_{perc,t} \frac{1}{(2i-1)^2} \left(1 - e^{-\frac{\Delta t (2i-1)^2}{K_q}} \right) \right\} + q_{quick,i,t-1} \times e^{-\frac{\Delta t (2i-1)^2}{K_q}}$$

$$q_{slow,i,t} = q_{slow,i,t-1} \cdot e^{-\frac{\Delta t}{K_s}} + q_{slow,i-1,t} \left(1 - e^{-\frac{\Delta t}{K_s}}\right)$$

↓

$$Q_{quick,t} = a . A_{uppaved} . \left(\sum_{i=1}^{d} q_{quick,i,t}\right)$$

$$Q_{slow,t} = a . A_{uppaved} . q_{slow,i,t}$$

Figure 4.5 : OPEN WATER

Initial Values f_0 , K_0, a

Input

$P_{b,t}$, $E_{r,t}$, f_0 , K_0, Δt, a
$A_{open\ water}$, $q_{open\ water}$

↓

$$P_{N,open\ water,t} = P_{b,t} - f_0 \times E_{r,t}$$

↓

$$q_{open\ water,\ t} = q_{open\ water,\ t-1} \times e^{-\frac{\Delta t}{K_0}} + P_{N,open\ water,t} \times \left(1 - e^{-\frac{\Delta t}{K_0}}\right)$$

↓

$$Q_{open\ water,\ t} = a\ A_{open\ water} \times q_{open\ water,\ t}$$

↓

$Q_{open\ water}$

Figure 4.6 : **PAVED SURFACE**

Initial Values f_0 , K_{sewer} , a

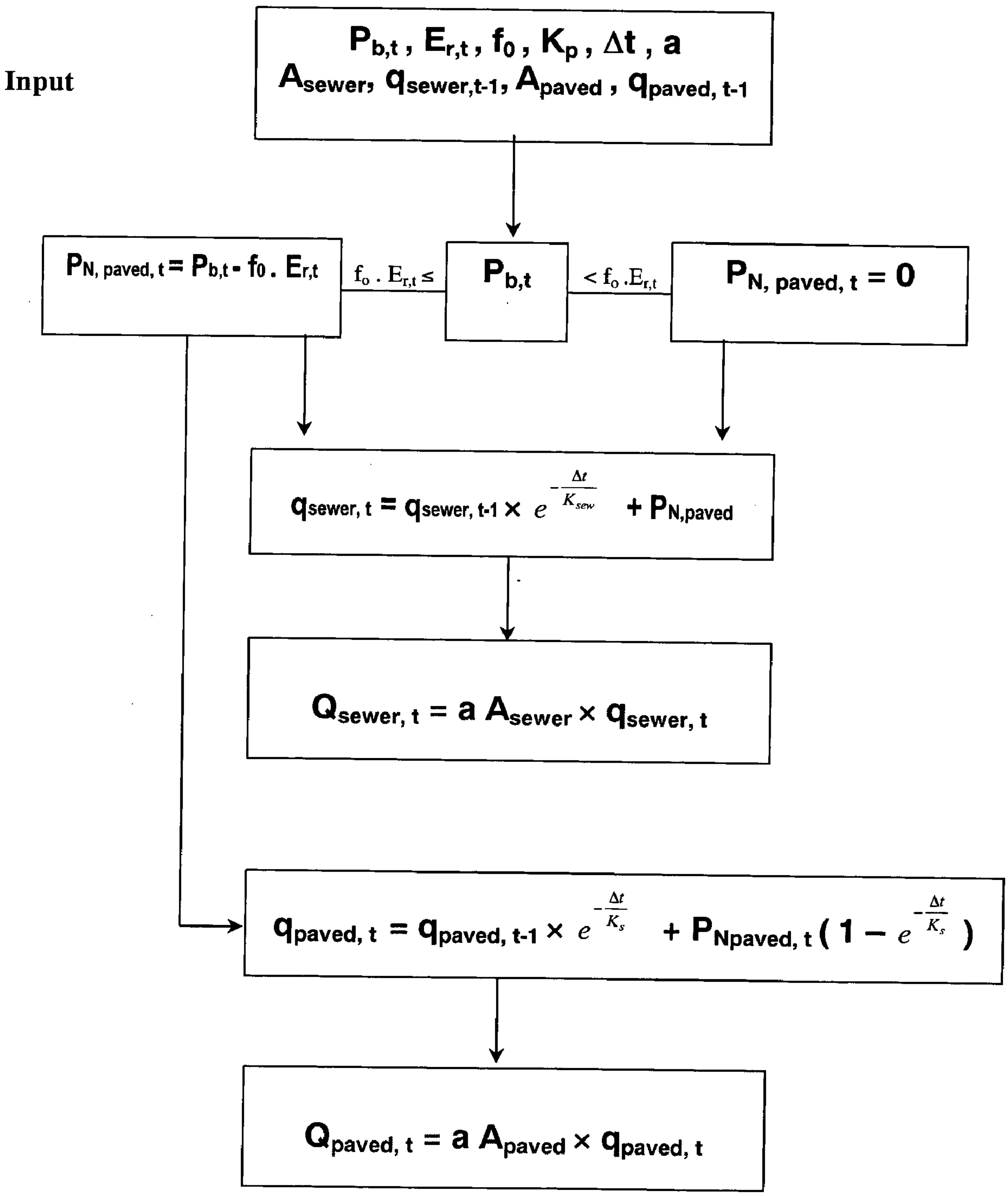
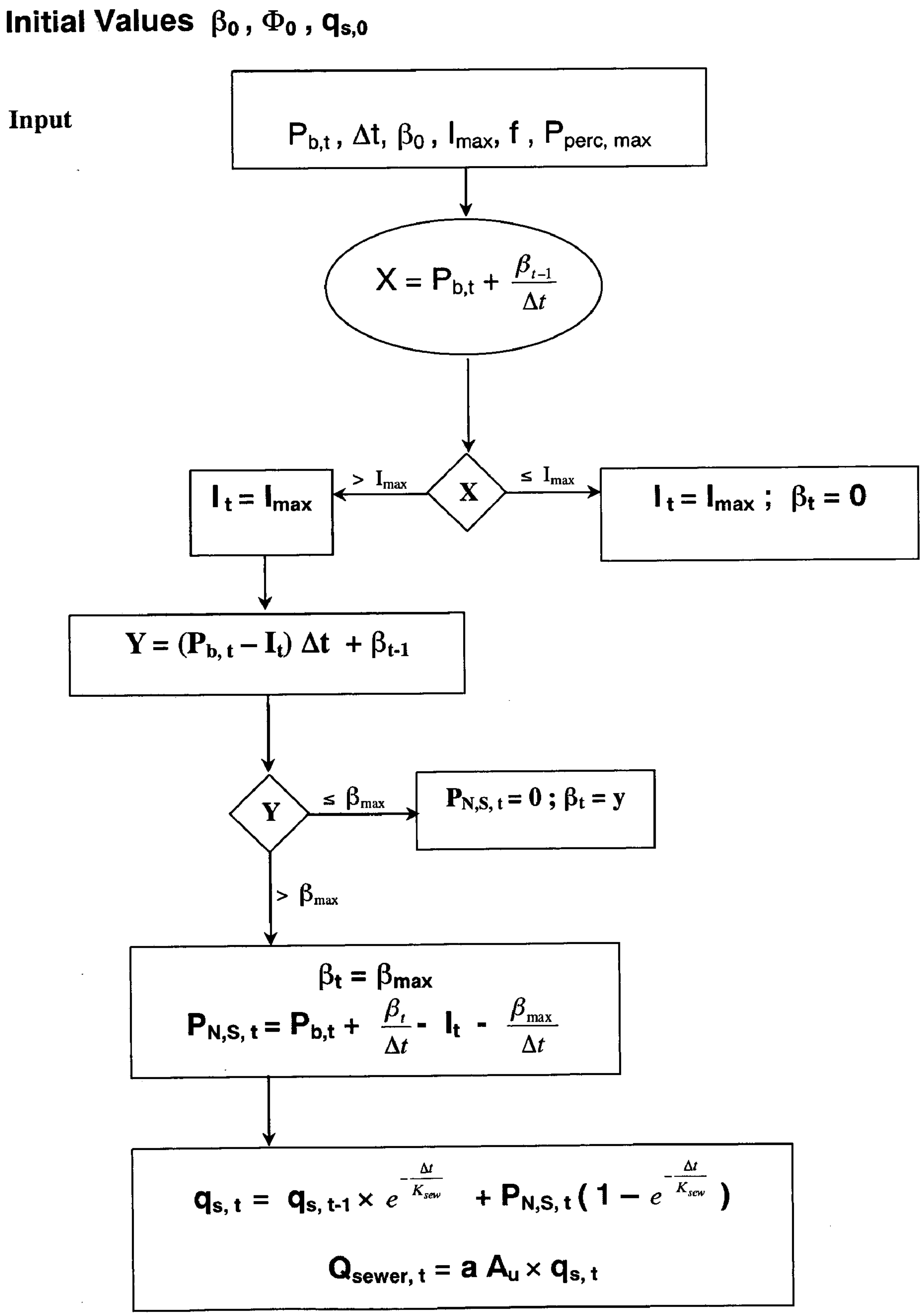


Figure 4.7 : UNPAVED SURFACE



4.8. APPLICATION OF RAM MODEL

4.8.1. General

Chapter III describing the basin characteristics as well as the data availability in the Be river basin, and these can be summarized as follows:

- The Be river basin area is 7,201 km^2, of which about 10% forms to cover open water and 90% unpaved surface.

- Daily discharge at the Phuoc Long gauging station located downstream of the dam site (Note: Till 1994, these flows were natural, and after 1994, release from the reservoir affects the flows).

- The downstream Be river flows are affected by tides from South China Sea.

Based on flow characteristics and conditions in the Be river basin, the catchment is divided into three sub-catchments (Figure 3.1 and Table 4.2).

Table 4. 2 Subcatchments in Be river basin

Sub-Catchment	Sub-catchment area (km^2)	Characteristic of sub-catchment area
1 2 3	A_1 = 2,215 A_2 = 2,493 A_3 = 2,493	The existing Thac Mo reservoir and Phuoc Long gauging station downstream the dam site (point A in Figure 3.1).
Total	A_t = 7,201	

In the Be catchment, the rainfall data are limited and flow or discharge data are only available downstream of the present dam site. Assuming that the rainfall distribution and land use are comparable all over the catchment, it is reasonable to assume the calibrated runoff parameters of the upper sub-catchment as representative for the others. A survey on vegetation, surface, slope, soil conditions, and other parameters also warrants this assumption. The other assumptions are:

- Areal distribution of rainfall and evapotranspiration is homogeneous all over the catchment.
- Conditions of soil, land use, hydrogeology, etc. are the same in three sub-catchments.

Steps to calculate the total runoff of Be river basin are given as follows:

(i) Computational set-up.
(ii) Prepare input data.
(iii) Calibration and verification.
(iv) Model fitting.
(v) Simulation of total runoff.

4.8.2. Preparation Of The Input Data

Catchment rainfall runoff simulation is applied to sub-catchment 1. The data required for the RAM model include:

(i) **Catchment data:** Determined for sub-catchment 1. The model parameters are adjusted during calibration.

(ii) **Rainfall data:** Daily areal rainfall from 1977 to 2000 was used to simulate the runoff during years with wet (P = 5%), average (P = 50%) and dry (P = 95%) rainfall distributions.

(iii) **Evapotranspiration:** Monthly reference evapotranspiration computed using Makkink method for 1984 to 1999 was used to calibrate and calculate runoff. Average monthly evapotranspiration data were used to simulate the runoff during wet, average, and dry years.

(iv) **Discharge data:** Daily discharge data observed at Phuoc Long from 1986 to 1990 to calibrate and validate the model.

(v) **River topographic data:** The section between Phuoc Long and the mouth of Be river has a length of 180 km and includes five cross-sections.

4.8.3. Model Calibration And Verification

The evaluation of model performance is divided into two stages. The first stage involves model calibration or estimation of model parameters. The calibration of a model means the selective improvement of initial parameter estimates by a comparison between observed and simulated hydrological variables. There are a number of approaches which may be adopted for calibrating parameters of a rainfall-runoff model (Schulze, 1998):

- Trial and error method, which involves the adjustment of parameter values by trial and error.
- Automatic parameter optimization techniques, which adjust values of parameters according to a predefined accuracy criterion without intervention from the user.
- Combination method, which is the combination between trial and error and automatic search methods.

4.8.4. Model Fitting

The calibration and verification goal is to obtain the best fit between computed and observed data by minimizing the differences. The goodness of fit may be judged by some objective criterion such as the least sum of squares of the deviations between the observed outputs of the system and the model outputs generated from the corresponding inputs. The Nash and Sutcliffe (1970) criterion is frequently used. To this end, the remaining and initial variances are computed, respectively, as below:

$$F^2 = \sum_{t=1}^{n} (Q_{o,t} - Q_{c,t})^2 \quad (4.38)$$

$$F_o^2 = \sum_{t=1}^{n} (Q_{o,t} - \bar{Q}_{o,t})^2 \qquad (4.39)$$

where F^2 is the remaining variance; F_o^2 is the initial variance; $Q_{o,t}$ and $Q_{c,t}$ are the observed responding computed runoff, respectively; and $\bar{Q}_{o,t}$ is the average discharge.

The value of F_o^2 is the "no model" value of F^2. This enables to define the efficiency of a model by R^2 as the proportion of the initial variance accounted for by the model.

$$R^2 = \frac{(F_o^2 - F^2)}{F_o^2} x100 \quad -\infty < R^2 < 100 \qquad (4.40)$$

The coefficient of efficiency is used for measuring the degree of association between the observed and simulated values. Its value gives a good indication of 1:1 fit between simulated and observed values. Values of R^2 can be below zero, but not > 100. The aim of this objective function is to maximize it to the value 100 for good simulation.

Besides that, the Pearson correlation coefficient, r, is a measure of the strength of the linear relationship (i.e. it is an index of the degree of association) between sets of observed and simulated values and is given by:

$$r = \frac{\sum_{t=1}^{n} (Q_{o,t} - \bar{Q}_o)(Q_{c,t} - \bar{Q}_c)}{\sqrt{\sum_{t=1}^{n} (Q_{o,t} - \bar{Q}_o)^2} \sqrt{\sum_{t=1}^{n} (Q_{c,t} - \bar{Q}_c)^2}} \qquad (4.41)$$

The simulation aims to maximize the correlation coefficient close to unity (= 1.0).

4.8.5. RAM Calibration

The calibration of RAM is carried out to simulate the daily discharge at Phuoc Long gauging station, i.e. runoff from sub-catchment 1 from 1986 to 1988. Using the combination Nash-cascade-Krayenhoff van de Leur J-model (3 for quick components and 5 for slow), the calibration results of the RAM model are shown in Table 4.2 including soil moisture storage at saturation, field capacity and wilting point, maximum percolation, the quick and slow conductive coefficients, the divider coefficient, infiltration capacity, etc. The optimized parameters are obtained by trial and error through visual inspection of the computed and recorded hydrographs till the best fit was obtained. Table 4.3 presents the model correlation coefficients (r) and model efficiency (R^2) along with the annual mean discharge for both computed and observed runoff for comparison.

Table 4.3 **The results of RAM parameters in subcatchment 1**

Performance measures / Year	*1986*	*1987*	*1988*	*Average*
R^2	91.9	82.0	71.1	81.7
R	0.960	0.911	0.845	0.892
Open water surface				
k_o (day)	0.0015	0.0015	0.0015	0.0015
f_o	1.25	1.25	1.25	1.25
Unpaved surface				
I_{max} (mm/day)	220	220	220	220
f	1	0.85	0.96	0.937
F0 (mm)	330	300	330	320
F2 (mm)	150	130	150	143.3
F4.2 (mm)	15	15	15	15
L_{Bv0} (mm)	700	800	700	733.3
n	0.5	0.5	0.5	0.5
$P_{percmax}$ (mm/day)	220	220	220	220
$k_{surface}$ (day)	6.5	4.0	6.0	5.5
k_{quick} (day)	47	55	55	52.3
k_{slow} (day)	122	130	130	127.3
β_{slow}	0.7	0.7	0.7	0.7

In this table, the parameter description of is as follows:

R^2	Model efficiency coefficient	
r	Model correlation coefficient	
f_o	Cropfactor Makkink for open water	
Imax	Infiltration capacity	(mm/day)
ko	Time constant reservoir open water	(day)
f	Cropfactor Makkink.	
F0	Moisture storage at pF = 0	(mm)
F2	Moisture storage at pF = 2	(mm)
F4.2	Moisture storage at pF = 4.2	(mm)
L_{Bv0}	Initial depth of the unsaturated zone	(mm)
n	Pore content	
$P_{percmax}$	Percolation to saturated zone between pF = 0 and pF = 2 (maximum)	(mm/day)
$k_{surface}$	Time constant reservoir unpaved surface	(day)
k_{quick}	Time constant fast groundwater discharge	(day)
k_{slow}	Time constant slow groundwater discharge	(day)
β	Distribution formula for fast and slow groundwater discharge	

Table 4.3 shows that the model efficiencies of the RAM calibration range from 71.1% to 91.9%. They show that the results are fairly good in these three years, especially the year of 1986 exhibitting R^2 = 91.9%. The correlation coefficients have values of 0.96, 0.911, and 0.892 for 1986-1988, respectively. The RAM parameters do not vary much in these years, as in Figures 4.8 and 4.9 showing parameter variation.

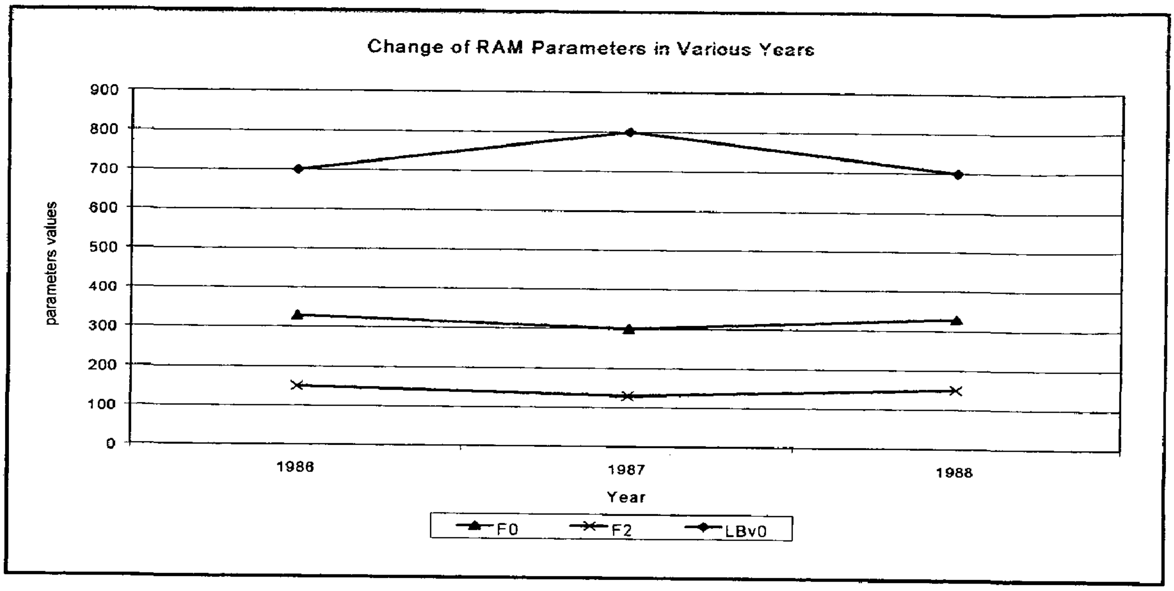


Figure 4. 8 **Calibration results of RAM in subcatchment 1**

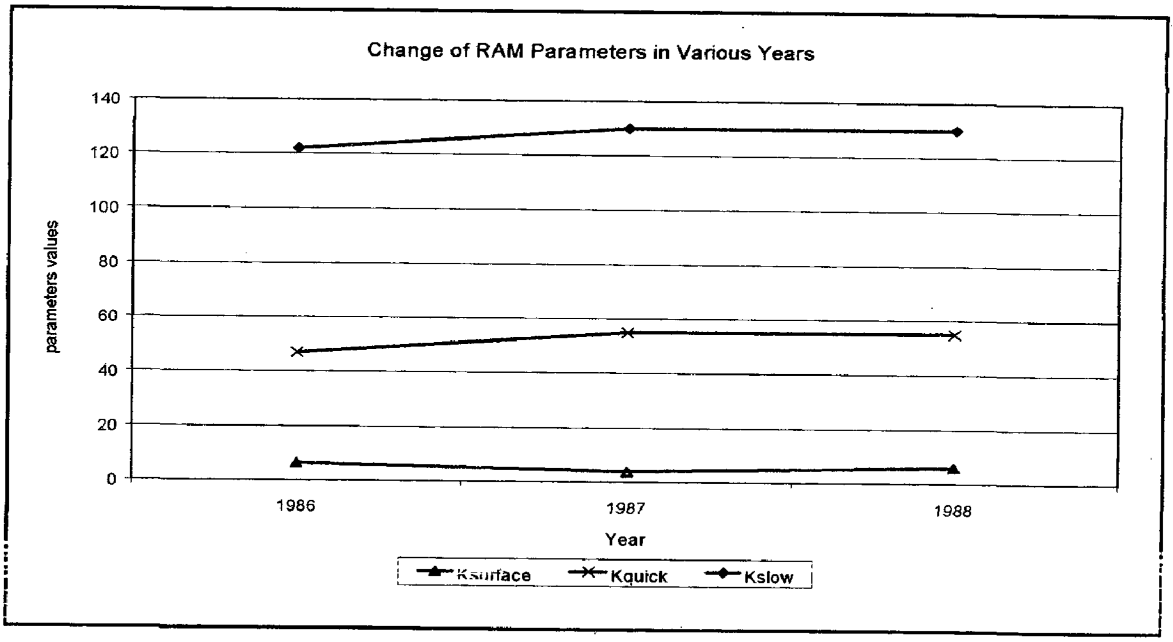


Figure 4. 9 **Calibration results of RAM in subcatchment 1**

Table 4. 4 **Comparison of mean observed and simulated runoff**

Year	1986	1987	1988
Qcalculated (m^3/s)	122.84	101.02	71.91
Qobserved (m^3/s)	122.88	104.38	71.18
Ratio	1.00	0.97	1.01

Table 4.4 shows that the values of the mean annual observed and calculated discharge are near to each other, and the computed hydrographs present the general trend of the observed one. However, the simulated runoff in the dry period is often

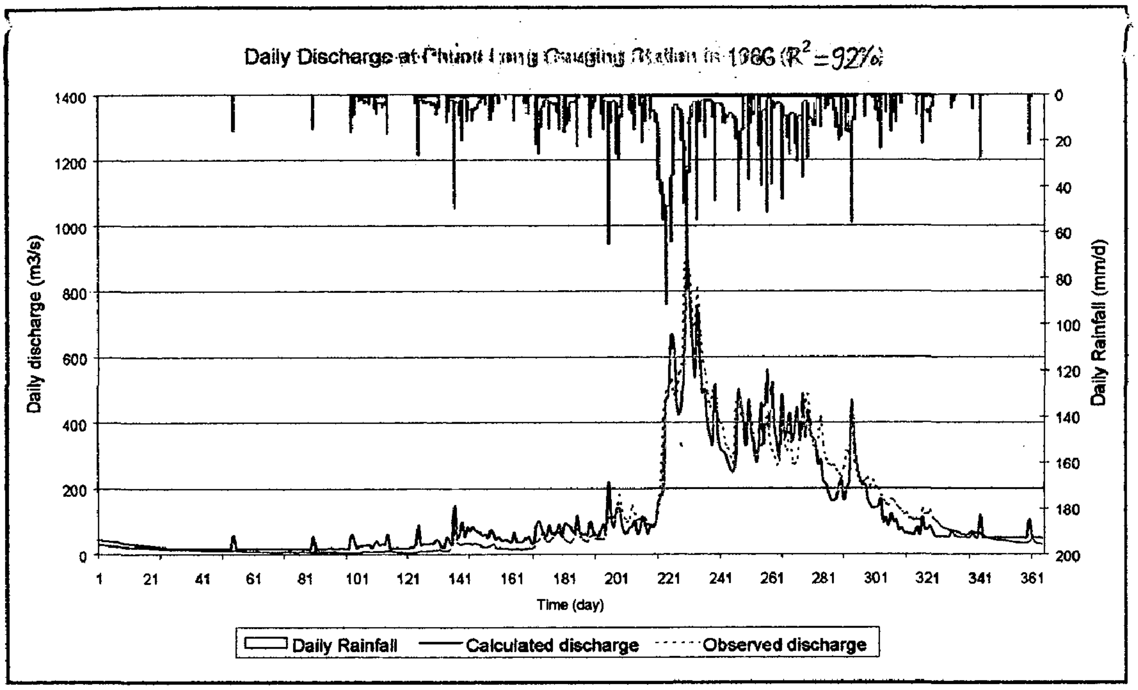


Figure 4. 10 RAM calibration in 1986 in Subcatchment 1

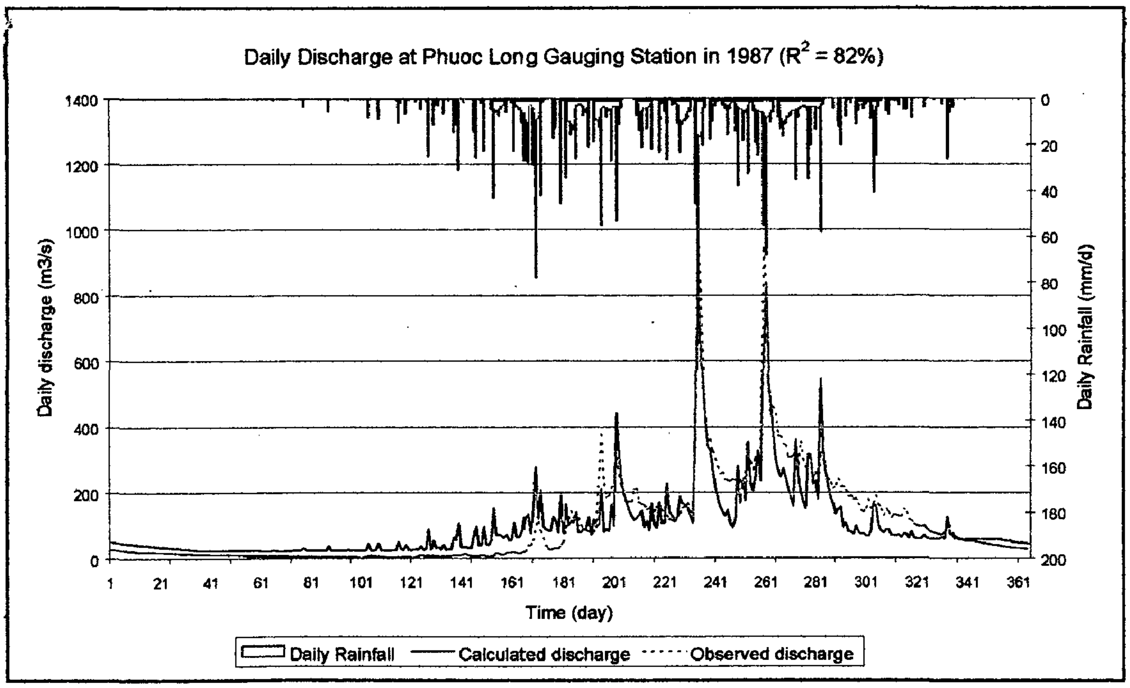


Figure 4. 11 RAM calibration in 1987 in Subcatchment 1

higher than the observed, and the calculated hydrographs are sometimes not smooth enough. This can be explained by the poorly represented areal rainfall distribution due to a limited number of rainfall stations. Another aspect is that the RAM model does not include capillary rise to the root zone, resulting in a (too) high computation of base flow. Figures 4.10-4.12 present the hydrographs of RAM calibration. In general, the result of RAM calibration in subcatchment 1 of Be river basin is fairly good.

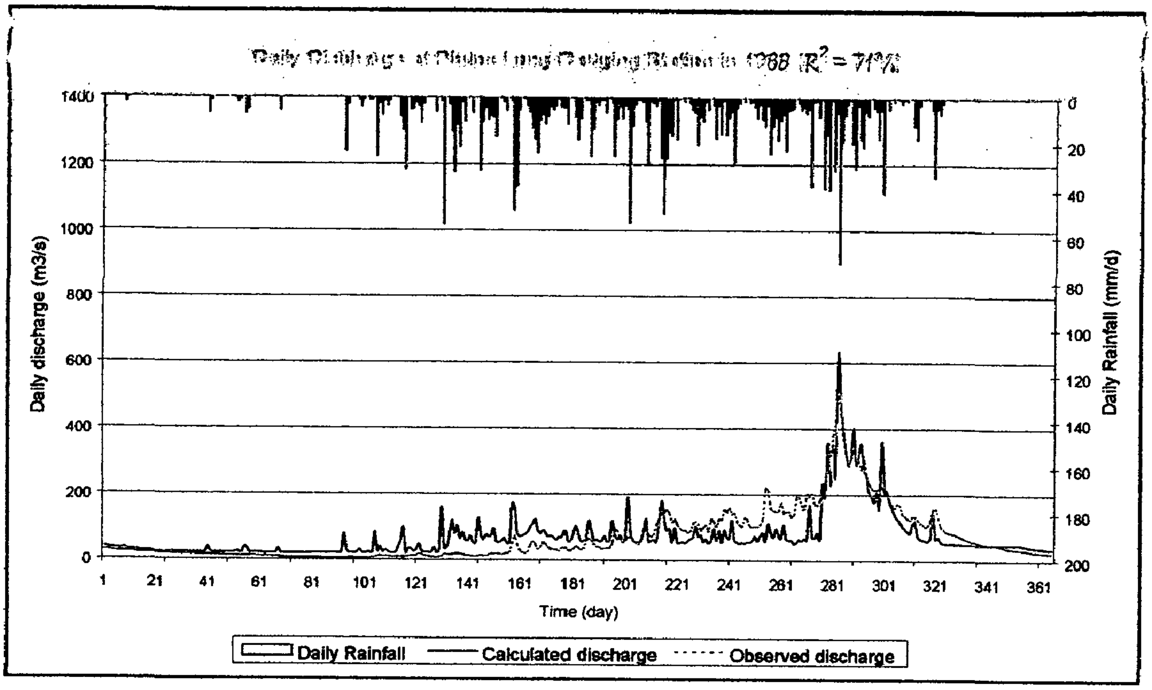


Figure 4.12 RAM calibration in 1988 in Subcatchment 1

4.8.6. RAM Verification

From the calibration results of the RAM model, the average parameter values obtained for subcatchment 1 were applied to the data of year 1989 for verification, and these results are shown Figures 4.13 and 4.15. The resulting model efficiency (R^2) and correlation coefficient (r) of 78% and 89%, respectively, exhibit a reasonable match of the computed values with the observed. The simulated mean discharge of 104.7 m^3/s, which is only 7% more than the observed value, indicates a satisfactory model performance.

4.9. DISCUSSIONS

The RAM model was calibrated for sub-catchment 1 in the Be river basin using a daily time interval for the period 1986 to 1988. The model was verified for the 1989 data. From the viewpoint of model efficiency (R^2), the simulation results using RAM are fairly good as is in the case with the correlation between the simulated and observed hydrographs. The means of the calculated and observed runoffs are almost equal and the correlation coefficient values are very high. However, the simulated runoff values are little higher than the observed ones during the dry period and the calculated hydrographs are not always smooth.

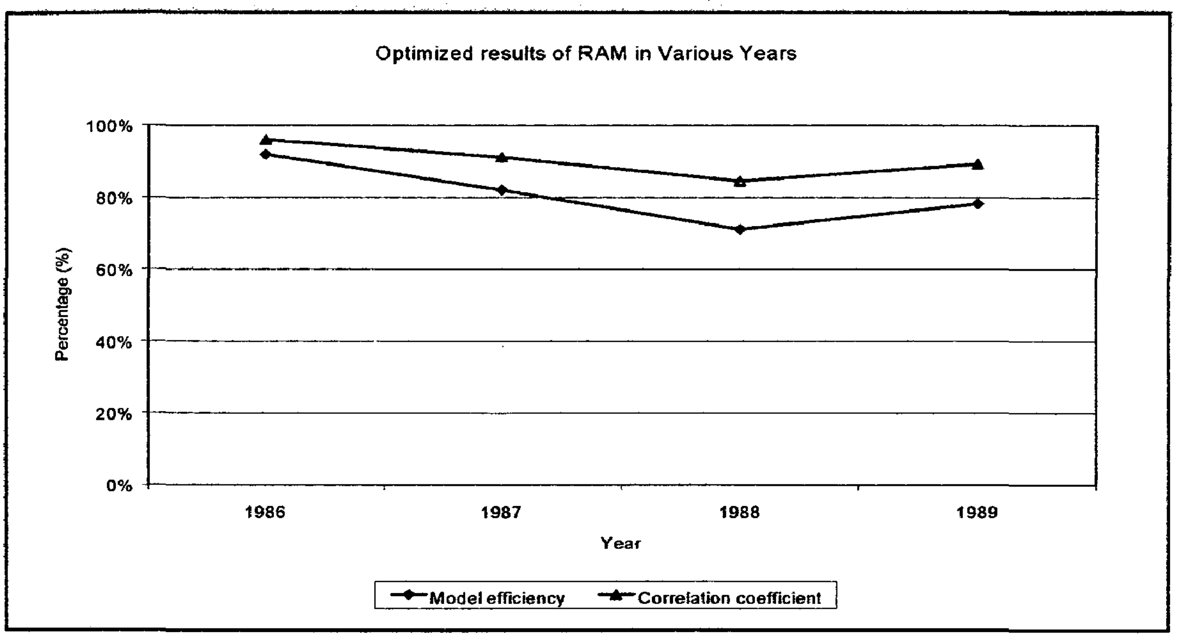


Figure 4. 13 Model efficiency and correlation coefficient of RAM calibration and verification in the subcatchment 1

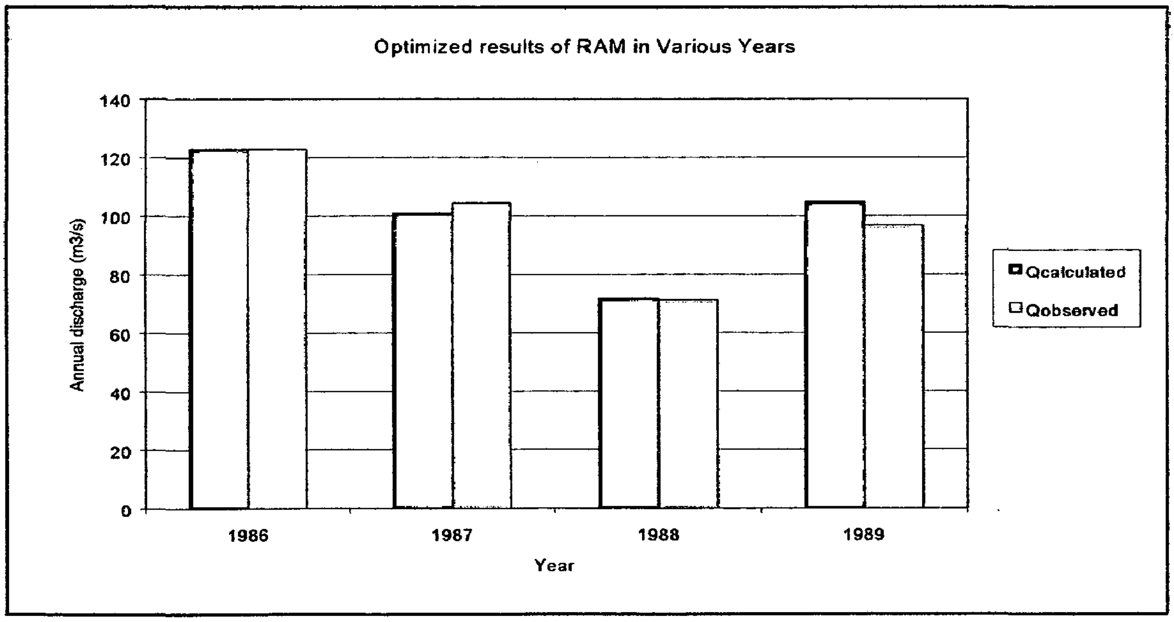


Figure 4. 14 Comparison of the calculated and observed mean runoff in subcatchment 1

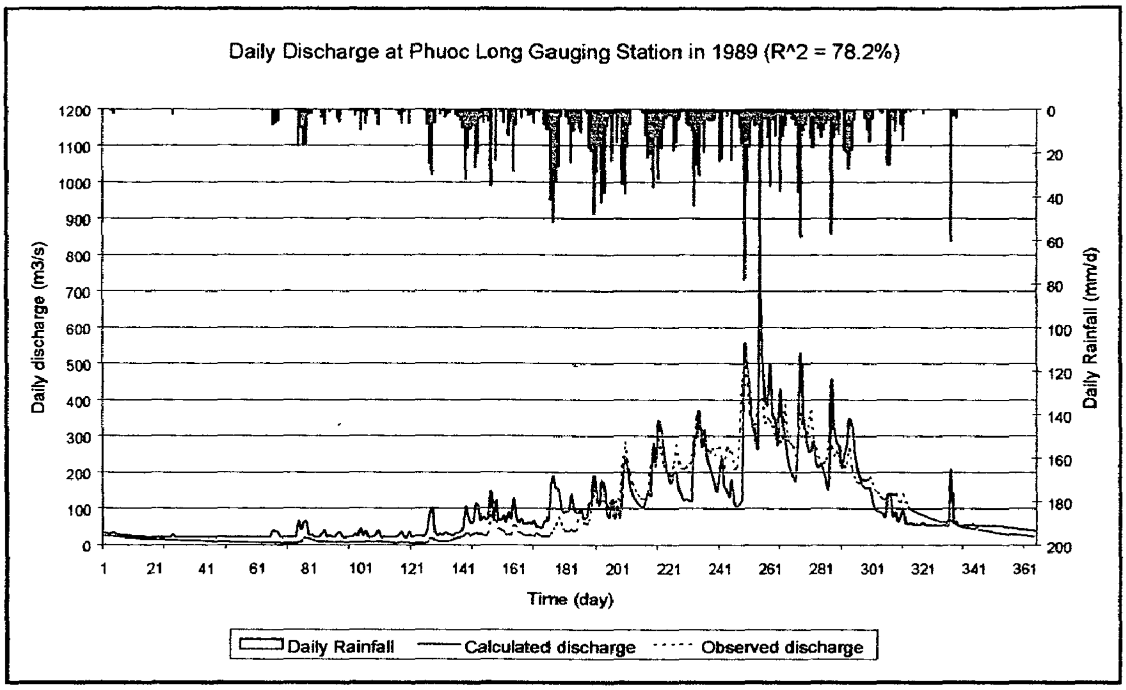


Figure 4. 15 RAM verification in 1989 in subcatchment 1

The high base flow computation during the dry period can be explained by analyzing RAM module structure. In case of soil moisture shortage (water content below the field capacity), the soil moisture is replenished by capillary rise from the saturated zone and becomes available again for transpiration or evaporation. But in the rainfall runoff module, the capillary rise from the ground water to the unsaturated zone is not included. Furthermore, the infiltration is assumed to immediately result in percolation, and the retarding effect is ignored, resulting in less evapotranspiration. Here, it is noted that the evapotranspiration coefficient, f, which varies with the cropping calendar, can not liable to be changed in a simulation run, and thus, it is a model limitation.

CHAPTER V

SCS - CN - BASED LONG - TERM DAILY FLOW SIMULATION MODEL & ITS APPLICATION

5.1. INTRODUCTION

For simulating the rainfall-runoff process, there exist a range of models varying from black box to physically based models. There, however, still exists the problem of runoff estimation on real time basis for forecasting and for synthesis of series of runoff in a variety of situations and it continues to be an important topic of research. It is however desirable that the process of providing a satisfactory answers to these problems should involve as minimum cost as possible.

The physically based models for rainfall-runoff process have advantage over the other methods particularly when it is necessary to derive the spatially and temporarily distributed information about runoff at the outlet and within various segments of the catchment area. But such models are found to have limitations related to data requirements, calibration, running cost *etc.*, because of which these models are still not adopted for day-to-day use in practice. The conceptual models have problems associated with the parameter calibration and model application. The empiricism involved in determining the excess precipitation and separating the base flow for getting the DRH in case of the UH based models make their application subjective. A catchment is generally hydrologically nonlinear. Use of linear model such as UH therefore often results in gross underestimation or overestimation of peak runoff. Thus, the objective of this chapter to present a simple Soil Conservation Service Curve Number (SCS-CN)-based long term hydrologic simulation model, sensitivity analysis, and comparison of the results of its application to the data of Be River system.

5.2. SCS-CN METHOD

The SCS-CN is a widely used event-based rainfall-runoff or infiltration loss model (Ponce and Hawkins,1996; Mishra and Singh, 1997) and accounts for the infiltration component reasonably well (Mishra and Singh, 1997). The Existing SCS-CN method is primarily based on two equations. First is the universal water balance equation:

$$P = I_a + F + Q \tag{5.1}$$

and the second is a hypothesis expressed as:

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{5.2}$$

Where P total precipitation

I_a initial abstraction

F cumulative infiltration excluding I_a

Q direct runoff

S potential maximum retention or infiltration

From (5.1) and (5.2) can be written for Q as below:

$$Q = \frac{(P-I_a)^2}{P-I_a+S} \qquad (5.3)$$

Here, $P \geq I_a$, Q = 0 otherwise. I_a is assumed to be a fraction of S as follows:

$$I_a = \lambda S \qquad (5.4)$$

Where λ is an initial abstraction coefficient. For routine applications, $\lambda = 0.2$, which is a standard value. The parameter S is conventionally mapped with the Curve Number (CN) as follows:

$$S = \frac{1000}{CN} - 10 \qquad (5.6)$$

where S is in inch and CN is a non-dimensional quantity and the latter varies from 0 to 100.

5.3. PREVIOUS SCS-CN METHOD APPLICATIONS TO LONG-TERM SIMULATION

The SCS-CN method being an infiltration loss model is restricted to the modeling storm losses (Ponce and Hawkins, 1996). The method has, however, been used in some long-term hydrologic simulation models employing various assumptions. For example, Williams and LaSuer (1976) developed an SCS-CN-based models for daily, monthly, and yearly water yield analysis, which utilize evapotranspiration that veried from the one storm to next storm. They assumed an arbitrary upper limit or 20 inches for S which can, of course, range from zero to infinity and a constant CN for a storm whereas it is a continuous function of soil moisture (Mishra and Singh, 1997b). Soni and Mishra (1985) developed a daily simulation model based on the approach suggested by Hawkins (1979) with the difference that the evapotranspiration was computed using the root zone depth. They applied it to only 1 year data of Hermavati catchment – India (area = 600 km^2). Other available simulation models of Huber et al (1976) and Knisel (1980) are worth citing. Woodward and Gburek (1992) compared these models and found them varying in degree of success. Some of the SCS-CN-based models are overviewed by Mishra and Singh (2003), and their advantages and limitations discussed. In the light of the recent advancements (Mishra and Singh, 2003) suggesting the variation of S (or CN) being largely dependent on antecedent moisture condition (besides other catchment charaterestics), it is useful to explore the potential of the SCS-CN method in simulating continuous long-term daily flows.

5.4. FORMULATION OF SCS-CN-BASED SIMULATION MODEL

The formulation of the SCS-CN-based long-term hydrologic simulation model basically depends on antecedent moisture condition (AMC) that governs the variation of CN with progressing time (day), consistent with the usual application of the existing SCS-CN method. Since the SCS-CN method is an infiltration loss model, the resulting runoff due to the application of this method is the amount of water that appears as surface runoff which, in turn, needs to be routed for computing the net flow at the outlet of the catchment. It holds particularly for a large catchment with pronounced geomorphology. The base flow contribution is accounting for as a part of the infiltrated amount of water, which, in turn, is assumed to appear at the basin outlet. A sum of the routed rainfall-excess and baseflow forms to be the total flow at the basin outlet. Mathematical formulation of the model follows.

Replacing Q by RO (runoff) in Eq. 5.3. SCS-CN method for avoiding confusion, this equation can be re-written, with time (in day) as subscript, as below:

$$RO = \frac{(P_e)_t^2}{S_t + (P_e)_t} \tag{5.7}$$

where $(P_e)_t = P_t - (I_a)_t$, S_t = time varying potential maximum retention, and $(I_a)_t = \lambda S_t$. Eq. 5.6. can be re-written as:

$$S_t = \frac{254000}{CN_t} - 254 \tag{5.8}$$

where S_t = time varying potential maximum retention (mm) and CN_t = time varying curve number which is computed for varying antecedent moisture condition (AMC) as shown in Table 5.1 and expressed mathematically for AMC I and AMC III, respectively, as:

Table 5.1: Antecedent Moisture Condition (AMC)

AMC	**Total 5 days antecdent rainfall** (cm)	
	Dormant season	***Growing season***
I	< 1.3	< 3.6
II	1.3 to 2.8	3.6 to 5.3
III	> 2.8	> 5.3

$$CN_t = \frac{CN_0}{2.3 - 0.013 CN_0} \tag{5.9}$$

and

$$CN_t = \frac{CN_0}{0.43 - 0.057 CN_0} \tag{5.10}$$

Here, CN_0 corresponds to AMC II.

The computed RO is transformed to direct flow using the single linear reservoir scheme of routing, as follows:

$$q_t = d_1 RO_{t-1} + d_2 RO_t + d_3 q_{t-1} \tag{5.11}$$

where

$$d_1 = \frac{\Delta t}{\Delta t + K} \tag{5.12a}$$

$$d_2 = d_1 \tag{5.12b}$$

$$d_3 = \frac{\Delta t - K}{\Delta t + K} \tag{5.12c}$$

Here, K is reservoir storage coefficient.

The base flow (q_b) is assumed to be a fraction, b_f, of F as follows:

$$q_{b(t)} = b_f F_t \tag{5.13}$$

which is routed using the same single linear reservoir concept of routing using a different storage constant, K_b, for ground water reservoir. The remaining soil moisture which is equal to $(1 - b_f \times F)$ is taken to account for S (or) CN variation as follows :

$$S_{t+1} = S_t - (1 - b_f \times F_t) \tag{5.14}$$

Taking the resulting CN-value from Eq. (5.14) to correspond to AMC II, it is modified using the above AMC criteria for the next day runoff computation.

Thus, the total magnitude of daily flow Q_t is the sum of q_t and q_b. Here all variable rainfall (or precipitation) and runoff (or flow) quantities are in mm. The parameters of the above model (equations 5.7 through 5.14) are CN_0, K, b_f, K_b, which can be computed using an appropriate optimization scheme using a suitable error criterion, such as the Nash and Sutcliffe efficiency as described by equation 4.40. The efficiency varies at the scale of 0 to 100 and it can also assume a negative value if RI > IV, implying that the variance in the observed and computed runoff value is greater than the model variance. In such a case, the mean of the observed data fits better than the applied model. The efficiency of 100 implies that the computed values are the same as the observed ones, which stands for the perfect fit.

5.5. APPLICATION OF SCS-CN BASED LONG TERM DAILY FLOW SIMULATION MODEL FOR BE RIVER BASIN

This section employs the above SCS-CN-based long term simulation model to five years, viz. from 1986 to 1990, data of the Be River catchment, the details of which are given in Chapter 3. The model application first requires the estimation of its parameters and then its testing on the data not used in parameter estimation.

5.5.1. Parameter Estimation

For parameter estimation, the non-linear Marquardt algorithm of constrained least squares was applied. Its application requires initial guess values of the model parameters and the upper and lower bounds within which these parameters are likely to vary. Table 5.2 provides the initial and the lower and upper bounds (range) of the parameter values. Here, it is noted that these values were arrived at by trial and error. If any of the calibrated parameter values attained either the lower minimum or upper maximum values of the supplied range in a test run, the lower minimum and/or the upper maximum value was extended in that direction appropriately so that the resulting final parameter estimates fall in the range fixed for parameter-variation. The initial values were changed arbitrarily one by one to check for the improvement of the resulting efficiency. The values shown in Table 5.2 correspond to the set yielding the highest model efficiency. Here, it is worth emphasizing that while attempting for maximum model efficiency, the initial abstraction coefficient λ was fixed at 0.01, which is consistent with the description of recent work of Hawkins et al. (2001), who recommended a λ-value of the order of 0.05, and the antecedent 2-day rainfall was considered in place of the usual 5-day rainfall while using Table 5.1.

5.5.2. Calibration and Validation

Using the above set of initial parameter values and the range of their variation, the model was calibrated on the first two years, viz. 1986 and 1987, of data and then it was tested on the remaining three years, viz., 1988-1990, of data. This application is referred here to as Case A. To check for consistent employment and performance of the model, another application was carried out using the validation data of Case A in calibration, and then the remaining data, viz., the calibration data of Case A, were used for validation. This case is referred to as Case B and the results are shown in Table 5.2, and graphically in Figs.5.1-5.5 for Case A. From the figures, a good match can be observed in the calibration years.

Table 5.2 : Calibration and Validation Results of SCS-CN-Based Model

Case	Calibration					Validation
	CN_0	b_f	K	K_b	Efficiency (%)	Efficiency (%)
Not Applicable	Initial estimate				Not Applicable	
	0.1	0.5	1.0	2.0		
	Range					
Upper bound	0.01	0.01	0.2	0.01		
Lower bound	99.99	10.0	60.0	100.0		
A	0.29	0.92	53	9.2	78.89	69.41
B	0.42	1.19	1.25	37.1	80.18	69.90

Note: Case A considers first two years (1986 and 1987) data for model calibration, and the remaining three years data for validation. Case B considers the last three years (1988-90) data for model calibration, and the remaining two years data for validation.

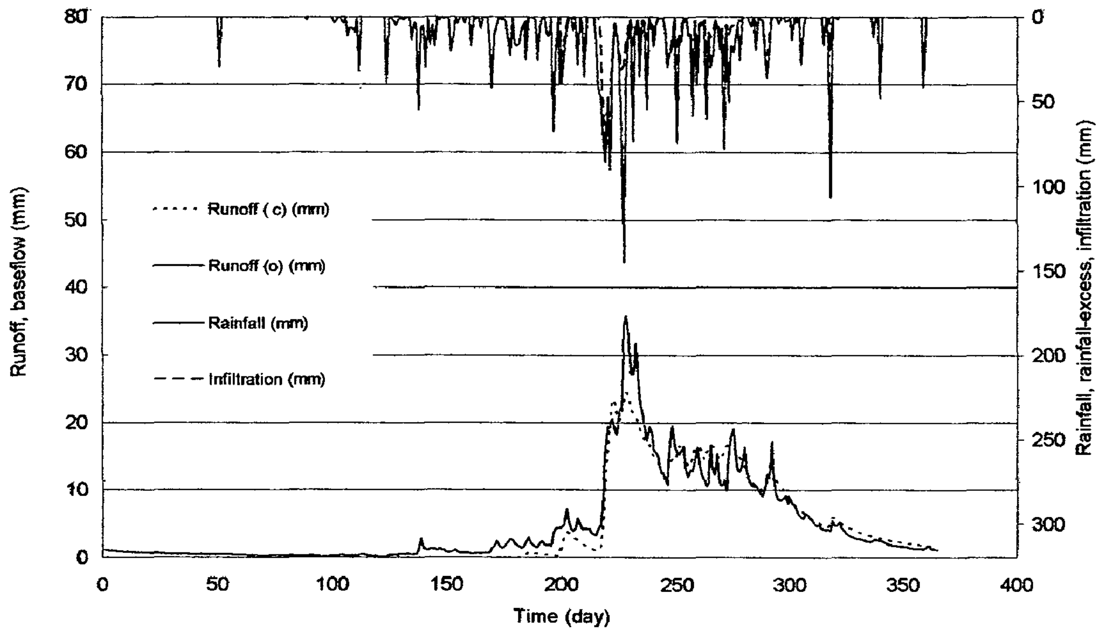


Figure 5.1 Daily flow simulation in calibration (Case A) for the year 1986

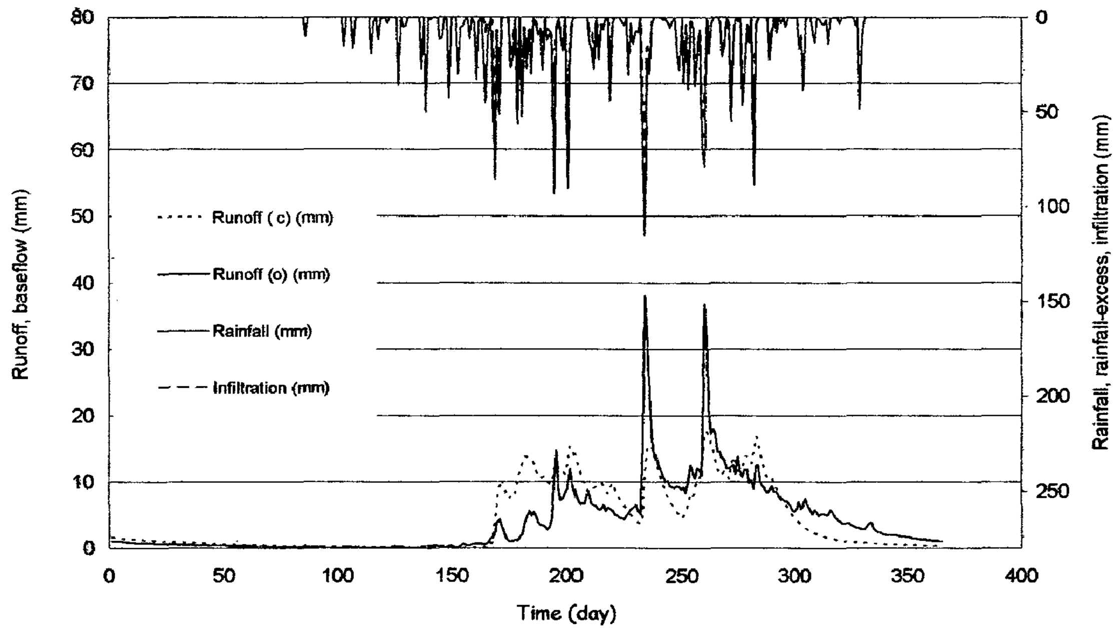


Figure 5.2 Daily flow simulation in calibration (Case A) for the year 1987

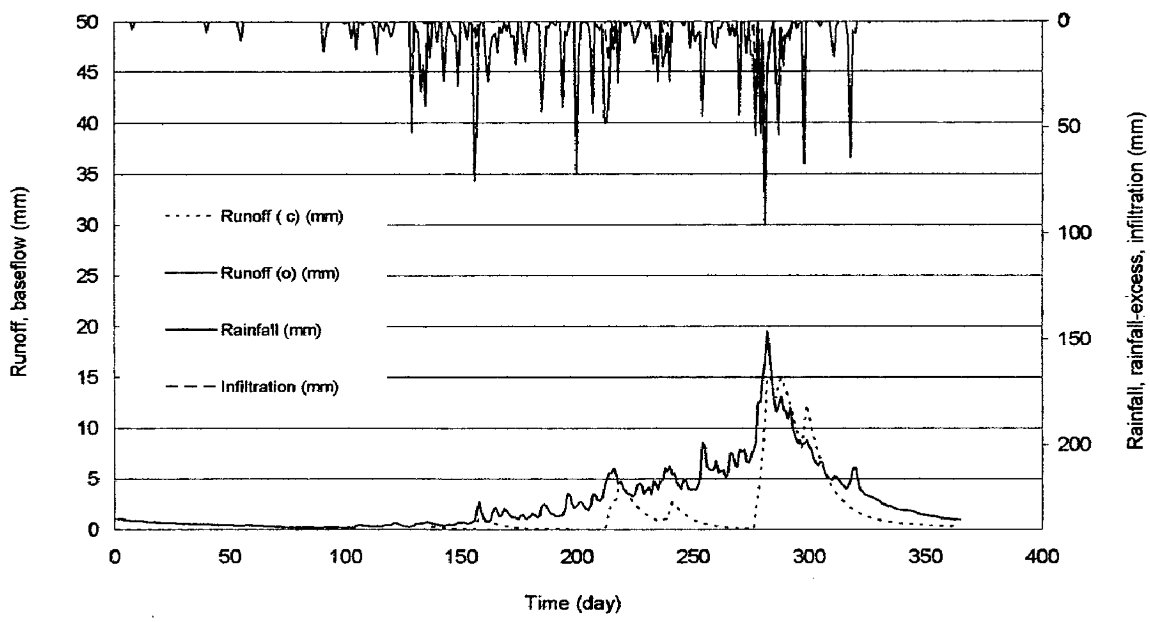


Figure 5.3 Daily flow simulation in validation (Case A) for the year 1988

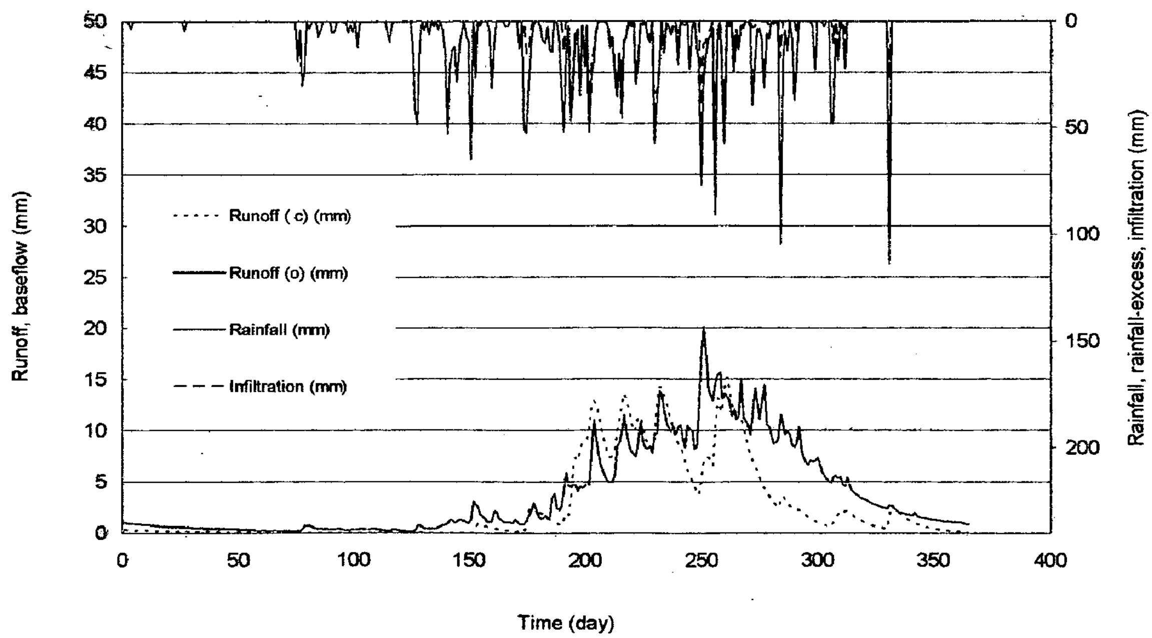


Figure 5.4 Daily flow simulation in validation (Case A) for the year 1989

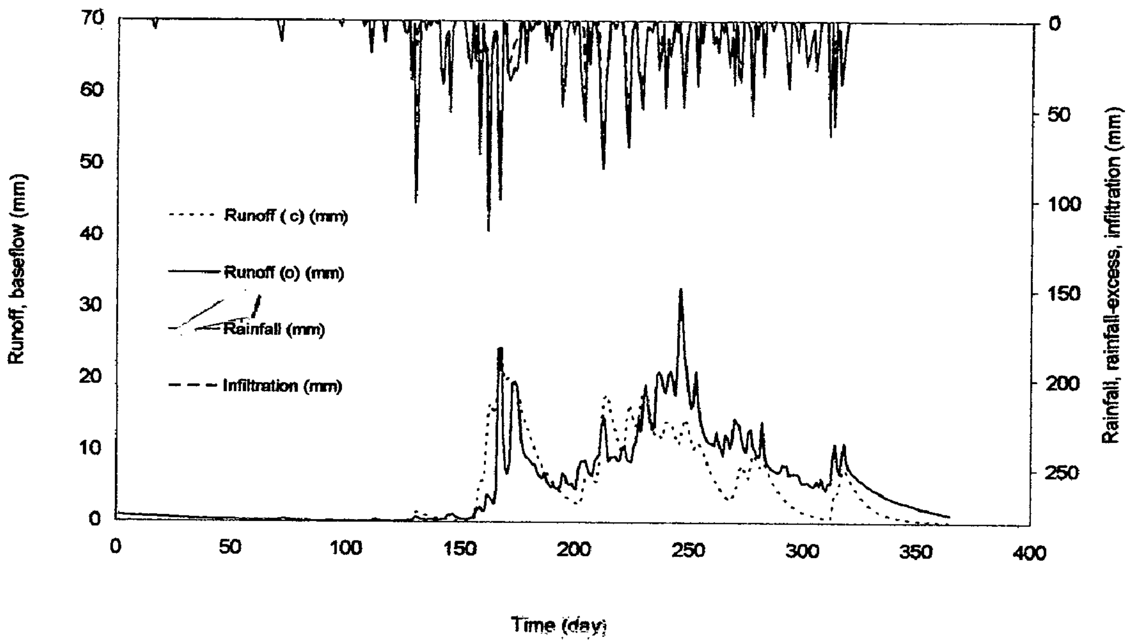


Figure 5.5 Daily flow simulation in validation (Case A) for the year 1990

It is seen from Table 5.2 that the model efficiency in calibration is 78.89% in Case A, and 80.18% in Case B. The high values of model efficiency suggest the model to perform well in calibration. It also implies that the model formulation to be reasonable for long-term hydrologic simulation. However, the model efficiency in validation for Cases A and B are 69.41% and 69.90%, respectively. Though significantly lower than those in calibration, these values suggest the model to still perform reasonably in validation. As expected, the model efficiency in validation comes out to be generally lower than those in calibration because of the model parameters optimized using minimum error criterion using the calibration data. However, if the long-term observed data belong to the same population and there has not been much change in the watershed's hydrologic regime, the model efficiency in both calibration and validation should, in principle, be close to each other. There can be significant deviation in model efficiency if the watershed experiences significant changes in land use pattern, climate, and others.

5.5.3 Computation of Annual Runoff Coefficients

The above changes in watershed regime can be seen by computation of runoff coefficients for different years using the annual rainfall-runoff data, as shown in Table 5.3. This table also shows the annual computation of various hydrological components using the above SCS-CN model and it is described later. In both the years 1986 and 1987, the runoff coefficient is equal to 0.59. However, in the years 1988, 1989, and 1990, it is equal to 0.48, 0.52, and 0.67. Because of low runoff coefficient, the first two years appear to be relatively dry years whereas the last year appears to be wet year. It can occur for two reasons: 1. The occurrence of rainfall in the first two years (equal to 2125 and 2645 mm, respectively) can be quite low compared to the last year rainfall which equals 2858 mm. Notably, the year 1988 has experienced the lowest rainfall in the considered number of years of data, and the highest rainfall was observed in 1986. 2. There can be changes in hydrologic regime of the catchment. Such a possibility is apparent from the amount of rainfall in 1990 (= 2858 mm) being of the order of 1986 (the year of maximum) rainfall. However, as stated above, the runoff coefficients in these years are 0.67 and 0.59, respectively. It clearly indicates that the hydrological regime in 1990 changed to favour the runoff generation in the watershed and it is possible if the land use changes to urbanized one from, say, agricultural or forested one. The resulting values of the runoff coefficient in the first four years, viz., 1986 – 1989, are indicative of the land use to vary in such a way that affects the runoff. The deforestation of the catchment in 1990 may be a possibility to relatively high runoff generation.

Table 5.3 : Annual Computation of Various Hydrological Components In Long-Term Hydrologic Simulation

Year	Rainfall (mm)	Infiltration (mm)	Rainfall-excess (mm)	Baseflow (mm)	Runoff (c) (mm)	Runoff (o) (mm)	Relative error (%)	Runoff coefficient
1986	2961	1011	707	930	1551	1746	11.17	0.59
1987	2505	1290	245	1186	1497	1486	-0.76	0.59
1988	2125	576	277	485	707	1014	30.29	0.48
1989	2645	1177	347	1100	1420	1380	-2.93	0.52
1990	2858	1619	555	1526	2083	1920	-8.47	0.67

5.5.4. Analysis for Stability of Model Parameters

From Table 5.2, it is seen that the values of curve number CN_0 and baseflow fraction b_f parameter do not vary as significantly as do others when the data sets are changed from Case A to those of Case B in model calibration. For example, CN_0 varied from 0.29 to 0.42, and b_f did from 0.92 to 1.19. On the other hand, the storage coefficient K and ground water storage coefficient K_b changed from 53 to 1.25 and 9.2 to 37.1, respectively, and this variation is quite significant. Therefore, it led to carry out an analysis for the stability of the model parameters. To this end, parameters were computed using the same initial and other lower and upper range of parameter values (shown in Table 5.2), but varying length of data, as shown in Table 5.4. This table shows that the models performs as well to yield a very high model efficiency as 91.16% when it is applied to only one 1986-year data. However, the efficiency lowers to 78.89% when the 1987 data set is included in parameter computation. It further generally goes down with the increasing number of years and experiences the lowest efficiency of 68.47% when all 5 years of data are considered in parameter estimation. Notably, there is a sudden fall of efficiency as soon as the fifth year data set is included. It also implies that there is a sudden change in the pattern of runoff generation characteristic of the watershed as stated above. Had the hydrologic regime of the watershed been constant, the parameters could have achieved the stability with the first four or five years of data. As an alternative to it, a sufficiently large number of years data is required for attaining stability of parameters to a reasonable extent. However, the limitation of data availability appears to be a major limitation of this study, for it is difficult to ascertain the validity of estimated parameters to be of use in runoff prediction in future.

Table 5.4 : Test runs for stability of parameters with varying length of data

Data length (Years)	Calibrated parameters				Efficiency (%)
	CN_0	b_f	K	K_b	
1	0.48	0.77	14	6.8	91.16
2	0.29	0.92	53	9.2	78.89
3	0.51	0.92	54	11.0	76.67
4	0.67	0.93	57	14.0	78.14
5	0.05	0.89	50	3.5	68.47

5.5.5. Daily Variation of Curve Number

Since the CN primary drives the process of runoff generation, it is in order to show its variation with time. Such a typical variation is shown for one year, i.e. 1986, the results of which are given in Table 5.4. It is selected for the reason that the model application this data set yielded the highest efficiency of 91.16%. The plot of CN-variation is shown in Figure 5.6.

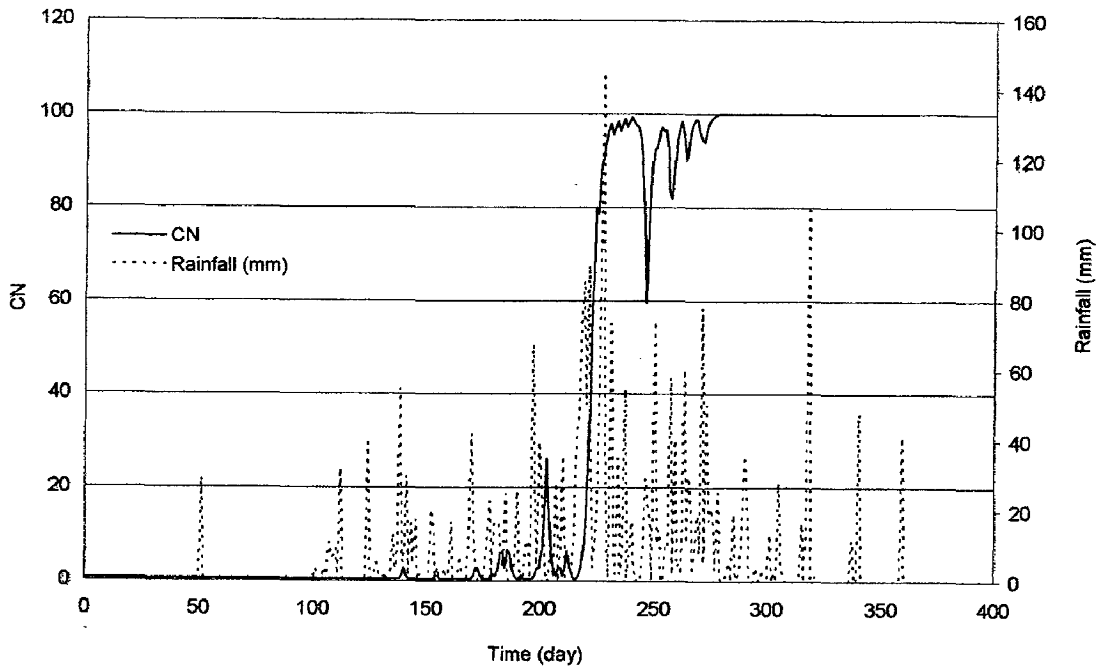


Figure 5.6 Variation of curve number CN and rainfall in year 1986

It is visible from Fig. 5.6 that the CN initially begins with a very low value (near zero) when there is no or very scant rainfall occurring in the catchment. As the rainfall increases, the curve number also increases and it decreases as the rainfall decreases. In the period of monsoon when continuous rainfall occurs, the curve number reaches almost as high as 100. It is consistent with the general notion that during the high rainfall period or the wet period with high antecedent moisture, CN should attain a high value, and vice versa. Thus, despite a few model limitations, the CN-variation, which forms key to the runoff generation in model formulation, is quite reasonable.

5.5.6. Sensitivity Analysis

To infer about the model sensitivity to variation in its parameters for field use, a sensitivity analysis is often carried out. To this end, the parameter values of Table 5.4 corresponding to 1 year data, for which the model yields the highest efficiency, are taken as the base values and these are varied one by one keeping the others fixed at their base values to compute the model efficiencies. The results of such an analysis are presented in Table 5.5.

Table 5.5 : Sensitivity analysis using the data of year 1986

Percent change	Resulting efficiency (%) due to change in			
	CN_0	b_f	K	K_b
-50	90.38	80.46	86.04	86.46
-25	90.95	86.59	90.47	90.45
0	91.16	91.16	91.16	91.16
+25	91.11	87.94	90.82	90.79
+50	90.47	74.45	89.87	89.75

It is seen from Table 5.5 that the efficiency consistently decreases as the parameter value deviates farther from its base value. Since the departure of the resulting efficiency for CN_0-variation by the same amount is the minimum of all, it is the parameter which can be taken to be least sensitive. Similarly, the parameters K and K_b can be ascribed to be of almost same sensitivity and b_f to be the most sensitive. Such an inference is also consistent with the above description of baseflow mechanism signified as a dominant process and rainfall-excess which is directly governed by the CN-variation as a dormant process in the runoff generation.

5.6. COMPARISON OF RAM AND SCS-CN-BASED MODEL RESULTS

As evident from Chapter 5, the process-based 13-parameter RAM model was calibrated for three years, viz., 1986-1988, data and then, it was validated on the data of remaining years 1989 and 1990 using the average value of the parameters computed for these three individual years. In this section, to evaluate the comparative performance of the two models, it is in order to use the same data of calibration years in SCS-CN application as used in RAM application. Here, it is noted that the SCS-CN method was applied on the same three individual years' data sets, rather than the continuous series of two and three years as shown in Table 5.4, and the results are presented in Table 5.6 and discussed below.

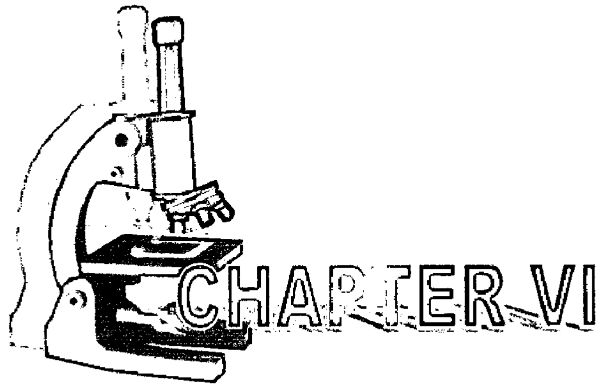
Table 5.6 : Percent Efficiency of RAM And SCS-CN-Based Model Application

Model	1986	1987	1988	Average
RAM Model	91.9	82.0	71.1	81.67
SCS-CN-based model	91.16	74.56	77.29	81.33

It is apparent from Table 5.6 that the resulting efficiencies due to both the models for the year 1986 application are of the same order. These, however, are lower and higher in SCS-CN application than those due to RAM application for 1987 and 1988, respectively. The average of these (= 81.33%) due to SCS-CN application is of the same order (= 81.67%) resulting from the RAM application. It leads to inferring that both the model results are comparable to each other and exhibit the performance of the same order. Here, it is interesting to note the following:

1. The SCS-CN-Based model is only 4-parameter model whereas the RAM is a 13-parameter model.

2. The SCS-CN-Based model is easy to understand, grasp, and apply compared to the process-based RAM model which embodies not only sophistication in its structure but also requires skill to run the model using field data.



CHAPTER VI

CONCLUSIONS

Modeling of long-term daily flows is of paramount importance in the planning and management of water resource systems. Such models are primarily developed for the determination of continuous daily flow series from the available precipitation and other meteorological data for extending flow record or filling the record of flows for their use in water availability analyses. Long-term hydrologic simulation is required for augmentation of hydrologic data that are specifically required for analyses of water availability; computation of daily, fortnightly and monthly flow for reservoir operation. Since the rainfall data are generally available for much longer period than are the stream flow data, long-term hydrologic simulation helps extend the gauged data required for above application.

There exists a multitude of rainfall-runoff models and these are generally categorized to fall in the category of empirical models, conceptual models, or physically based distributed models, in the increasing order of complexities involved in modeling various processes of the hydrologic cycle. The last two types of models are generally used for daily flow simulation. Despite their comprehensive structure, many of the state-of-the-art physically based models have not yet become standard tools in hydrologic practice in developing countries because (a) most basins in these countries are ungauged and there is little hydrologic data available and (b) these models contain too many parameters, which are difficult to estimate in practice and vary from basin to basin. Although some of these models have been applied to ungauged basins, the fact is that they are not easy for practical applications. Furthermore, when these models are compared on the same basin, they are found to be widely varying in their performance. Thus, what is needed in developing countries is simple models which can provide reasonable simulations and need little data.

The following conclusions can be derived from the study:

- RAM is a conceptual model, describing in fair detail the physical processes from precipitation to surface and groundwater runoff. It distinguishes various types of surface, i.e. open water, paved and unpaved surfaces.

- RAM is a complex model with a large set of parameters. The selected structure can be two parallel sets of Nash-cascades or a combination of a set of Nash-cascades (slow) with a Krayenhoff van de Leur (rapid) J-model cascades. For the Be river basin, the latter was used.

- RAM was applied to a large sub-catchment of the Be river basin with an area of 2,215 km^2. The model provided fairly good results, its model efficiency ranging from 71 to 92%, and the correlation coefficient from 85 to 96%.

- I_{max}, f, L_{Bv0}, n, $K_{surface}$, K_{slow} showed to be the sensitive parameters of RAM model.

- RAM does not take into account capillary rise and thus limits the increase of soil moisture. This may lead to reduced evapotranspiration and higher simulated base flows.

- The Makkink crop factor was constant during the simulation, which hampered the goodness of fit of the hydrographs.

- Hydrological data in the study area are limited, especially the number of rainfall stations. This also affects the calculated results.

- The total runoff of the Be basin was extrapolated from the RAM model of a sub-catchment. Physical and land use conditions were assumed to be more or less the same in the catchment. Uncertain is the unknown rainfall distribution over the catchment.

- The SCS-CN-based model performs reasonably well in calibration and fairly well in validation.

- Daily variation of CN shows a rational behavior with increasing or decreasing rainfall.

- Parameter CN_0 and b_f are the least and most sensitive model parameters, respectively.

- A larger than the available number of years of data is required for proper evaluation of the SCS-CN-based model.

- The SCS-CN-Based model is only 4-parameter model whereas the RAM is a 13-parameter model. The former requires only rainfall and runoff data only whereas the latter does a large set of data besides rainfall and runoff data.

- The SCS-CN-Based model is easy to understand, grasp, and apply compared to the process-based RAM model which embodies not only sophistication in its structure but also requires skill to run the model using field data.

- Thus, the SCS-CN-Based model can be a useful tool for augmentation of gauged data under the situation of limited data availability which exists in Vietnam./.

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Appendix I

- **FAO Penman-Monteith Method**

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. This so-called combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors.

The Penman-Monteith combination equation is:

$$E_{r,t} = \frac{C}{L} \frac{sR_N + c_p \rho_a \frac{e_s - e_a}{r_a}}{s + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad \text{(A1.1)}$$

where:

Er,t	reference evapotranspiration of grass in mm/day
C	constant to convert units from $kg/m^2/s$ to mm/day (C = 86400)
R_N	net radiation at the earth's surface in W/m^2
L	latent heat of vaporization ($L = 2.45\times10^6$ J/kg)
s	slope of the temperature-saturation vapour pressure curve (kPa/K)
c_p	specific heat of air at constant pressure (c_p = 1004.6 J/kg/K)
ρ_a	density of air (ρ_a = 1.2047 kg/m^3 at sea level)
e_a	actual vapour pressure for the air at 2 m height in kPa
e_s	saturation vapour pressure for the air temperature at 2 m height in kPa
γ	psychrometric constant (γ = 0.067 kPa/K at the sea level)
r_a	aerodynamic resistance (s/m)
r_c	crop resistance (s/m)

The reference evapotranspiration is defined as the rate of evapotranspiration from a hypothetical crop with an assumed crop height (12 cm) and a fixed canopy resistance (r_c = 70 s/m), and albedo (r = 0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading ground and not short of water.

The crop resistance depends on the pressure head in the root zone, h, or the 'dryness of the soil'. If the crop is amply supplied with water the crop resistance, r_c, reaches a minimum value, known as the basic canopy resistance. The relation between r_c and h is crop dependent. Minimum values of r_c range from 30 (s/m) for arable crops to 150 (s/m) for forest.

The aerodynamic resistance r_a is a function of wind speed. The following expression is used by the FAO (FAO, 1998) for wind velocities, U_2 (m/s), observed at a height of 2 m over.

$$r_a = \frac{208}{U_2} \tag{A1.2}$$

Values for e_s and s may be obtained from:

$$e_a = 0.6108e^{\frac{17.27T_a}{237.3+T_a}} \tag{A1.3}$$

$$s = \frac{4098e_a}{(237.3+T_a)^2} \tag{A1.4}$$

where:

T_a the 24 hour mean temperature of the air in °C

The actual or dewpoint vapour pressure e_a is calculated from measurements of relative humidity RH, thus

$$e_a = e_s \frac{RH}{100} \tag{A1.5}$$

R_N (the net radiation) is calculated as the incoming short wave radiation at the earth's surface. This equals to the global radiation R_S minus the fraction r that is reflected, minus the net outgoing long wave radiation R_{nL}

$$R_N = (1 - r)R_S - R_{nL} \tag{A1.6}$$

The reflection coefficient for grass is r = 0.23

Short wave radiation R_S is calculated from the general equation

$$R_S = (0.25 + 0.50\ n/N)R_A \tag{A1.7}$$

and the net outgoing long wave radiation R_{nL} (W/m^{-2}) may be estimated from the following empirical formula (De Laat and Savenije, 1992)

$$R_{nL} = \sigma(273+T_a)^4(0.34-0.139\sqrt{e_a})(0.1+0.9n/N) \tag{A1.8}$$

where:

- σ Stefan-Boltzmann constant ($\sigma = 5.6745\times10\text{-}8\ W/m^2/K^4$)
- n actual hours of sunshine
- N possible hours of sunshine (obtained from given table)
- R_A short wave radiation received at the outer limits of the at atmosphere expressed in W/m.

Values for radiation received at the outer limits of the atmosphere R_A and possible hours of sunshine N are read for a given date and latitude from.

The psychrometric constant γ may be estimated from:

$$\gamma \approx 0.00066\ p_a \tag{A1.9}$$

and the atmospheric density ρ_a (kg/m^3) depends on the temperature T_a (°C) and the pressure of the air p_a (kPa). Its value may be approximated with the following formula

$$\rho_a = \frac{p_a}{0.287(T_a + 275)} \qquad \text{(A1.10)}$$

For a temperature at mean sea level of 20°C, and p_a as a function of the height z in meters above mean sea level, may be approximated with:

$$p_a = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \qquad \text{(A1.11)}$$

- **Radiation Method**

The evapotranspiration flux of a grass crop, amply supplied with water, is largely governed by the available radiation energy. Makkink found that saturation deficit of the air and wind speed were relatively unimportant factors in the equation of Penman. The equation of Makkink is based on global radiation and temperature data only (De Laat, 1996). Neglecting the storage of heat below the surface, a slightly adapted version of the reference evaporation to Makkink may be written as:

$$E_{r,t} = CC_M \frac{s}{s+\gamma}\frac{R_S}{L} \qquad \text{(A1.12)}$$

where C_M is a constant. All other parameters in (A1.12) have been specified earlier.

With the constant C_M = 0.8 equation (A1.12) yields the evaporation of open water. The equation of Makkink, with C_M = 0.65, is presently used as the standard method to estimate the reference crop evaporation (the potential evapotranspiration of grass) by the Royal Meteorological Institute of The Netherlands.

- **Calculation of Reference Evapotranspiration**

For the Be river basin, meteorological data were collected at:

- Tan Son Nhat Airport station: longitude106°42' E, latitude 10°47' N, and altitude +9 m; with monthly data available from 1986 to 1999 (14 years).
- Phuoc Long station: longitude 106°59'E latitude 11°50' N, altitude +45 m; with monthly data available from 1984 to 2000 (17 years).

In the computations, the reference evaporation in Be river basin is taken as the arithmetic mean of these stations. The results, which are calculated by two methods, are shown in figure A1.1.

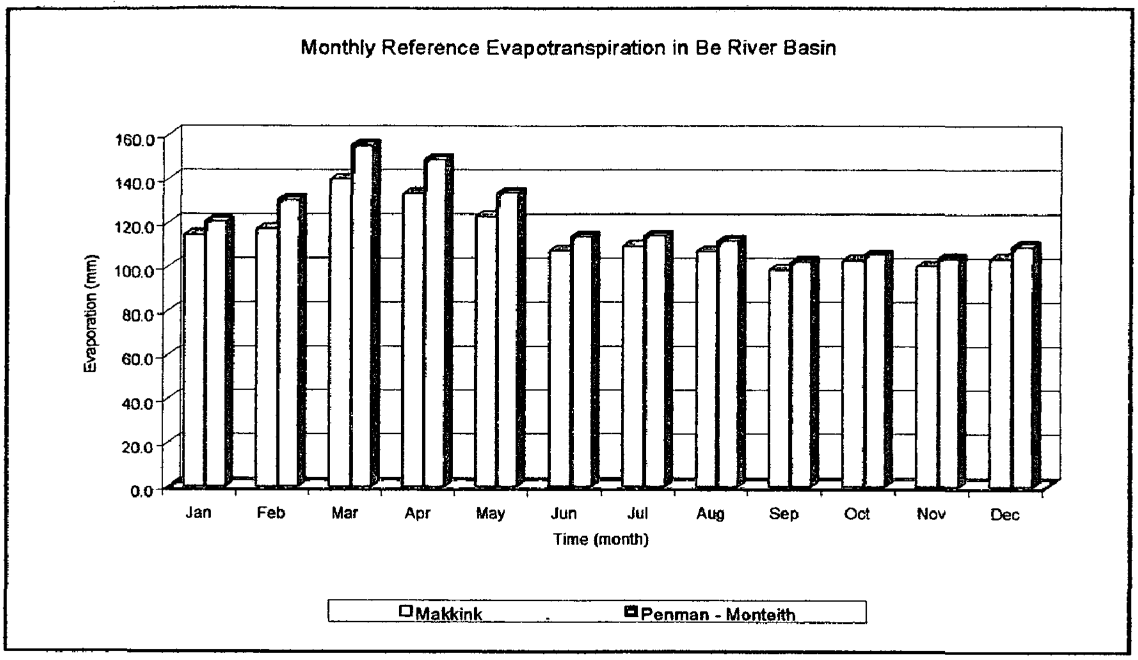

Figure A1.1 : Calculated monthly reference evapotranspiration in Be river basin

Form the calculated results in the Be river basin can be concluded that the average reference evapotranspiration Penman-Monteith ($E_{P\text{-}M}$) is equal to 1,449 mm/year, while Makkink, E_{Mk} = 1,358 mm/year. The difference of 91 mm/year (6 – 7%) is small. Thus, in this study, the reference Makkink evapotranspiration was used for the RAM modelling.

♧ Total Evapotranspiration

The Be river basin is considered to be a natural catchment covered by forests, bush, grass and bare land, etc. The area is 90% unpaved surface and 10% open water. So, according to Makkink:

$$E_{total} = A_{open}E_{open} + A_{unpaved}E_{unpaved} \qquad \text{(A1.13a)}$$

where

$$E_{open,t} = f_0 E_{r,t} \qquad \text{(A.13b)}$$

and

$$E_{unpaved,t} = fE_{r,t} \qquad \text{if } \Phi_{pF=0} \geq \Phi_{t-1} > \Phi_{pF=2} \qquad \text{(A1.13c)}$$

$$E_{unpaved,t} = \frac{\Phi_{t-1} - \Phi_{pF=4.2}}{\Phi_{pF=2} - \Phi_{pF=4.2}} fE_{r,t} \quad \text{if } \Phi_{pF=2} \geq \Phi_{t-1} > \Phi_{pF=4.2} \qquad \text{(A1.13d)}$$

$$E_{unpaved,t} = 0 \qquad \text{if } \Phi_{t-1} < \Phi_{pF=4.2} \qquad \text{(A1.13e)}$$

where

Φ_{t-1}	actual moisture storage (mm)
$\Phi_{pF=0}$	moisture storage at pF = 0 (mm)
$\Phi_{pF=2}$	moisture storage at pF = 2 (mm)
$\Phi_{pF=4.2}$	moisture storage at pF = 4.2 (mm)
$E_{r,t}$	reference crop evaporation Makkink (mm/day)
$E_{open,t}$	open water evaporation (mm/day)
$E_{unpaved,t}$	unpaved surface evapotranspiration (mm/day)
E_{total}	total evapotranspiration (mm)
A_{open}	percentage of open water area (%)
$A_{unpaved}$	percentage of unpaved area (%)
f_{open}	crop factor Mak. for open water ≈ 1.25
f	crop factor Makkink.

The Makkink crop factor, f, must be adjusted during calibration of the model to distinguish between the type of crops. However, no such crop factor data are available in the basin. Basically, data were derived from literature and adjusted accordingly.

Appendix II

♣ *Daily rainfall distribution for representative years*

(i) For a wet year:

- Choose a year of which the observed rainfall pattern coincides with that of the specific design year (e.g. 5% wet year).
- The rainfall of the representative year in rainy season must be high, and the month of highest rainfall coincides with observed series.
- Daily rainfall of the design year, X_{ip}, will be calculated from the observed daily data of representative year, $X_{i,rep.}$

$$X_{ip} = K_{wet} * X_{i,\ rep.} \quad \text{(A2.1)}$$

where K_{wet} is the called adjustment coefficient, calculated as:

$$K_{wet} = \frac{X_p}{X_{rep.}} \quad \text{(A2.2)}$$

X_p, $X_{rep.}$ are total annual rainfall of the design wet year and representative year.

(ii) **For an average year:**

- Choose the year where observed rainfall is near the probability of design rainfall (e.g. 50%).
- The monthly rainfall distribution of representative year nearly coincides with the average monthly rainfall of the observed series.
- Daily rainfall of the designed average year, X_{ip}, will be calculated from the observed daily data of representative year, $X_{i,rep.}$

$$X_{ip} = K_{ave.} * X_{i,\ rep.} \tag{A2.3}$$

(iii) **For dry year:**

- Choose the year that observed rainfall is near the probability of design rainfall (e.g. 95% dry year).
- The month with the smallest rainfall coincides with the month of smallest rainfall in the observed series.
- Daily rainfall of the designed dry year, X_{ip}, will be calculated from the observed daily data of representative year, $X_{i,rep.}$

$$X_{ip} = K_{dry.} * X_{i,\ rep.} \tag{A2.4}$$

According to the criteria above and the results of the frequency analysis, applied for the Be river basin, the year 1994 with a rainfall of 2790 mm, 1982 (2390 mm), and 1983 (2093 mm) were chosen as representative wet, average and dry years, respectively. The results are shown in figure A2.1 to A2.3.

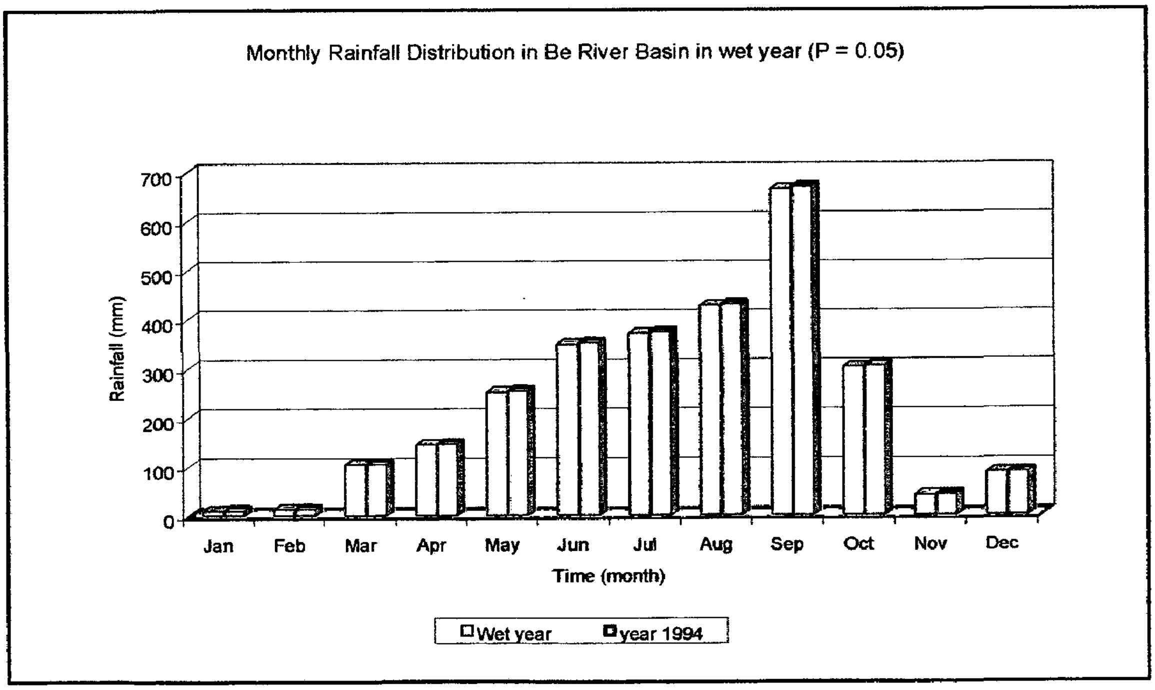

Figure A2.1. : Calculated monthly rainfall in the Be river basin in wet year (P = 5%)

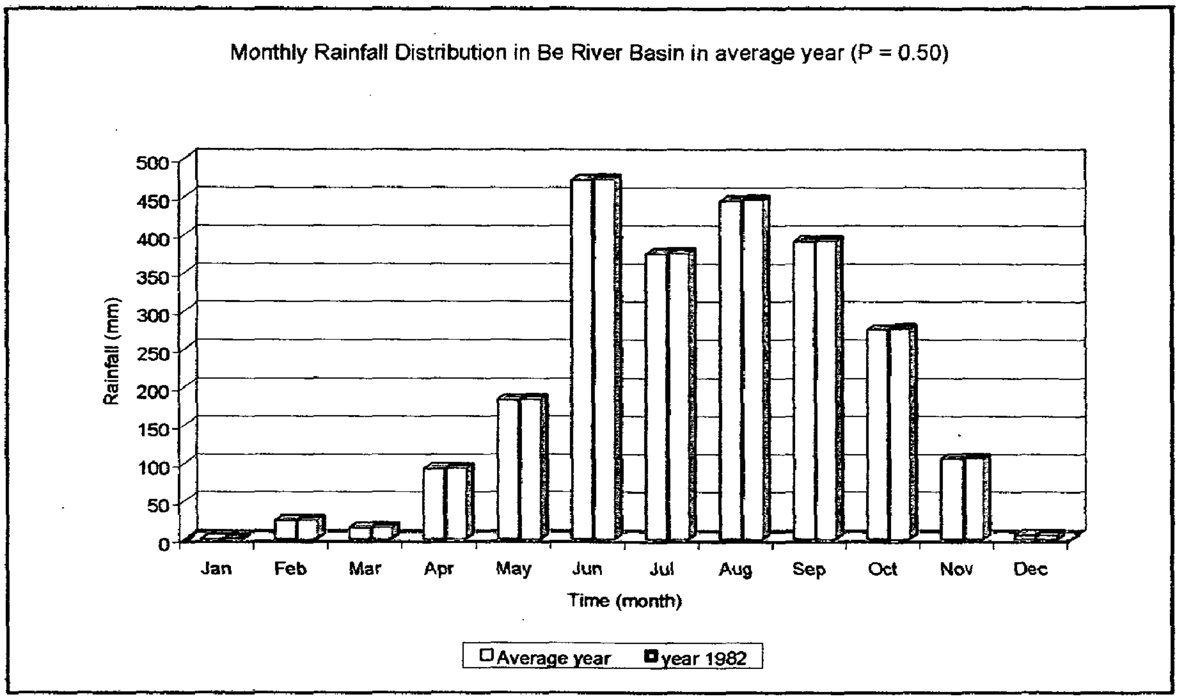

Figure A2.2 : Calculated monthly rainfall in the Be basin in average year (P = 50%)

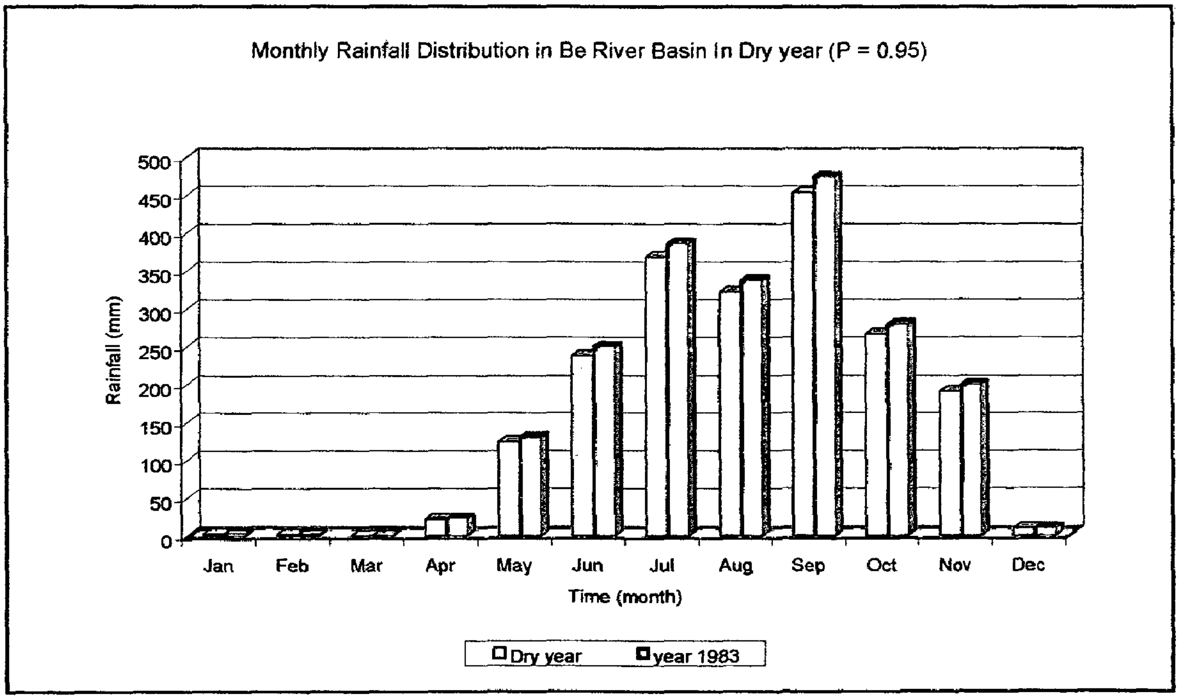

Figure A2.3 : Calculated monthly rainfall in the Be river basin in dry year (P = 95%)