A COMPARISON OF DISTRIBUTED HYDROLOGICAL MODELS FOR THE BOREAL FOREST OF NORTHERN MANITOBA

By

GATOT EKO SUSILO

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE

Department Civil and Geological Engineering
The University of Manitoba
Winnipeg, Manitoba

0-612-53232-1

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION PAGE

A COMPARISON OF DISTRIBUTED HYDROLOGICAL MODELS FOR THE BOREAL FOREST OF NORTHERN MANITOBA

BY

GATOT EKO SUSILO

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree

of

MASTER OF SCIENCE

ABSTRACT

This research aims to apply deterministic models in northern Manitoba in order to observe the ability and the appropriateness of the models in simulating runoff in northern Manitoba. The conceptual, deterministic models chosen for this research are the SLURP model and the WATFLOOD model. The Sapochi River Basin in the Northern Study Area of the Boreal Ecosystem-Atmosphere Study (BOREAS) is the river basin chosen as the study area for this research. Archived data for 1994 and 1995 were used to calibrate and verify the SLURP and WATFLOOD models in the Sapochi River Basin. The model is first calibrated with 1994 data and then verified with 1995 data. Furthermore, 1995 data is used as a calibration year and 1994 data as the verification year. Finally, both models are optimized on 1994 and 1995 together. The application of each model in the Sapochi River Basin produced different results with the SLURP model achieving a Nash and Sutcliffe efficiency of 80% over 1994 and 1995. WATFLOOD produces about 70% for 1994 and 1995. Parameters associated with snowmelt and slow storage are the most influencing parameters for SLURP simulations, with the latter dominating summer and fall runoff. Parameters associated with the upper and lower zone, specifically the upper zone specific retention, are the most influential on WATFLOOD simulation for this region. The northern Boreal forest region is dominated by snowmelt and slow discharge from interflow. The research also indicates that the ASA concept from the SLURP model is more representative than the GRU concept in depicting the natural condition of a watershed. One ASA was sufficient to simulate runoff in SLURP adequately while a 5km x 5 km GRU was necessary in the WATFLOOD simulations.

ACKNOWLEDGEMENTS

By the name of God, most gracious, most merciful. I would like to express my thankfulness to the members of my thesis committee. Special appreciation and gratitude are expressed to my supervisor Dr. Caterina Valeo for her guidance and suggestions that have greatly contributed to the progress of my study, and for her mental support and remarkable patience, which have motivated me in obtaining a masters degree. I would like to thank my friends, Marc, Jodi, Craig, Rony and Mundzir for their assistance and advice in my research development. I would like to thank Dr. Nicholas Kouwen and Dr. Frank Seglenieks from the Civil Engineering Department of the University of Waterloo, and the BOREAS PROJECT team for their advice and data support in my thesis.

I would very much like to thank my wife, son, parents, and my brothers for all their support, prayers, and patience. Sincere appreciation is expressed to The Government of the Republic of Indonesia and the University of Lampung for their financial support. Finally, thanks to all my teachers who have made contributions to my life.

TABLE OF CONTENTS

CHAPTER 5 : CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF NOTATION

SLURP Notation

$\mathbf{A}$ = area of the land cover (km^2)
A, B = Priestley-Taylor coefficients for interception
C_0, C_1, C_3, C_4 = constant for Muskingum routing method
D_r = depth of depression storage (mm)
D_{sc} = depression storage capacity (mm)
E = evapotranspiration (mm/d)
E_a = actual evapotranspiration (mm/d)
E_p = Penman's potential evapotranspiration (mm/d)
Ev_r = relative evaporation
E_w = evaporation from water surface (mm/d)
E_r = relative evapotranspiration (mm/d)
E_{soil} = soil limited transpiration rate (mm)
E_{water} = water limited transpiration rate (mm)
F^2 = efficiency of SLURP model
F_u = wind speed function (mm d/kPA)
G = soil heat flux (mm eq./d)
H = average change in elevation (m)
I = interception (mm)
I_1 = inflow at time 1 for Muskingum routing method (m^3/s)
I_2 = inflow at time 2 for Muskingum routing method (m^3/s)
If = infiltration rate (mm/d)
If_{max} = maximum possible infiltration rate (mm/d)
K = time of travel along the channel reach for Muskingum routing method (day)
L = average to-stream distance
LAI = Leaf Area Index
LAI_{max} = Leaf Area Index maximum
O_1 = outflow at time 1 for Muskingum routing method (m^3/s)
O_2 = outflow at time 2 for Muskingum routing method (m^3/s)
P = precipitation (mm)
P_d = drying power (mm eq./d)
Q_I = inflow for simple routing method (m^3/s)
Q_O = outflow for simple routing method (m^3/s)
Q_f = fast storage flow (mm/d)
Q_i = interflow (mm/d)
Q_p = percolation flow (mm/d)
Q_s = slow store flow (mm/d)
Q_{sr} = surface runoff (m^3/d)
R = hydraulic radius (m)
R_n = net radiation (mm eq./d)
R_l = daily snowmelt rate for Degre Day method (mm/d/°C)

R_2 = daily snowmelt rate of 2.0 mm/day/°C for SRM method
S = average channel slope
S_f = current contents of the fast storage (mm)
S_{fmax} = maximum capacity of the fast storage (mm)
S_m = snowmelt (mm/d)
S_s = current contents of the slow storage (mm)
S_{smax} = maximum capacity of the slow storage (mm)
S_0 = the average overland slope
T = temperature (°C)
T_{cr} = critical temperature (°C)
V = channel velocity (m/s)
X = relative weight of inflow and outflow for Muskingum routing method
Z_0 = aerodynamic roughness
a,b = coefficient for simple routing method
c = kinematic wave speed (m/s)
e = vapour pressure (kPa)
e_a = actual vapour pressure (kPA)
$e_a{}^*$ = saturated vapour pressure at the air temperature (kPA)
i = day index
k_f = retention constant of fast storage
k_s = retention constant of slow store
n = Manning's roughness
q_0 = unit width reference discharge for kinematic wave speed calculation
q_1 = discharge per unit width at time 1 for Muskingum routing method (m^3/s/m)
q_2 = discharge per unit width at time 2 for Muskingum routing method (m^3/s/m)
s = slope of vapour pressure curve (kPA/°C)
Δt = time length (s).
Δx = channel length (m)
α = conversion factor SRM snowmelt calculation method
α_{water} = Priestley-Taylor coefficient for water
α_{soil} = Priestley-Taylor coefficient for soil
γ = psychometric constant (0.066 kPa/°C)
θ = constant that depends on the cross section shape for kinematic wave speed calculation
$\bar{q}_{obs}$ = average observed flow (m^3/s)
q^i_{obs} = observed flow in day i (m^3/s)

WATFLOOD Notation

A = area of the basin element (km^2)
AET = actual evapotranspiration (mm/d)
AK_2 = intermediate zone resistence parameter
AX = channel cross section area that is related to storage by dividing the storage by the channel length (m)
C = capillary potential at the wetting front (mm)
C_t = temperature reduction coefficient
D = depth of water in the soil surface (mm)
DRNG = upper zone drainage (mm)
D_s = depression storage (mm)
D_{sc} = depression storage capacity (mm)
F = depth of infiltrated water (mm)
FCAP = the field capacity (mm)
FFCAP = percent soil moisture at the permanent wilting point (%)
IET = interception (mm/d)
I_1, I_2 = inflow to the reach consisting of overland flow, interflow, baseflow, and channel flow from all contributing basin element (m^3/s)
J = Julian day
K_n = short-wave radiation (energy/area/d)
K_s = saturated conductivity (mm/s)
LZF = lower zone drainage function parameter
LZS = lower zone storage (mm)
L_n = long-wave radiation (energy/area/d)
M = daily snowmelt depth for WATFLOOD (mm)
MF = rate of melt per degree per unit time or Melt Factor (mm/°C/h)
O_1, O_2 = outflow from the reach (m^3/s)
PET = potential evapotranspiration (mm/d)
PWP = amount of soil moisture at permanent wilting point (mm)
PWR = lower zone drainage exponent
Pe = accumulated rainfall excess (mm)
Q = channel flow (m^3/s)
QINT = interflow (mm/d)
QLZ = base flow (mm/d)
REC = interflow coefficient
RETN = upper zone specific retention
R_a = total incoming extraterrestrial solar radiation
R_3 = combined roughness and channel length parameter (mm for WATFLOOD)
S = square root of average overland slope
SAT = amount of soil moisture at a level of saturation (mm)
SPORE = percent soil moisture at the saturation point (%)
S_c = channel slope
S_d = surface detention storages (mm)
S_2, S_1 = storage in the reach (m^3)

T = temperature (°C)
TBASE = temperature at which the snow begins to melt (°C)
TTO = total of degree-days temperature (°C)
T1, T2, T3 = temperature components of degree days in evapotranspiration factor formula (°C)
UZS = amount of soil moisture in the upper zone soil (mm)
UZSI = upper zone storage indicator
d_r = relative distance between the earth and the sun
dt = is the time step of the routing
f_{pet} = evapotranspiration factor
f_{pet2} = reduction coefficient based on the total number of degree-days
f_{tall} = forest vegetation coefficient
k = constant for depression storage calculation
m = moisture contents (mm)
m_0 = initial moisture content (mm)
n = channel roughness parameter
sT_a = slope of the saturation-vapour pressure versus temperature curve (kPa/°C)
t = time step in infiltration calculation
w_a = relative humidity (%)
w_s = sunset hours angle (radians)
α = Priestley-Taylor coefficient for evaporation
δ = solar declination (radians)
δ_t = difference between the mean monthly maximum and mean monthly minimum temperatures (°F)
ϕ = latitude (degree)
γ = psychrometric constant (kPa/°C)
λ_v = is the latent heat of vaporization (kcal/kg)
ρ_w = mass density of water (t/m^3)
$\bar{T}$ = mean temperature (°C)

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

Watershed modeling is primarily accomplished by two types of methods: stochastic and deterministic. In providing information to hydrologists, a combination of deterministic and stochastic approaches is proving to be very successful (Shaw, 1983). Stochastic models incorporate probability in modeling and the input data is usually historical data. They are convenient and can provide accurate predictions for a river basin, but they rely on the assumption of stationarity, which is not always valid. Deterministic models, on the other hand, seek to simulate the physical processes of a watershed that transform rainfall or snowfall to stream flow. In this transformation, a deterministic model employs mathematical equations that describe the physical processes in a watershed that lead to observed streamflow. Therefore, unlike stochastic models, deterministic models use watershed characteristics to model the hydrological processes in a watershed.

For deterministic models, watersheds may be modeled by using a lumped approach in which watershed characteristics are averaged over the entire basin. Lumped approaches, however, are not conducive to accurately describing the behavior of a watershed. Alternatively, distributed approaches consider all the relevant watershed characteristics that govern the behavior's response to a hydrological event. The response of a watershed to a hydrological event is affected by the spatial variability of the input (rainfall or snowfall), of the boundary conditions and watershed system characteristics, and of the processes involved. Distributed approaches attempt to utilize the spatial variability in a watershed to model behavior, and therefore, they offer a more physically based way of modeling. However, they tend to require large amounts of data that are sometimes unavailable. In distributed models, the role of Geographical Information Systems (GIS) can be very useful. GIS is a computer system that is able to assemble, store, manipulate, and display geographically referenced information (USGS, 1997). The data used by a GIS can be collected by either ground surveys or remote sensing. Remote sensing is the most modern form of data acquisition today. Remote sensing is defined as the acquisition and measurement of data or information on some properties of a phenomenon, object, or material by a recording device without physical or intimate contact with the features under surveillance. The techniques involve amassing knowledge pertinent to environments by measuring force fields, electromagnetic radiation, or acoustic energy employing cameras, radiometers and scanners, lasers, radio frequency receivers, radar systems, sonar, thermal devices, seismographs, magnetometers, and gravimeters (NASA, 1998). It can provide various data for hydrological modeling purposes, including information on vegetation, land use, snow cover, cloud cover, elevation, land use, and temperature. There are several hydrological models that use remote sensing and GIS. SLURP, WATFLOOD, HYDROTEL, and SHE models are examples. They use GIS and remotely sensed data to accurately represent watershed conditions. GIS and remote sensing support the division of a watershed into many sub-modeling units, each modeled separately, and the resulting outflow is routed along a predefined channel reach (Kite and Kouwen, 1992).

While the approach to modeling the watershed characteristics is important, so too is the form of the equations that model the transformation process. The calculation process in hydrological models can be classified into three types: black box, conceptual, and physically based. Black box models provide output for a given input using simple, non-physically representative equations. Simple watershed parameters such as runoff coefficients are used in the transformation. Runoff processes are not physically explained but they can be advantageous because the methods used are simple and use a minimum amount of input data. Conceptual methods employ simplified mathematical representations of watershed processes that are more physically-based than the black-box model. These models attempt to explain clearly and somewhat simply, every process occurring in the transformation from inputs such as rainfall and snow, into runoff. Conceptual models require more watershed characteristic data than black box models. The most complicated model, the physically based model, attempts to describe runoff generation in the watershed with as much attention to physical detail as possible. They tend to use very complicated mathematical equations to describe watershed behavior, and therefore, tend to use many parameters and require a great deal of input data.

1.1 Deterministic Modeling in Northern Manitoba

Northern Manitoba has an abundance of natural resources and great diversity in flora and fauna. There are three large rivers in northern Manitoba: the Churchill River, the Nelson River, and the Hayes River, which all flow into Hudson Bay. These rivers and the hundreds of lakes distributed throughout the region present a vast source of fresh water storage and a potential water resource for hydropower development. In 1975, Manitoba Hydro started to exploit this resource by establishing the Kelsey Hydropower Generation Station in the Nelson River. The exploitation was continued and several generating stations were built for hydropower development. In the development of those generating stations, stochastic hydrological models played an important role in modeling runoff behavior of northern Manitoba Rivers. Until recently, deterministic models had never been applied in northern Manitoba for simulating runoff. Applying deterministic models in northern Manitoba would be advantageous to water resources development. Therefore, this research aims to apply deterministic models in northern Manitoba in order to observe the ability and the appropriateness of the models in simulating runoff in the region.

The conceptual, deterministic models chosen for this research are the SLURP model and the WATFLOOD model. SLURP was developed by Geoff Kite at the National Hydrology Research Institute (NHRI), in Saskatchewan in 1975. WATFLOOD was created by Nicholas Kouwen from Civil Engineering at the University of Waterloo in 1972. SLURP and WATFLOOD were selected for this study for several reasons. The first reason is that they are well adapted to using both remotely sensed data and ground-truth data. Different from other distributed deterministic models such as SHE models, SLURP and WATFLOOD are not very data intensive. They avoid large amounts of data and computational time in simulating watershed behavior (Kite, 1997). In general, both models only need surface physiographic data of a watershed and climate data that can be obtained either from remote sensing or ground surveys. There are not many watershed parameters required for both models. Both models were developed for regions affected by snowmelt and both have been successfully calibrated and verified on other remote cold regions in Canada.

The modeling approach used in this research will endeavor to be of a distributed nature. However, due to the large number of processes, inputs, boundary conditions, and system characteristics in the watershed, distributed approaches can become very cumbersome and impractical. Facing these circumstances, hydrologists have developed various methods for dividing the watershed into hydrological modeling units in order to simplify the complexity of the data requirements, yet at the same time, sustain an appropriate level of accuracy in the simulation results.

The literature contains several sub-division concepts. One of the simplest is the Hydrological Response Unit (HRU). Leavesley and Stanard (1990) defined the Hydrological Response Unit (HRU) as a homogeneous area having a distinct hydrological response. This area has a locally uniform hydrologic response to meteorological stimuli. The HRU maybe defined by land cover, by soil type, by slope, or by any other characteristic that governs runoff response. In the application of a hydrological model to a watershed, for example, an HRU is sometimes identified as a 'sub-watershed', which has parameters having uniform characteristics. Other concepts include the Grouped Response Unit (GRU) and the Aggregated Simulation Area (ASA). Grouped Response Unit (GRU) is a special term introduced by Nicholas Kouwen in order to describe watershed sub-division in the WATFLOOD hydrological model, while the term ASA is specially used by Geoff Kite to describe watershed sub-division in the SLURP hydrological model. Detailed explanations of both concepts are presented in the next chapter. Every type of hydrological modeling unit devised has advantages and disadvantages but the subdivision of the watershed depends on the watershed characteristics, data availability, computer power, and the experiences of the modeler.

The issue of watershed sub-division is certainly a significant one in northern Manitoba because of the unique landscape that is flat and of a uniform Boreal forest cover. By applying several hydrological models, each with their own concept of watershed sub-division, it is possible to identify the best watershed sub-division concept, and hydrological model, for watershed simulation in northern Manitoba.

The Sapochi River Basin in the Northern Study Area of the Boreal Ecosystem-Atmosphere Study (BOREAS) is the river basin chosen as the study area for this thesis. The main reason for choosing this basin is that it is unregulated in northern Manitoba, and there is a sufficient database of information for SLURP and WATFLOOD implementation.

1.2 Thesis Objectives

In general, the objectives of this thesis are:

a) To apply the SLURP and WATFLOOD hydrological models to the Sapochi River Basin
b) To analyze and evaluate the application process and theoretical implications of both models.
c) To compare the results produced by SLURP and WATFLOOD in the Sapochi River Basin.
d) To recommend the optimum level of watershed sub-division in the study area.

1.3 Thesis Organization

This thesis consists of five chapters. Chapter 2 contains a literature review. This review is divided into two parts: the description of the SLURP hydrological model, and the description of the WATFLOOD hydrological model. The description of the SLURP and WATFLOOD models will include an overview, conceptual representation of the watershed, runoff processes in the model, information on the data requirements, the description of the model application, and the calibration process. Chapter 3 will present a description of the research study area. It contains an overview of the BOREAS project, the BOREAS - Northern Study Area, and the Sapochi River Basin. This section also describes the physiographic, meteorological, and hydrometric characteristics of the Sapochi River Basin. Chapter 4, as the core of the thesis, is divided into three parts. The first and second sub-sections report the individual applications of the SLURP and WATFLOOD models to the Sapochi River Basin. These sub-sections capture the process of watershed division, details of the application, results of the calibration and verification processes, and assessment and discussion of the results. The third sub-section provides a comparison and evaluation of the application of SLURP and WATFLOOD models to the Sapochi River Basin. Finally, conclusions derived from the research and analysis of the application of the SLURP and WATFLOOD model to the Sapochi River Basin, as well as recommendations for possible future study are presented in Chapter 5. Tables and Figures for each chapter are given in the back of the chapter. Appendices containing detailed climatology data are presented at the end of the thesis.

CHAPTER 2: LITERATURE REVIEW

This chapter contains the descriptions of the hydrological models used in this research. The SLURP hydrological model is described in Section 2.1, followed by a description of the WATFLOOD model in Section 2.2.

2.1 SLURP Hydrological Model

SLURP is an acronym for Simple Lumped Reservoir Parametric and is a hydrological model developed in 1978 by Geoff Kite at the National Hydrology Research Institute in Saskatchewan (Kite, 1997). SLURP is a semi-distributed conceptual hydrological model. It was initially established for modeling meso-scale Canadian watersheds as an alternative to the use of larger and more complicated hydrological models used in the past (Kite, 1978). The primary advantage of this model is that it is well adapted to using both remotely sensed data and ground truth data. SLURP is also able to simulate the behavior of a watershed continuously and avoids the data and calculation excesses of other distributed models (Kite, 1997). The latest version of SLURP, version 12, was developed in FORTRAN 90.

2.1.1 Conceptual Representation of Watershed by SLURP

In SLURP, the watershed is divided into modeling units called Aggregated Simulation Area (ASA). An ASA is the group of smaller areas that have known properties. There is no certain limitation to form an ASA. The ASA does not have a regular shape and is more usually based on stream network (Kite, 1997). There is also no limit on ASA area and the modeler can create an ASA based on the watershed area or hydrometric station position by declaring the outlet of the watershed or hydrometric station position as the outlet of the ASA. The determination of the ASAs can be undertaken by either Geographical Information System (GIS) software or by manual delineation. In delineating the watershed, GIS software requires a Digital Elevation Model (DEM). Figure 2.1 explains the presentation of watershed sub-division using the ASA concept.

2.1.2 Vertical Water Balance in SLURP

Figure 2.2 displays a simplified system of the vertical water balance that the SLURP model employs to each land cover within each ASA. The system consists of four non-linear storages, or tanks. They are *the canopy storage, snow storage, rapid storage, and slow storage*. The vertical water balance in SLURP operates at daily time step.

2.1.3 Interception

The flow of operation for a particular ASA and land cover is started by the main model input, precipitation. Precipitation in SLURP is categorized into two forms, snow and rainfall. If the mean temperature of the day is less than a critical temperature $\mathbf{T_{cr}}$, then the precipitation is considered snowpack. Conversely, if the mean temperature of the day is greater than $\mathbf{T_{cr}}$, the precipitation is assumed to be rainfall. A part of the precipitation enters the fast storage tank and another part is retained in canopy storage as interception. The amount of interception is formulated as follows (Spittlehouse, 1989):

$$I = A \times LAI \times P^{B} \qquad (2.1)$$

where **I** is the interception (mm), **LAI** is the leaf area index, **P** is the precipitation (mm), and A and B are coefficients. The model initially sets A to $1/(\mathbf{LAI_{max}})$ and sets B to 1.0. $\mathbf{LAI_{max}}$ is the maximum Leaf Area Index.

2.1.4 Evapotranspiration

Intercepted water evaporates back to the atmosphere and there are three different methods that can be used in the SLURP model to compute evapotranspiration. Those methods are the Complementary Relationship Areal Evaporation (CRAE) method, the Granger method, and the Spittelhouse and Black method.

The CRAE method states that (Morton, 1983):

$$E_a = 2(E_w - E_p) \qquad (2.2)$$

where $\mathbf{E_a}$ is the actual evapotranspiration (mm), $\mathbf{E_w}$ is the evaporation from the water surface (mm), and $\mathbf{E_p}$ is the Penman's potential evapotranspiration (mm).

The Granger method determines that (Granger, 1991):

$$E_a = \frac{(sGR_n + \gamma GE_a)}{(sG + \gamma)} \qquad (2.3)$$

where $\mathbf{E_a}$ is the actual evapotranspiration (mm), **s** is the slope of vapour pressure curve (kPa/°C), $\mathbf{R_n}$ is the net radiation (mm eq./day), $\mathbf{Ev_r}$ is the relative evaporation (dimensionless), $\boldsymbol{\gamma}$ is the psychometric constant (0.066 kPa/°C), and $\mathbf{P_d}$ is the drying power (mm eq./day). The relative evaporation $(\mathbf{Ev_r})$ is derived from the equation:

$$Ev_r = \frac{1}{(0.905 + 0.905e^{(6.2E_r)})} + (0.2E_r) \qquad (2.3a)$$

where **e** is the vapour pressure (kPa), and $\mathbf{E_r}$ is the relative evapotranspiration (mm) derived from:

$$E_r = \frac{P_d}{(P_d + R_n)} \quad (2.3b)$$

$\mathbf{P_d}$ is derived from:

$$P_d = F_u(e_a^* - e_a) \quad (2.3c)$$

where $\mathbf{F_u}$ is the wind speed function in (mm d/kPa), $\mathbf{e_a}$ is the actual vapour pressure of air (kPa), and $\mathbf{e_a}$***** is the saturated vapour pressure at the air temperature (kPa). $\mathbf{F_u}$ is derived from:

$$F_u = (8.19 + 0.22Z_0) + (1.16 + 0.08Z_0) \quad (2.3d)$$

where $\mathbf{Z_0}$ is an aerodynamic roughness (s/m).

In the Spittelhouse and Black method (Spittelhouse, 1989) evapotranspiration is computed using a function of plant transpiration. It is defined by:

$$E_{water} = \alpha_{water} \frac{s}{s+\gamma}(R_n - G) \quad (2.4)$$

$$E_{soil} = \alpha_{soil} \frac{s}{s+\gamma}(R_n - G) \quad (2.5)$$

where $\mathbf{E_{water}}$ is the water limited transpiration rate (mm), $\mathbf{E_{soil}}$ is the soil limited transpiration rate in (mm), $\boldsymbol{\alpha_{water}}$ is the Priestley-Taylor coefficient for water, $\boldsymbol{\alpha_{soil}}$ is the Priestley-Taylor coefficient for soil, **G** is the soil heat flux (mm eq./day). Evapotranspiration is given by:

$$E = soil\,cover \times E_{soil} + crop\,cover \times E_{water} \quad (2.6)$$

soilcover and **cropcover** are the relative area fractions of soil and crop cover, respectively (%).

Research evaluating those three evapotranspiration methods in SLURP were conducted in the Kootenay River Basin, a mountainous basin in British Columbia (Barr et.all., 1997). Simulation results produced by those methods were evaluated against recorded stream flow of the Kootenay River Basin between 1986 and 1990. Results of the research showed that the Spittelhouse/Black method gave the closest agreement between recorded and simulated streamflow.

2.1.5 Snow Storage

The second tank of the SLURP vertical water balance model describes processes in the snow storage. If the daily mean temperature is below or equal to the critical temperature, the precipitation is considered as snowfall and accumulated to a snowpack. If the mean temperature is above the critical temperature, any snowpack is depleted to snowmelt and the snowmelt flows vertically. SLURP offers two alternative methods in calculating the snowmelt process. They are the simple Degree-Day method, and the Snowmelt Runoff Model (SRM) method.

The Degree-Day method states that:

$$S_m = R_1(T - T_{cr}) \qquad (2.7)$$

where $\mathbf{S_m}$ is the snowmelt (mm/d), $\mathbf{R_1}$ is the daily snowmelt rate (mm/d/°C), **T** is the temperature (°C), and $\mathbf{T_{cr}}$ is the critical temperature (°C),

The Snowmelt Runoff Model (SRM) method (Martinec et. al., 1994):

$$S_m = R_2(T - T_{cr}) + \alpha R_n \qquad (2.8)$$

where $\mathbf{R_2}$ is the daily snowmelt rate of 2.0 mm/day/°C, $\boldsymbol{\alpha}$ is the conversion factor, and $\mathbf{R_n}$ is the net radiation (MJ/m^2/d).

2.1.6 Fast Storage

Water in this storage consists of water from fast storage's initial content and water from rainfall, throughfall from canopy storage, and snowpack infiltration. The rate of infiltration of rainfall and snowmelt to the fast storage is given by:

$$If = (1 - \frac{S_f}{S_{f\max}}) If_{\max} \tag{2.9}$$

where **If** is the infiltration rate (mm/d), **S_f** is the current contents of the fast storage (mm), **$S_{f\max}$** is the maximum capacity of the fast storage (mm), and **$If_{\max}$** is the maximum possible infiltration rate (mm/d). If the water supply from rainfall and snowpack is more than **If** or if **S_f** is equal to **$S_{f\max}$**, then the water is depleted to surface runoff. The surface runoff is calculated based on Manning's equation as follows:

$$Q_{sr} = (D_r - D_{sc})^{1.67} S_0^{0.5} \frac{A}{n} \tag{2.10}$$

where **Q_{sr}** is surface runoff (m^3/d), **D_r** is the depth of depression storage (mm), **D_{sc}** is depression storage capacity (mm), **S_0** is the average overland slope, **A** is the area of the land cover, and **n** is Manning's roughness for the land cover. The fast storage also produces fast storage flow calculated as:

$$Q_f = \frac{S_f}{k_f} \tag{2.11}$$

where **Q_f** is the fast storage flow (mm/d), **k_f** is the retention constant of fast storage (day), S_f is the current contents of the fast storage (mm). The fast storage flow furthermore splits into two components of flow, percolation and interflow. The calculation of percolation is given by:

$$Q_p = \frac{Q_f}{1 + \frac{S_s}{S_{smax}}} \tag{2.12}$$

where Q_p is the percolation (mm/d), Q_f is the fast storage flow (mm/d), S_s is the current contents of the slow storage (mm), S_{smax} is the maximum capacity of the slow storage (mm). The interflow, Q_i, is described as the difference between the fast storage flow and the percolation flow and given as:

$$Q_i = Q_f - Q_p \tag{2.13}$$

2.1.7 Slow Storage

The last tank of the SLURP vertical water balance model designates the process of groundwater flow in the model. Like the fast storage calculations, groundwater flow is calculated based on liner reservoir equation and given by:

$$Q_s = \frac{S_s}{k_s} \tag{2.14}$$

where Q_s is the slow store flow (mm/d), k_s is the retention constant of slow store (days), and S_s is the current contents of the slow store (mm).

2.1.8 Routing Within ASA

In the routing within an ASA process, runoff from each land cover is routed to the nearest stream and later routed down to the outlet of ASA. Data required in this process are the mean and standard deviation of the distance between land cover and the nearest stream, the mean distance between each point in the stream and ASA's outlet, and the mean of the elevation of each land cover in the ASA. These data can be derived from a digital elevation model and land cover maps using Slurpview, the GIS extension of SLURP (Fast, 1999a). In computing travel times for each land cover, the calculations of a velocity for travel to-stream, and a velocity for travel down-stream, are important quantities. In SLURP, the travel time of flow in each land cover to the nearest stream is computed by using the velocity formula from Manning's equation:

$$V = \frac{1}{n} R^{0.67} \left(\frac{H}{L} \right)^{0.5} \tag{2.15}$$

where **V** is the velocity (m/s), **n** is the Manning's roughness, **R** is the hydraulic radius (m), **H** is the average change in elevation in (m), and **L** is the average to-stream distance (km). By using a similar equation, the travel time of each point in the stream to the ASA's outlet can be calculated by using the mean distance down-stream and the change in elevation down-stream. Those two travel times, to-stream and down-stream, furthermore are summed and become the total travel time of the ASA. This total travel time is used to analyze the relationship between runoff from each land cover and time.

2.1.9 Routing Between ASA

Since the runoff from each land cover has been collected in the outlet of the ASA, this flow will be routed into the next or lower ASA. The final destination of flow in this process is the outlet of the basin. In SLURP, there are three methods to analyze flow routing between ASAs. The simplest but least accurate method is a hydrological storage routing method. The formula for this method is:

$$Q_O = a\left(\frac{Q_I}{a}\right)^{\left(\frac{1}{b}\right)} \tag{2.16}$$

where Q_O is the outflow (m^3/s), **a** and **b** are coefficients, and Q_I is the inflow (m^3/s).

Another method that is also considered is the Muskingum method developed by McCarthy in 1938 (Linsley, et. al., 1958). This method uses two constants in its calculation. The relative weight of inflow and outflow, **X**, is used for calculating channel storage, while the time of travel along the channel reach, **K**, is employed for solving the storage equation. The value of **X** varies between 0 to 0.5 and **K** is measured in days. Every ASA has a specific **X** and **K** value for routing flows from the ASA outlet to the lower ASA. The basic equation of this method is:

$$O_2 = C_1 I_2 + C_2 I_1 + C_3 O_1 + C_4 \tag{2.17}$$

where $\mathbf{O_2}$ is the outflow at time 2 (m^3/s), $\mathbf{C_1}$, $\mathbf{C_2}$,$\mathbf{C_3}$,$\mathbf{C_4}$ are constants, $\mathbf{I_1}$ is the inflow at time 1 (m^3/s), $\mathbf{I_2}$ is the inflow at time 2 (m^3/s), and $\mathbf{O_1}$ is the outflow at time 1 (m^3/s). $\mathbf{C_0}$, $\mathbf{C_1}$, $\mathbf{C_2}$,$\mathbf{C_3}$,$\mathbf{C_4}$ are calculated by using equations as follows:

$$C_0 = K - KX + \frac{\Delta t}{2} \tag{2.17a}$$

$$C_1 = -\frac{KX - \frac{\Delta t}{2}}{C_0} \tag{2.17b}$$

$$C_2 = \frac{KX + \frac{\Delta t}{2}}{C_0} \tag{2.17c}$$

$$C_3 = \frac{K - KX - \frac{\Delta t}{2}}{C_0} \tag{2.17d}$$

$$C_4 = \frac{0.5(q1 + q2)\Delta x \Delta t}{C_0} \tag{2.17e}$$

where $\mathbf{q_1}$ is the discharge per unit width at time 1 ($m^3/s/m$), $\mathbf{q_2}$ is the discharge per unit width at time 2 ($m^3/s/m$), $\mathbf{\Delta x}$ is the channel length (m), and $\mathbf{\Delta t}$ is the time length (s).

The more sophisticated routing method, Muskingum-Cunge method, can be used in case channel characteristics such as channel length, change in elevation of the channel, average channel width, channel depth and channel roughness are available. The main equation of this method is the same as Muskingum routing method. However, in this method the values of **K** and **X** are calculated using a specific formula. The storage constant, **K**, is calculated as:

$$K = \frac{\Delta x}{c} \qquad (2.18)$$

where **Δx** is the channel length (m), and **c** is the kinematic wave speed (m/s) and computed as:

$$c = 1.27\theta \frac{S^{0.3}}{q_0^{\ 0.4}} n^{0.6} \qquad (2.19)$$

where θ is a constant that depends on the cross section shape and is sometimes assumed to be 5/3 for rectangular channel, **S** is the bottom slope, q_0 is a unit width reference discharge, and **n** is the Manning roughness. The weighting constant, **X**, in this method has value between 0 to 0.5 and calculated as:

$$X = 0.5(1 - \frac{q_0}{c} S_0 \Delta x) \qquad (2.20)$$

2.1.10 Data Requirements

The SLURP model basically requires three groups of data. Those groups are physiographic data, parametric data, and time series data *(Kite, 1997)*. Physiographic data is the type of data that is related to the physical condition of the ASA in the watershed.

This data can be obtained from topographic and land cover maps. The examples of physiographic data are (Teklemariam, 1997):

a) ASA boundary and area
b) Land cover percentages in each ASA
c) Latitude and altitude of ASA
d) Stream network
e) Distance to the nearest stream
f) Distance to the stream network
g) Mean elevation of each land cover in the ASA
h) Difference in elevation between upstream and downstream points in the ASA
i) Weight for climatic station influence

Some of this data above can be acquired from satellite images.

The second group of data, parametric data, are constants that control the way the model transforms precipitation into runoff through processes such as evaporation, infiltration, interception, and snowmelt. These coefficients and parameters are derived from laboratory or field experiments. The parameters and coefficient data in this model are (Kite, 1997):

a) Interception coefficients, and maximum and minimum Leaf Area Index (LAI)
b) Maximum capacities for the canopy and detention storage
c) Initial content of the snowpack and fast and slow stores
d) Surface albedo and maximum soil heat flux
e) Snowmelt rates and energy conversion factors
f) Conductivity
g) Saturated infiltration rate
h) Roughness coefficient for land covers and channels in the ASA
i) Lapse rate for temperature and precipitation/elevation adjustment rate
j) Parameters for specific evapotranspiration methods such as the winspeed function, wilting point, field capacity and Priestley-Taylor coefficient.

Time series data involves climatology data at a daily time step:

a) Daily mean temperature
b) Daily dewpoint temperature
c) Daily total precipitation
d) Daily net radiation
e) Daily hours of bright sunshine
f) Daily ratio of observed to maximum hours of bright sunshine

Finally, another type of data is the data achieved from the satellite such as daily cloud cover, and snow cover data. However these satellite data are optional in SLURP operations. It is necessary to note that for a calibration, daily discharge data must be provided.

2.1.11 Calibration of the Parameters

Calibration is generally a necessary step in accurate watershed modeling. In order to determine what parameters should be calibrated, a sensitivity analysis is required. The goodness of fit of the SLURP model can be judged by statistical criteria. The testing the goodness of fit of SLURP in this thesis is undertaken using the Nash and Sutcliffe efficiency method. The equation for the Nash and Sutcliffe efficiency is (Nash and Sutcliffe, 1970):

$$F^2 = \frac{\sum\left[(q_{obs}^i - \overline{q}_{obs})^2 - (q_{obs}^i - q_{calc}^i)^2\right]}{\sum(q_{obs}^i - \overline{q}_{obs})^2} \qquad (2.21)$$

where F^2 is the efficiency, q_{obs}^i is the observed flow in day i in m^3/s, $\overline{q}_{obs}$ is the average observed flow (m^3/s), and q_{calc}^i is the calculated flow in day i (m^3/s). The perfect value of this method is 100% meaning that the observed flow and the calculated flow have the same value for the entire simulation.

2.1.12 Presence in Literature

SLURP has been successfully employed in modeling several large and small rural catchments in Canada. SLURP was implemented initially in the 7,219 km^2 area of Kootenay River Basin in southeastern British Columbia (Kite, 1991). The SLURP model, calibrated for Kootenay basin, used daily data from January 1 to December 31, 1988. The model was tested using three kinds of data. In the first test, only ground data was used and without satellite data. In the second test, data used in the model were snow and cloud data from NOAA/AVHRR satellite, while the third test only used snow data, derived from satellite data. Verification was undertaken using daily data from 1 January 1989 to 31 July 1989. The test showed that the best result was obtained when the simulation was run using satellite snow cover data. It was also shown that using snow and cloud data derived from satellite data did not produce good results. Simulations using ground data produced even better results than others using snow and cloud data derived from satellite data. It is important to note that for this model, snow course data did not improve the output. The daily variation due to melt pattern, drifting snow, and location of snow courses caused large fluctuations in computed runoff.

Another implementation of the SLURP model in the Kootenay River Basin is in the area above Skookumchuck, a sub-basin of the Kootenay River Basin (Kite and Kouwen, 1992). The main goal of the research was to observe and compare the final hydrograph result produced by the SLURP application using a lumped application and a semi-distributed application. The classification of land cover in this research was undertaken by using a Landsat multi spectral scanner (MSS) image. This classification resulted in 3 types of land cover on the basin: bare ground, coniferous forests, and crop and grass type. ASAs were designed based on the similarity of area characteristics such as slope, aspect, soil type, vegetation type, elevation, and vegetation distribution. Computational elements were derived in two different ways. The first was by way of a grid system and the second was by sub-basin. The result of the research showed that the semi-distributed model resulted in a better hydrograph than the lumped model when compared to the observed hydrograph. Other advantages of using the semi-distributed-model was that the model can be more easily calibrated to the physical catchment and more easily transferred to other basins that have known distribution of land classes. The semi-distributed model can also be used to investigate the change of watershed behavior due to the change of watershed characteristics. If compared to a fully distributed model, computational and data requirements in semi distributed model are much less and the calibration process is much easier.

Research using data produced by general circulation models (GMCs) and the SLURP hydrological model for a macro scale watershed application was conducted in the Mackenzie River Basin. This basin is 1.6×10^6 km^2 in area (Dalton et. all., 1994) and was divided into five ASAs. A 1-km resolution land cover data was derived from NOAA AVHRR satellite imagery. The research was undertaken in three phases. The first phase involved deriving runoff for the Mackenzie River Basin from water balances of the Canadian Climate Centre GCM II at appropriate grid points. The second phase involved calibrating and verifying the SLURP model using 5 years of recorded climatology and hydrometric data for the Mackenzie River Basin. The last phase used the climatological outputs from CCC GCM II as distributed input data into SLURP. As the result, generating a hydrograph directly from the CCC GCM II did not give any satisfying simulation results. The runoff hydrograph from this simulation was nearly twice that of the observed hydrograph. The second phase of the research generated a good fit for the calibrated model. The Nash and Sutcliffe criterion had a value of 0.91. The last phase produced the best results. Compared with long term (1972-1990) mean monthly streamflow at station 10LC014 on the Mackenzie River, this simulation produced the minimum difference between calculated and observed hydrographs. The research of using GCM data in SLURP applications indicated a great improvement over using only the aggregate water excess from GCMs in producing streamflow hydrographs. It also confirmed the importance of having a realistic land phase model in future applications.

SLURP is a deterministic model that aims to maximize the use of remotely sensed data. The research for finding appropriate satellite data for estimating snow extent, snow water equivalent, and vegetation index to support SLURP applications in large watersheds was undertaken by G.W. Kite at the National Hydrology Research Institute in Saskatchewan (Kite, 1995). The application of SLURP in this research was undertaken as a part of a study to investigate design floods using detailed precipitation data from the Numerical Weather Prediction model as input to hydrological models. The upper Columbia Watershed with its 36,000 km^2 catchment had been chosen as the research area. The watershed was divided into 48 ASAs that have areas varying between 15 and 7300 km^2, with a mean area of 785 km^2. Land cover data was derived from Landsat MSS and NOAA AVHRR satellite images. Eight Landsat MSS images were classified into six land cover classes while there were 12 land classes obtained from NOAA AVHRR satellite images. The authors recommended using NOAA AVHRR in estimating snow extent and the DMSP SSM/I sensor for estimating snow water equivalent in the SLURP simulation model. But no appropriate remotely sensed data that can determine the vegetation index accurately could be ascertained. Based on that research, NDVI (Normalized Difference Vegetation Index) data derived from 1.1 km resolution AVHRR data was not enough for describing vegetation index in the entire watershed.

Stolte and van der Kamp (1999), proved that SLURP can be modified for specific water resources management purposes. They did research aiming to apply SLURP to small watersheds. SLURP was used to simulate water level variation in the wetland area in St. Dennis National Wetland Area, Saskatchewan. The study area was wetland #50 and its 3 hectare wide catchment area. SLURP, usually used for predicting flow in the river basin, had been modified and used for predicting water level in the wetland. There is no flow hydrograph produced in this case but a relationship between water level and time as the result of equations constructed by involving wetland surface geometry, water volume and water level. Furthermore, the modified now SLURP distinguishes between the coefficient of saturated permeability of the fast storage for unfrozen and frozen soils while the original SLURP considers those conditions to have same value of the coefficient of saturated permeability. Some parameters that were calibrated in this application were the infiltration coefficient of the fast storage under unfrozen and frozen conditions, slow storage water transfer coefficients, maximum storage of the fast storage, and maximum storage of slow storage. The general result of this research indicates that the model generates appropriate responses of the wetland water level due to variations in intensity and time of rainfall. This result indicates that the modified SLURP model has the potential to be used for exploring the effect of climate change and land use change on wetland resources in the future. The researchers suggested conducting more applications of the modified SLURP model in different hydrologic conditions and different wetlands.

Most recently, SLURP was implemented in the 21,000km^2 catchment of the Upper Assiniboine River Basin (Saskatchewan Water, 1999). The study was undertaken in order to evaluate the impact on the water resources in that area due to the changes in the drainage system and bush clearing practices. The study area covers about 21,000 km^2, with 79% in eastern Saskatchewan and the rest of the area is in western Manitoba. The study focuses on calibrating SLURP for 1990 conditions. The simulation results will be used to extend the relationship between wetland surface area and water storage volume to the entire range of water bodies in the basin. The relationship will then be employed to determine the changes in storage in the basin between the 1950 and 1990. A Digital Elevation Model (DEM) and land cover data are used. The calibration and verification processes of the basin however are still continuing in order to find the best set of parameters for Upper Assiniboine River Basin.

2.2 WATFLOOD Hydrological Model

The WATFLOOD model, sometimes called SPL8, was developed in 1972 by Nicholas Kouwen at the Department of Civil Engineering, University of Waterloo, Ontario (Kouwen, 1998). The WATFLOOD model is a physically based simulation model of watershed behavior established in FORTRAN77 for the IBM-PC. WATFLOOD is an integrated set of computer programs to forecast flood flows for watersheds having response times ranging from one hour to several weeks. Continuous simulation can be carried out by chaining up to 100 annual events. WATFLOOD uses Grouped Response Units (GRU) to preserve the distributed nature of hydrologic and meteorological variability in the watershed. Typically, WATFLOOD executes a 50,000 km^2 watershed with a 10 km grid, for a 1 year simulation in hourly time steps. The emphasis of the WATFLOOD system is on optimizing the use of remotely sensed data.

Radar rainfall data, and LANDSAT or SPOT landcover data can be directly incorporated in the hydrologic modeling (Kouwen, 1998).

2.2.1 Conceptual Representation of Watershed by WATFLOOD

Grouped Response Unit (GRU) is special term introduced by Nicholas Kouwen in order to describe watershed sub-division in the WATFLOOD hydrological model. GRU is the computational unit that is an element that may have a range of land cover characteristics (Kouwen et. al., 1993). The element consists of pixels, each having unique characteristics of land cover and physiographical data. The element size is usually limited to uniform meteorological conditions. The element travel time must be considered small if compared with the overall basin travel time or the duration of meteorological events observed. There are certain limitations to forming a GRU. The GRU must be square shape and the optimum area of the GRU varies with the time scale and the basin size. For hourly event models, GRUs can have areas as small as 4% of the whole basin area for large basins (> 3000 km^2) and 100% of the basin area for small basins (<100 km^2) (Tao and Kouwen, 1989). For daily continuous models in a watershed of 10,000 km^2, four or five GRUs may be sufficient (Kite and Kouwen, 1992). So far, the applications of GRUs for distributed models have been applied successfully in the Kootenay River Basin and the Columbia River Basin in Canada. Runoff in the GRU is generated by calculating runoff contributions from hydrologically unique land covers of each pixel in the element. Identical hydrologic parameters are used for the same land cover of all elements in the basin. In the GRU method, it is assumed that all pixels in the element receive the same hydrological stimuli but each pixel will respond to that stimulus uniquely. Based on that circumstance, pixels in a GRU are grouped based on their land cover similarity. For example, one GRU contains 25 pixels that consist of 9 pixels of land cover A, 10 pixels of land cover B, 2 pixels of land cover C, and 4 pixels of land cover D. This means that the element has 36%, 40%, 8%, and 16% of land cover A, B, C, and D respectively. The hydrological processes of each group are modeled identically. The hydrological response of the GRU is determined by the response of each group according to the percentage of each group. Runoff produced is the sum of each group and routed to the stream network. Routing is calculated separately by considering topographical factors and land cover. Figure 2.3 explains the presentation of watershed sub-division using the GRU concept.

2.2.2 Vertical Water Balance in WATFLOOD

Figure 2.4 displays a simplified system of the vertical water balance that the WATFLOOD model employs to each land cover within each GRU. The system consists of four areas of calculation. They are *the atmospheric area, surface area, and subsurface area consisting of the upper zone and lower zone*. The vertical water balance in WATFLOOD operates at an hourly time step.

2.2.3. Evapotranspiration and Interception

Evapotranspiration rates in WATFLOOD are derived from a potential evapotranspiration (PET) value. There are two methods recommended for calculating PET: the Priestley-Taylor method and the Hargreaves method. The Priestley-Taylor method is used when radiation data is available while the Hargreaves method is used when only temperature data is available. For the Priestley-Taylor equation, PET is formulated as follows (Priestley and Taylor, 1972):

$$PET = \frac{\alpha(sT_a)(K_n + L_n)}{(\gamma + (sT_a))\rho_w \lambda_v} \qquad (2.22)$$

where α is a Priestley-Taylor coefficient, K_n is the short-wave radiation (energy/area/d), L_n is the long-wave radiation (energy/area/d), sT_a is the slope of the saturation-vapour pressure versus temperature curve (kPa/°C), γ is the psychrometric constant (kPa/°C), ρ_w is the mass density of water (t/m^3), and λ_v is the latent heat of vaporization (kcal/kg).

The Hargreaves method, on the other hand, is actually an empirical formulation with some modifications (Hargreaves and Samani, 1982). The equation is explained as:

$$PET = 0.0075 R_a C_t \delta_t^{0.5} \overline{T} \qquad (2.23)$$

where **PET** is the Hargreaves potential evapotranspiration (mm/d), R_a is the total incoming in the same units as evaporation (mm for WATFLOOD), C_t is a temperature reduction coefficient, δ_t is the difference between the mean monthly maximum and mean monthly minimum temperatures (°F), and $\overline{T}$ is the mean temperature in the time step (°F). The temperature reduction coefficient, C_t, is a function of relative humidity, w_a (%), that takes the form:

$$C_t = \frac{0.035(100 - w_a)}{3} \qquad \text{for } w_a \geq 54\% \qquad (2.24)$$

$$C_t = 0.125 \qquad \text{for } w_a < 54\% \qquad (2.25)$$

The total incoming extraterrestrial solar radiation, R_a, can be derived from the empirical equation as follows:

$$R_a = 15.392 d_r (w_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin w_s) \qquad (2.26)$$

where **ϕ** is the latitude (degree), and $\mathbf{d_r}$ is the relative distance between the earth and the sun given by:

$$dr = 1 + 0.033\cos\frac{2\pi J}{365} \tag{2.27}$$

where **δ** is the solar declination (radians) defined by:

$$\delta = 0.4093\sin(\frac{2\pi J}{365} - 1.405) \tag{2.28}$$

$\mathbf{w_s}$ is the sunset hours angle (radians) given by

$$w_s = \arccos(-\tan\phi\tan\delta) \tag{2.29}$$

and **J** is the Julian day.

Once the value of **PET** is obtained, the actual evapotranspiration rate, **AET**, can be calculated by using several equations involving Interception, **IET**. **IET** is basically a function of **PET**. The relationship between both of them is given by:

$$IET = f_{pet}PET \tag{2.30}$$

where $\mathbf{f_{pet}}$ is the evapotranspiration factor. This factor is 1.00 during the precipitation event but can range between 1.0 and 4.0 after rainfall cessation. Equation (2.31) is used to calculate **AET** if the value of **PET** is less than **IET**. The equation takes the form:

$$AET = PET \tag{2.31}$$

This equation is also used for the parts of the watershed that are water. If the **PET** is more than **IET**, the formulation change to the equation is as follows:

$$IET = f_{pet2}f_{tall}UZSI(PET - IET) \tag{2.32}$$

where **UZSI** is the upper zone storage indicator, $\mathbf{f_{pet2}}$ is the reduction coefficient based on the total number of degree-days, and $\mathbf{f_{tall}}$ is the forest vegetation coefficient. **UZSI** can be obtained by:

$$UZSI = \left(\frac{UZS - PWP}{SAT - PWP} \right)^{0.5} \quad (2.33)$$

where **UZS** is the amount of soil moisture in the upper zone soil (mm), **PWP** is the amount of soil moisture at permanent the wilting point (mm), and **SAT** is the amount of soil moisture at a level of saturation (mm). The **PWP** can be estimated by:

$$PWP = FFCAP \frac{RETN}{FCAP} \quad (2.34)$$

where **FFCAP** is the percent soil moisture at the permanent wilting point, **RETN** is the upper zone specific retention (mm), and **FCAP** is the field capacity (mm). **SAT** can be obtained by:

$$SAT = SPORE \frac{RETN}{FCAP} \quad (2.35)$$

where **SPORE** is the percent soil moisture at the saturation point (%) and **RETN** is the ratio of the retention factor.

f_{pet2} is calculated based on the total number of degree-days (**TTO**) that are accumulated to explain the seasonal heating of the soil with the function being defined by three other values. The **TTO** value is used for determining the values of **T1**, **T2**, and **T3**. **T1** and **T3** represent the lower and the upper limits of the relationship. **T2** is set between **T1** and **T3**. In detail, the relationship between **f_{pet2}**, **TTO**, **T1**, **T2**, and **T3** is given by:

$$f_{pet2} = \frac{(T2 - T1)}{(T3 - T1)} \qquad \text{if TTO} > \text{T2} \qquad (2.36a)$$

$$f_{pet2} = \frac{(TTO - T1)}{(T3 - T1)} \qquad \text{if T2} < \text{TTO} < \text{T3} \qquad (2.36b)$$

$$f_{pet2} = 1 \qquad \text{if TTO} > \text{T3} \qquad (2.36c)$$

where $\mathbf{f_{tall}}$ is a function of vegetation type. The value of $\mathbf{f_{tall}}$ is recommended as 0.70 and 1.00 for tall vegetation and short vegetation, respectively. In case **IET** = 0 the formulation of **AET** is given by:

$$AET = UZSIf_{pet2}f_{tall}PET \qquad (2.37)$$

2.2.4. Depression Storage

The runoff process is started by the process of rainfall water stored in depression storage (**D_s**). The amount of water in the depression storage in WATFLOOD is calculated as follows:

$$D_s = S_d(1 - e^{-kPe}) \qquad (2.38)$$

where **S_d** is the surface detention storages (mm), **Pe** is the accumulated rainfall excess (mm), and **k** is constant. The ASCE Manual of Engineering Practice No. 37 for the design of sanitary and storm sewers (Kouwen, 1997) gives typical values of **S_d** for various surface type as follows:

- Impervious Urban Areas = 1.25
- Pervious Urban Areas = 3.00
- Smooth Cultivated Land = 1.30 – 3.00
- Good Pasture = 5.00
- Forest Litter = 8.00

2.2.5 Snowmelt

In WATFLOOD, snowmelt process is calculated using the temperature index algorithm. The algorithm is given by following equation (Anderson, 1976):

$$M = MF(T - TBASE) \qquad (2.39)$$

where **M** is the daily snowmelt depth (mm), **MF** is the rate of melt per degree per unit time or Melt Factor (mm/°C/h), **T** is temperature (°C), and **TBASE** is the temperature at which the snow begins to melt (°C).

2.2.6 Surface Runoff

When the depression storage is full, the excess rainfall will become surface runoff. In WATFLOOD, the discharge of surface runoff or overland flow is calculated by using Manning's formula and takes the form:

$$Q = (D - D_{sc})^{1.67} S \frac{A}{R_3} \tag{2.40}$$

where **Q** is the channel flow (m^3/s), **D** is the depth of water in the soil surface (mm), $\mathbf{D_{sc}}$ is the depression storage capacity (mm), **S** is the square root of average overland slope, **A** is the area of the basin element (m^2), and $\mathbf{R_3}$ is the combined roughness and channel length parameter.

2.2.7 Infiltration

Water that is stored in depression storage, some surface runoff and some rainfall, will together flow vertically and become infiltration water. The infiltration process is one of the most important processes in hydrologic modeling due to its role in runoff calculation. In WATFLOOD, the infiltration rate is calculated by using Phillip's equation (1954) as:

$$\frac{dF}{dt} = \frac{K_s[1 + (m - m_0)(C + D_{sc})]}{F} \tag{2.41}$$

where **F** is total depth of infiltrated water (mm), **t** is time (s), **K_s** is saturated conductivity (mm/s), **m** is moisture content (mm), **m_o** is initial moisture content (mm), **D_{sc}** is the depression storage capacity (mm), and **C** is capillary potential at the wetting front (mm). Some infiltrated water is filling the upper zone storage (**UZS**) and the other portion is exfiltrated to nearby watercourses and called interflow (**QINT**), or percolate downward into the lower zone. In WATFLOOD, interflow is calculated as follows:

$$QINT = REC \times UZS \tag{2.42}$$

where **REC** is the interflow coefficient that cannot be predicted and can only be obtained by optimization. Water that percolates into the lower zone is called upper zone drainage (**DRNG**) and calculated by:

$$DRNG = AK_2(UZS - RETN) \tag{2.43}$$

where **AK_2** is an intermediate zone resistence parameter and **RETN** is the specific retention of the soil in upper zone. Both of these parameters are optimized parameters.

2.2.8 Base Flow

The last component of the runoff is base flow. Base flow in WATFLOOD is considered lower zone discharge. Base flow is calculated as:

$$QLZ = LZF \times LZS^{PWR} \tag{2.44}$$

where **QLZ** is the base flow (mm/d), **LZF** is the lower zone drainage function parameter, **LZS** is the lower zone storage (mm), and **PWR** is the lower zone drainage exponent. The initial base blow is determined from hydrograph measurements at the basin outlet. Since the base flow has been calculated, the total runoff of the basin can be calculated by adding the surface runoff, the interflow, and the base flow. This flow is later added to the channel inflow of the downstream basin element.

2.2.9 Routing Model

Routing in WATFLOOD is undertaken using a storage routing method. This simple model is chosen because it produces roughly the same accurate forecasting as other more sophisticated models in the application. In fact, resulting differences between routing methods may well be smaller than the differences due to the data variation (Ponche,1991). Using different methods of routing may change the time travel in the hourly basis. This condition will not significantly affect the daily average runoff as the result of WATFLOOD simulations. Simple routing minimizes calculations and uses river cross section, and profile data. The method is the straightforward application of the continuity equation given by:

$$\frac{(I_1 + I_2) - (O_1 + O_2)}{2} = \frac{(S_2 - S_1)}{dt} \qquad (2.45)$$

where $\mathbf{I_1}$ and $\mathbf{I_2}$ are inflow to the reach consisting of overland flow, interflow, base flow, and channel flow from all contributing basin elements (m^3/s), $\mathbf{O_1}$ and $\mathbf{O_2}$ are outflow from the reach (m^3/s), $\mathbf{S_2}$ and $\mathbf{S_1}$ are storage in the reach (m^3), and **dt** is the time step of the routing. The subscripts 1 and 2 indicate the quantities at the beginning and at the end of the time step. The relationship between flow and storage is explained by Manning's formula:

$$Q = \frac{1}{n}(AX)^{1.33} S_c^{\ 0.5} \qquad (2.46)$$

Where Q is the flow (m^3/s), **n** is the channel roughness parameter, **AX** is the channel cross section area that is related to storage by dividing the storage by the channel length (m), and S_c is the channel slope.

2.2.10 Data Requirements

For conducting watershed simulations using WATFLOOD, three groups of data have to be prepared and organized into files, each with a specific extension. The first group of data, watershed physiographic data, can be derived from either remotely sensed data or ground truth data. Data derivation is undertaken in the program called Maputil. Files included in the group of watershed physiographic data are:

a) <Basin_name.MAP> contains all the watershed data in a grid format;
b) <Basin_name.SHD> is a conversion of the MAP file that can be read by WATFLOOD for watershed simulations.

The second group of data, watershed parametric data, contains WATFLOOD parameters, and the location of climate and hydrometric stations on the watershed. The files of watershed parametric data are presented in following manner:

a) <Basin_name.PAR> contains all the parameters for WATFLOOD;
b) <Basin_name.SDC> contains the snowcover depletion curves for each land cover class;
c) <Basin_name.DAT> contains a table of climatic monthly evaporation;
d) <Basin_name.STR> contains the coordinates for the hydrometric stations, reservoirs, and lake outlet location;
e) <Basin_name.RAG> contains the coordinates for the precipitation, snow course, and temperature stations;
f) <calmet.PAR> is a parameter file for radar data calibration program;
g) <weight.PAR> is a parameter file for radar and rain gauge calibration program.

The third group of data is the time series data. The interval of data measurement can be daily, hourly, or any other interval determined by the modeler such as 4-hour and

6-hour intervals. As in the previous group of data, time series data are also specified in the specific files. They are:

a) <Initial_date_of simulation.RAG>, is the rain gauge data file;
b) <Initial_date_of simulation.STR>, is the streamflow data file;
c) <Initial_date_of simulation.REL>, is the reservoir release file;
d) <Initial_date_of simulation.SNW>, is the snow data file;
e) <Initial_date_of simulation.MET>, is the precipitation file;
f) <Initial_date_of simulation.SCN>, is the radar file;
g) <Initial_date_of simulation.CLT>, is the Clutter data file;
h) <Initial_date_of simulation.TAG>, is the point temperature data file;
i) <Initial_date_of simulation.TEM>, is the grid temperature data file.

It is necessary to note that not all of this data has to be available. In the case that radar precipitation data do not exist, the simulation can still be undertaken by using rain gauge data.

The event file, specified as <Initial_date_of simulation.EVT>, is one type of file that has to be established before running the simulation. The event file contains a list of all the files that relate to a specific event. All WATFLOOD programs refer to this file to determine which files are active. This file organizes all files related to the running of WATFLOOD.

Like in SLURP, the watershed simulation process in WATFLOOD is essentially a water balance process where precipitation, evaporation, infiltration, surface and subsurface runoff, and snow storage are functions of the runoff process.

2.2.11 Calibration of the Parameters

The calibration process in WATFLOOD is undertaken by optimizing the parameters. A sensitivity analysis is required in order to determine what parameters should be calibrated. Statistical criteria are used to test the goodness of fit of the

WATFLOOD model. Testing the goodness of fit of WATFLOOD in this thesis is undertaken using the Nash and Sutcliffe efficiency method.

2.2.12 Presence in Literature

Like the SLURP model, WATFLOOD has been employed successfully in modeling several catchments in Canada. WATFLOOD was used by The University of Waterloo in a series of collaborative studies held by Numerical Prediction Research (RPN) of Atmospheric Environment Service of Environment Canada, the National Water Research Institute (NHRI) and the Atmospheric Dynamics Corporation (ADC) to test a new generation of high-resolution models for simulating and forecasting precipitation and runoff (Kouwen, 1998). In this research WATFLOOD was used as a hydrologic model for flood forecasting for a major portion of the Columbia River Basin in British Columbia. The general objective of this study was to validate both the numerical weather data generated by RPN and ADC as well as the WATFLOOD system itself. Meteorological data used for WATFLOOD simulations in this study were distributed precipitation and temperature time sequences data generated by several meteorological models. The data was divided into two periods. The first period, from April 1 to August 31, 1983, was generated with Atmospheric Dynamics Corporation's High-resolution Variational Model. The second period was from April 1 to August 31, 1990 and modeled with Recherche en Prevision Numerique's Regional Finite Element Model (RFE) and the newer Mesoscale Compressible Community Model (MC2). The results of the study showed that WATFLOOD is adequate in simulating the basin. Except for a few streamflow stations, the computed flows produced by WATFLOOD matched the observed flows well (Kouwen, 1998).

Additional research aimed to apply the Grouped Response Unit in predicting water behavior in a wetland region (Pietroniro, et.all, 1996). Several river basins such as Jean-Marie River, Martin River, and Birch River were chosen as study sites for this research. The model was calibrated for the basins using daily data for year 1989 and validated by using daily data for the years 1990 and 1991. Validation tests of the research indicated that the parameters set by WATFLOOD had several deficiencies for applications in cold regions that are northern and wetlands. The problem of the limitations of sparse data networks of the study area was highlighted.

In another implementation, the WATFLOOD model was used to model extreme flood conditions in the Columbia River Basin (Luo, et.al., 1998). The main goal of the research was to compare the use of distributed applications and lumped applications in exploring historical floods and extreme floods such as the Probable Maximum Flood (PMF) for dam safety. The simulation results of two hydrological models: The SSARR model and the UBC Watershed model were used for comparison in this study. WATFLOOD was calibrated and validated with the 1972 – 1994 streamflow data from 32 tributaries over the Columbia River Basin. The results of the comparison demonstrated that the WATFLOOD model is more advantageous in assembling basin-related physical information, displaying spatial variability of the meteorological input data and runoff routing process, and reflecting more extreme flood characteristics in the model calibration.

WATFLOOD was involved in BOREAS project from 1993 to 1996 (Soulis et.al., 1997). In this project WATFLOOD was chosen by the BOREAS Hydrology Group – 09 for simulating the space-time distribution of the snow and subsequent meltwater within the Southern Study Area (SSA) and Northern Study Area (NSA). Streamflow data for 1994 to 1996 was used to calibrate and validate WATFLOOD in this study. Meteorological data was obtained from the BOREAS meteorological stations distributed in the area. Ground cover data were derived from classified LandSat imagery. Eight watersheds, three in NSA and five in SSA, were modeled by WATFLOOD. The initial conditions were defined from previous meterological data, snow course data, snow cover extent from remote sensing and, indirectly, from streamflow. Very good hydrograph fits were produced in by WATFLOOD for all of the stations. The effects of initial errors in predicting initial storages decreased over time.

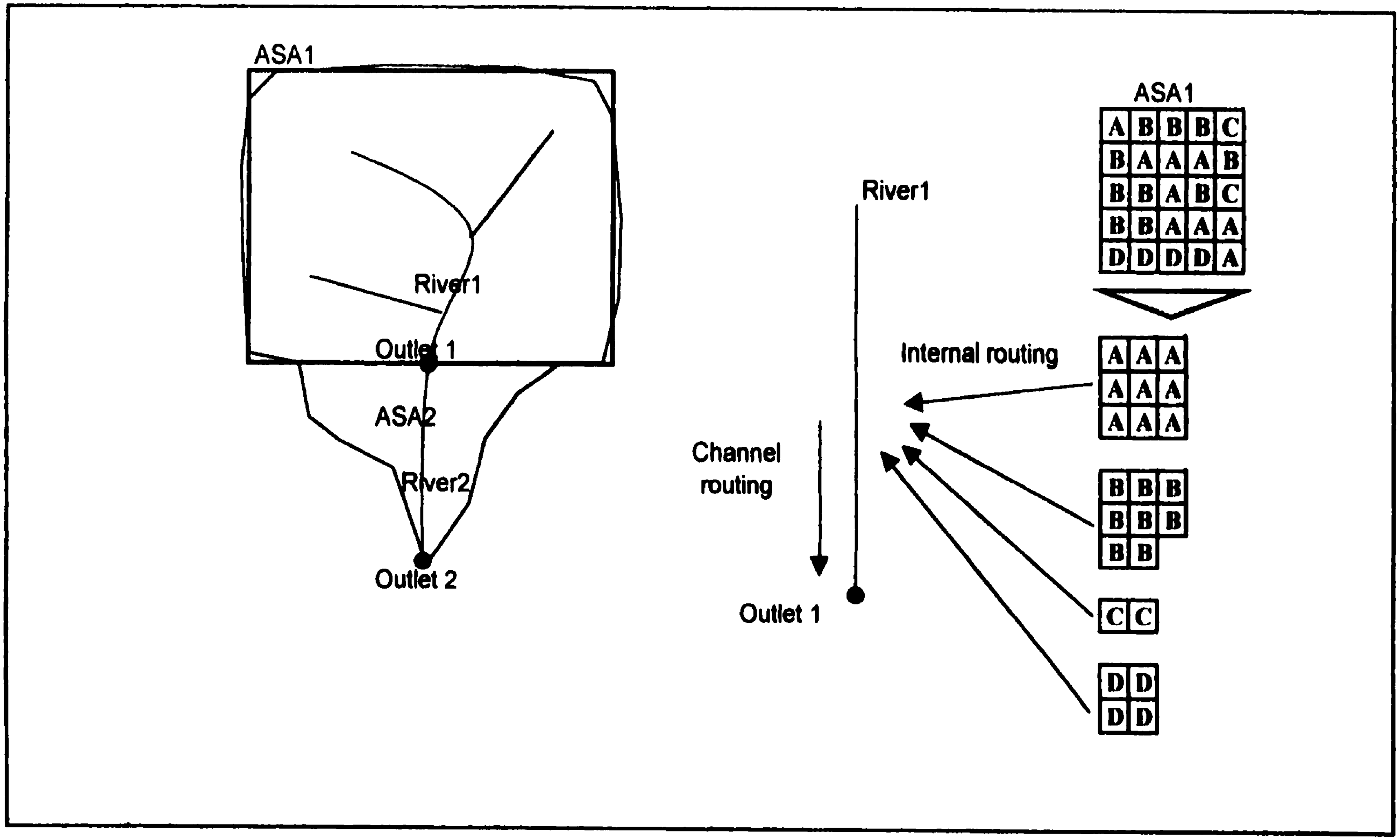


Figure 2.1 Presentation of Watershed Sub-division Using ASA concept (modified from Kite, 1997)

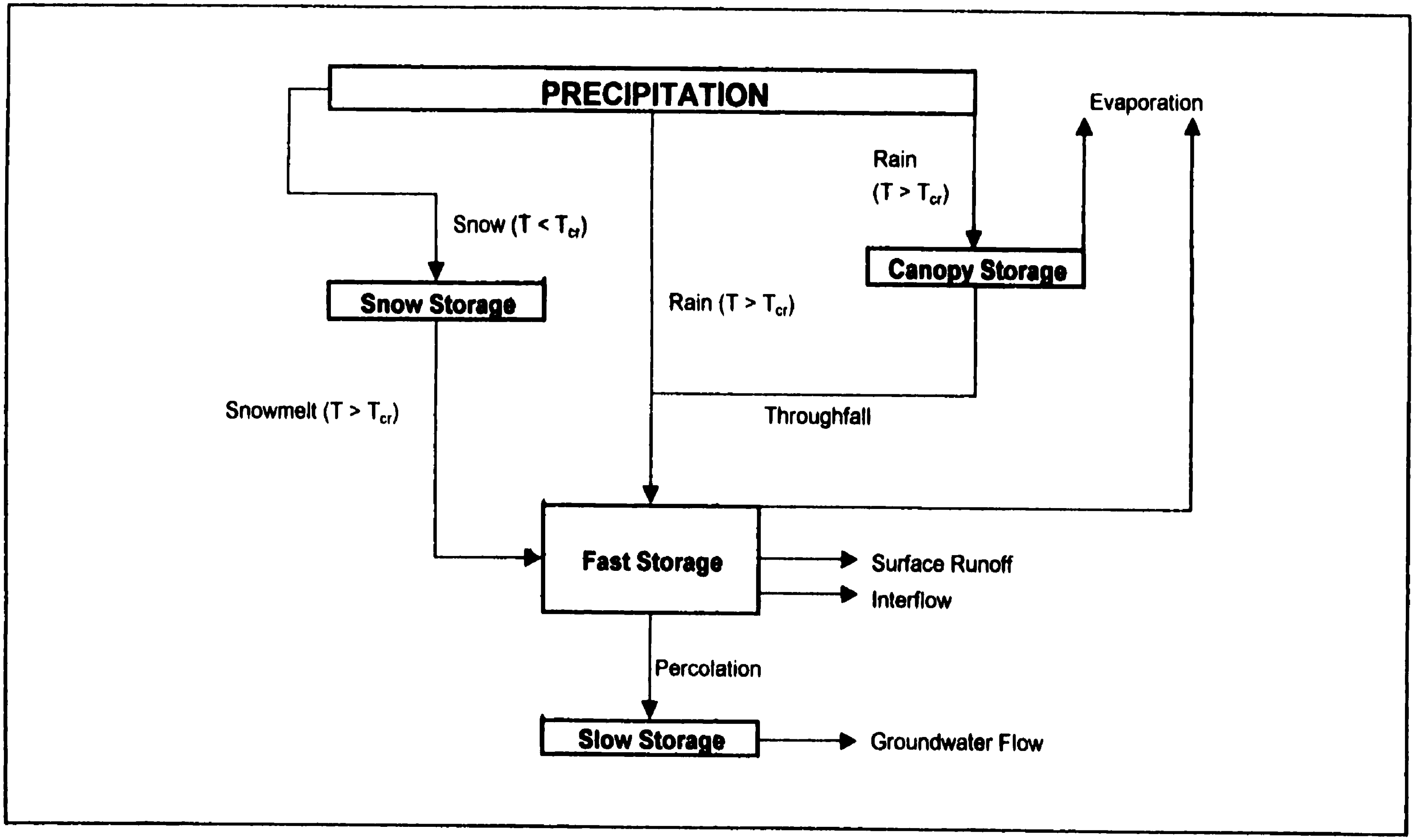


Figure 2.2 Simplified System of SLURP Vertical Water Balance (modified from Kite, 1997)

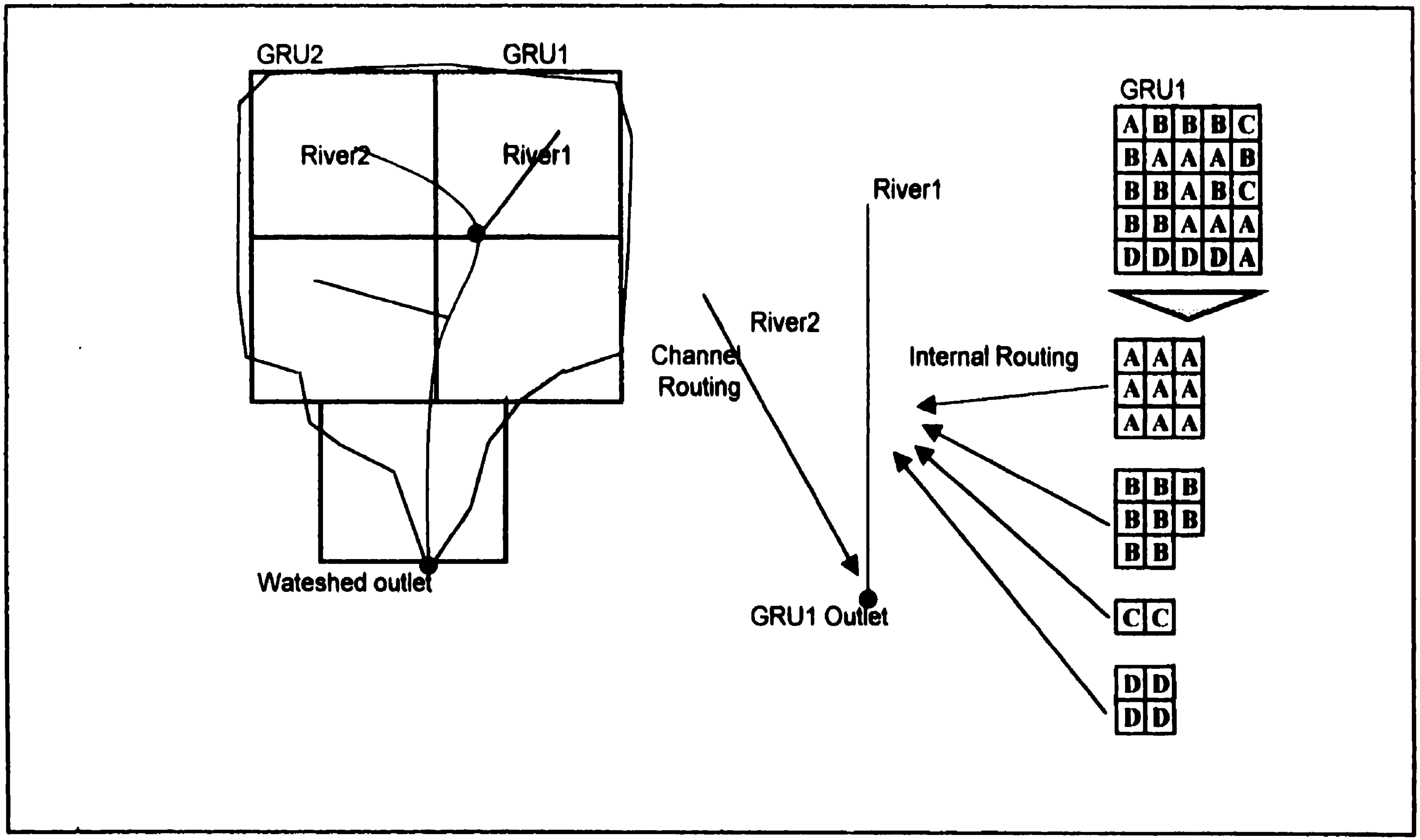


Figure 2.3 Presentation of watershed sub-division using GRU concept (modified from Kouwen, 1997)

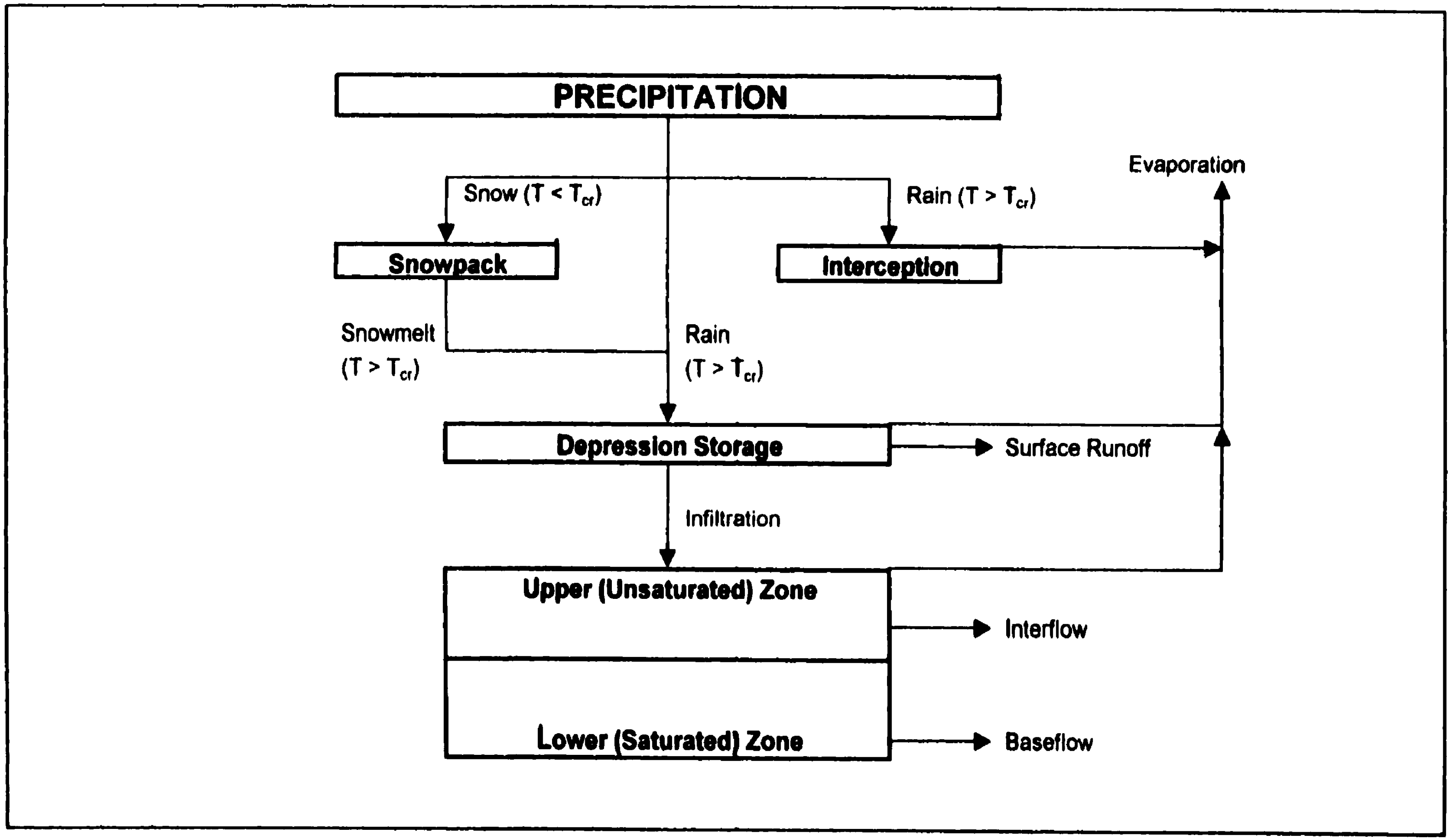


Figure 2.4 Simplified System of WATFLOOD Vertical Water Balance (modified from Kouwen, 1997)

CHAPTER 3: STUDY AREA BACKGROUND

This chapter presents a description of the study area used in this research. The meteorological parameters, watershed parameters, and hydrometric parameters of the Sapochi River Basin are presented in the last part of the chapter.

3.1 Overview of the Sapochi River Basin

The Boreal Ecosystem-Atmosphere Study (BOREAS) is a large-scale international interdisciplinary experiment in the northern boreal forests of Canada. BOREAS focuses on investigations of the exchanges of radiative energy, sensible heat, water, CO_2 and trace gases between the boreal forest and the lower atmosphere. The main goal of BOREAS is to collect data in order to support modeling of the important processes controlling these exchanges and to support scientists in anticipating the effects of global change. The BOREAS study areas are the Northern Study Area (NSA) and the Southern Study Area (SSA). The Sapochi River Basin geographically is located in the BOREAS - NSA area (see Figure 3.1).

NSA is an area of 8,000 square km, located between Thompson Manitoba and Nelson House Manitoba. The area is bordered by longitude and latitude coordinates – 98.82 and 56.247 NW; -97.24 and 56.081 NE; -97.49 and 55.377 SE; and –99.05 and 55.540 SW, respectively. All of the NSA is forested with no population or agriculture.

The NSA represents the extreme northern boreal forest type. The terrain is mild with a small number of lakes. Black spruce is the dominant vegetation in the NSA. It occurs in stands of varying density such as in bogs, drier lichen and occasional rock outcrops. The forest can be categorized as mature forest indicated by some trees aging more than 100 years old. The tree heights vary from small black spruce in bog areas to 15m high trees. Aspen occurs only in very small patches (BOREAS, 1999). The surface topography of the NSA is flat with abundant wetlands. There are bare rock outcrops on the top of hills and some areas of discontinuous permafrost. Pre-Cambrian gneissic granite that has been glacially polished is the dominant underlying bedrock. Generally, drainage of much of the area is poor. The two main rivers in this area are the Sapochi and Odei Rivers with several significant tributaries. There are some large lakes (2x15 km^2) to the north and northwest of the area.

The climate type is mid-continental and the average annual precipitation is between 410 and 500mm, with 120 to 160 days of precipitation. About two thirds of them fall between April and September. The month of July, with 93.1 mm of total precipitation, is the month that has the highest total precipitation. The lowest total precipitation occurs in the month of February, with 9.7 mm of total precipitation (Environment Canada, 1982). The temperatures range from about 5° C to 21° C and -26 °C to -8 °C in the summer and winter, respectively. The average of the highest temperature is 19.4 ° C occurring in the month of July and the lowest is –24.7 ° C occurring in the month of January. Approximately 90 days of the year are frost-free days in the area (Soulis, et.al, 1997).

Five primary meteorological stations in the NSA are:

a) Beaver Pond (NSA-BP), a flux tower on a small lake;
b) Fen (NSA-Fen), a flux tower in a swampy wetland area;
c) Old Black Spruce (NSA-OBS), a flux tower in an area of old growth black spruce (wet soil);

d) Old Jack Pine (NSA-OJP), a flux tower in an area of old Jack Pine (dry soil);
e) Young Jack Pine (NSA-YJP), a flux tower in an area of young Jack Pine (dry soil).

With these stations, several supplementary sites are also supported in the NSA. They are:

a) BOREAS Operations (NSA-Ops) at the Thompson Airport;
b) Upland Black Spruce (NSA-UBS) a canopy access tower in a small stand of spruce;
c) Old Aspen (NSA-OA) -- Canopy access tower in a large stand of old Aspen trees.

3.2 Watershed Physiographic and Parameter Data

The Sapochi River Basin is located about 40 km from Thompson Manitoba in the northwest direction. The Sapochi River is an intermittent river with about 32 km of main streamflow and a drainage area of 444.11 km^2. It flows in the Northeast direction and ends in the Odei River. The Sapochi River basin cover purely consists of boreal forest area and is an unregulated basin. The basin is flat near the downstream end and has many wetlands in the upstream. Due to this topographic condition, the Sapochi River Basin drainage system is poor. As a part of the NSA area, the Sapochi River Basin has land cover consisting of boreal forest and land that is dominated by bog and marsh. Gray Luvisol type of soil is the most dominant soil type on that area. The predominant species is black spruce scattered in stands of irregular density. It occurs in bogs, drier lichen covered sites and occasional rock outcrops. There are some jack pine stands in the Sapochi River Basin.

Watershed physiographic data available on Sapochi River Basin include a digital elevation model (DEM) map and land cover map. The DEM, created by HYD-08 team, were produced from digitized contours at a cell resolution of 100 meters. Vector contours of the area were used as input to a software package that interpolates between contours to create a DEM representing the terrain surface. The vector contours have a contour interval of 7.62 m. The data cover for the BOREAS NSA is given in a UTM map projection. The data are stored in binary, image format files and were obtained from the BOREAS web site on the internet.

The land cover map was developed as part of a multitemporal 1-km AVHRR land cover analysis approach. The land cover classification was derived by using regional field observations from ground and low-level aircraft transits. The data are stored in binary, image format files.

Some of the watershed parameters for the Sapochi River Basin in this thesis are obtained from the typical parameters values for different land cover types given in the SLURP hydrological model manual and others are determined in the calibration process. Typical parameter values are presented in Table 3.1.

3.3 Meteorological Data

The snow cover season in the Sapochi River Basin is 160 to 200 days a year. Summer is approximately 40 to 80 days with 1800 to 2000 hours of bright sunshine. The Sapochi River Basin is monitored by all of NSA's meteorological measurement sites except for the Beaver Pond site. Data supplied by the sites were collected between 1993 and 1996 and are classified into meteorological data and radiation data. The data were provided in 15-minute or 1-hour intervals of measurement and can be accessed from the BOREAS web site in the internet. In this research, data is managed at a daily time-step. The types of data are:

a) Temperature data
b) Surface pressure data
c) Relative humidity data
d) Wind speed data

e) Rainfall data
f) Snow depth data
g) Radiation data
h) Soil temperature data

The meteorology data obtained from the Old Black Spruce (OBS) site (see Figure 3.2) is the most representative data of the Sapochi River Basin due to the position of the station in the basin. Therefore, the meteorology data used in this research are mostly taken from this station.

3.4 Hydrometric Data

The streamflow of the Sapochi River Basin is measured by three hydrometric stations. They are NW1, NW2, and NW3 stream gauge stations. The NW1 station, also called Sapochi (05TF005) station, is located at the Highway 391 bridge with coordinates 55°54'26" N of latitude and 98°29'40" W of longitude. The station captures a 433 km^2 drainage area of the Sapochi River. The NW2 station is located at latitude 55°54'55" N and longitude 98°31'39" W. It measures streamflow from a 35 km^2 drainage area of the of Sapochi River and the NW3 station monitors a 31 km^2 drainage area. The latitude coordinate of the NW3 station is 55°55'01" N and the longitude is 98°22'32" W. Streamflow data of the three stations is stored in the HYDAT CD-ROM produced and distributed by Environment Canada. The data used are daily and range between year 1993 and 1998.

Due to the limitations of the climate data collection periods, watershed simulations in this research are only undertaken for the year of 1994 and 1995. The streamflow data used for calibration in this research is NW1 station data for 1994. The streamflow daily data of 1995 is used for verification purposes. The use of streamflow daily data of 1995 for calibration purposes is also undertaken in order to compare results between calibrations conducted in 1995 and 1994.

Table 3.1 Watershed Typical Parameter Values for SLURP Application (Kite, 1997)

Parameter	Landcover				
	Deciduous Forest	Coniferous	Mixed	Crop or Grass	Bare Soil
Wilting point as fraction of soil water (%)	0.10	0.10	0.10	0.10	0.10
Field capacity as fraction of soil water (%)	0.50	0.50	0.50	0.50	0.50
Albedo	0.15	0.12	0.14	0.20	0.25
Conductivity (mm/d)	0.20	0.20	0.20	0.20	0.20
Saturated infiltration (mm/d)	45.00	45.00	45.00	40.00	1.00
Average snowmelt rate (mm/d)	2.00	2.00	2.00	10.00	10.00
Winspeed (ftcn)	25.00	25.00	25.00	17.00	12.00
Interception coefficient *A*	1.00	0.80	0.90	1.26	1.26
Interception coefficient ***B***	12.00	9.00	10.00	15.00	15.00

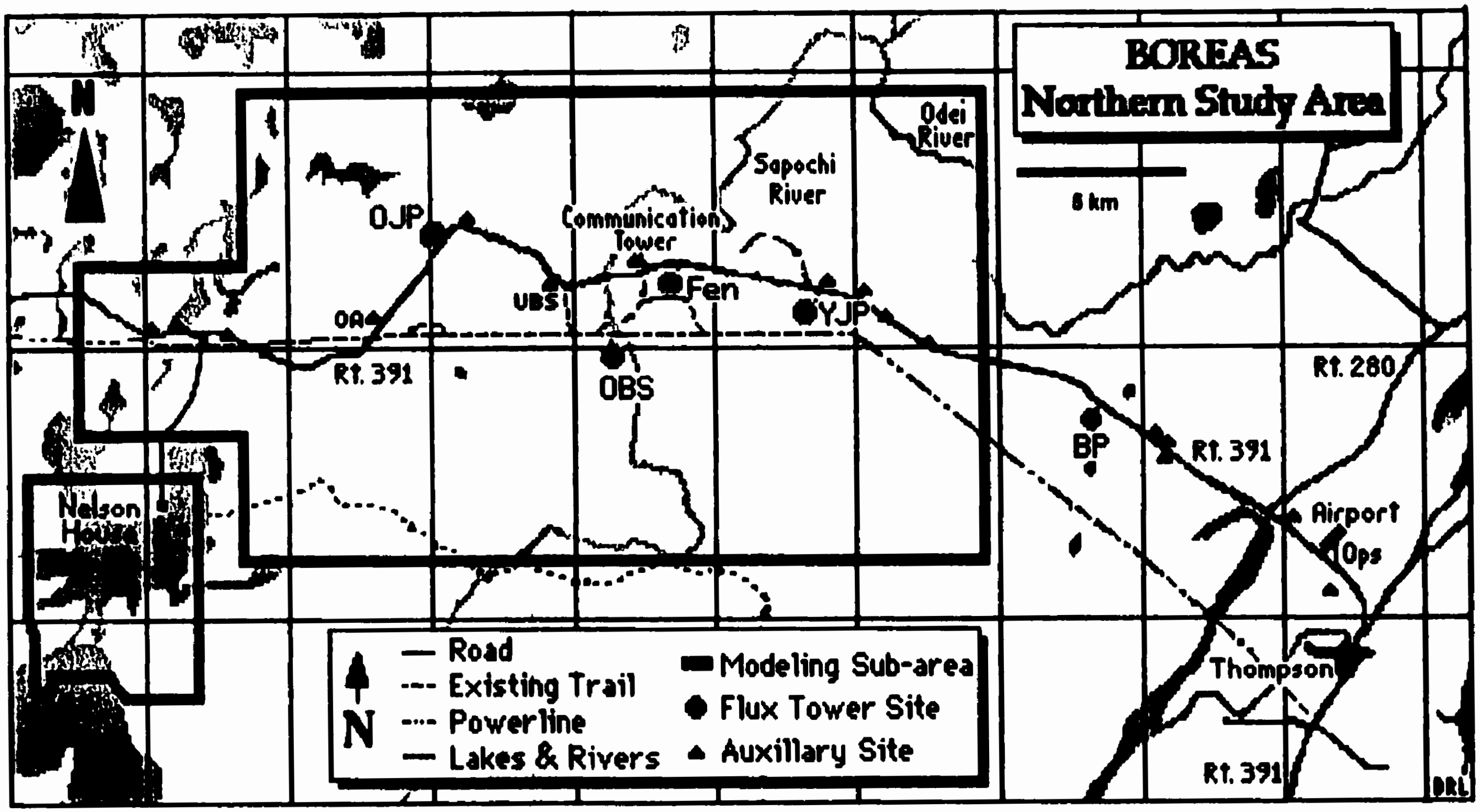


Figure 3.1 BOREAS Northern Study Area (NSA) (Derived from the BOREAS Website)

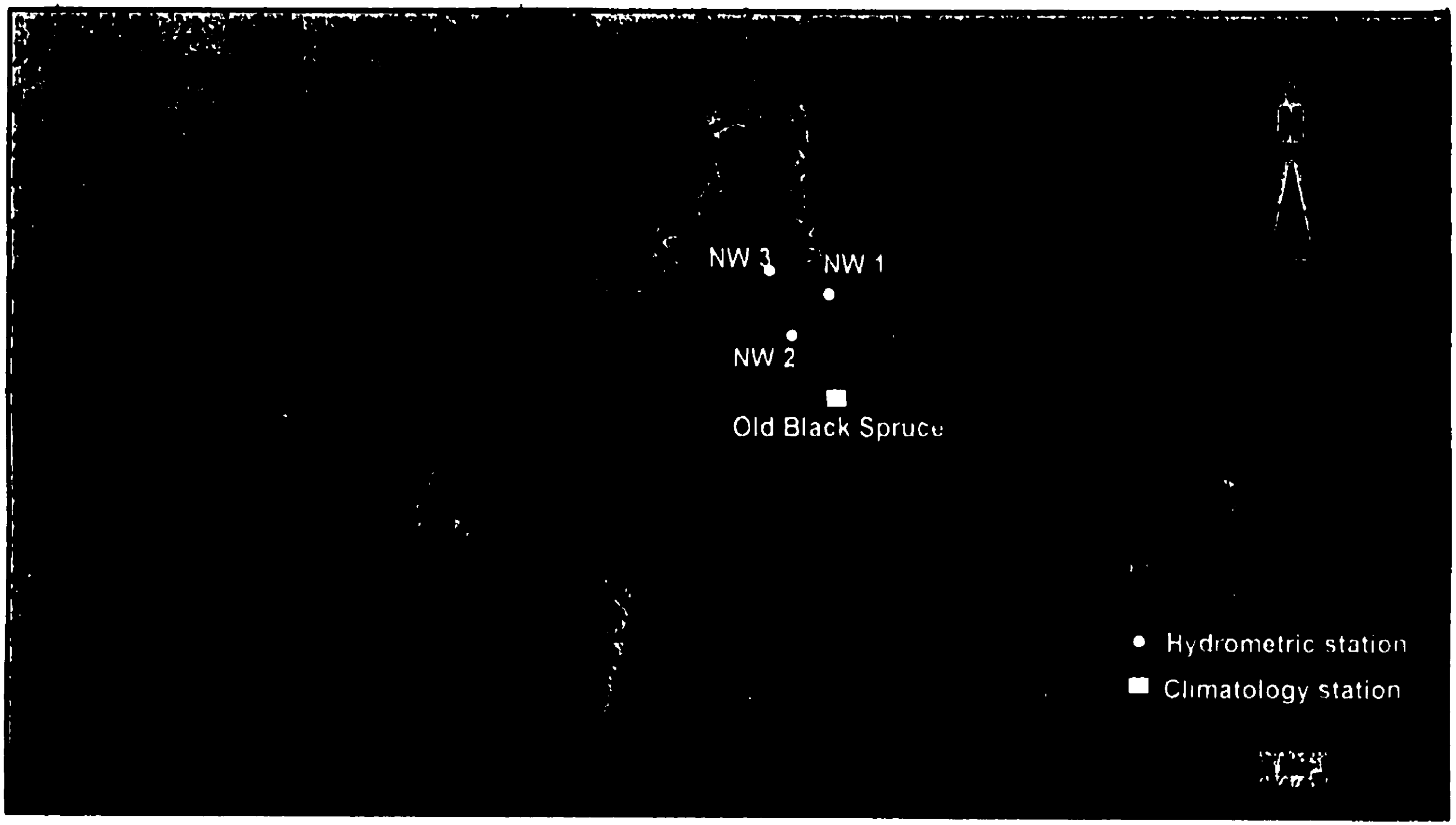


Figure 3.2 Hydrometric and Climatology Stations in the Sapochi River Basin

CHAPTER 4: APPLICATION OF THE MODELS

This chapter consists of three sections. The first section reports the application of the SLURP model to the Sapochi River Basin. The second section reports the application of the WATFLOOD model to the same river basin. The third section discusses a comparison and evaluation of the application of SLURP and WATFLOOD models in the Sapochi River Basin.

4.1 SLURP Model Application in the Sapochi River Basin

4.1.1 Data Preparation

The first step in preparing data for the basin is to derive the physiographic data from topographical and landcover maps. In this thesis, physiographic data derivation is conducted by using a digital elevation model and a landcover map. Both are managed by Slurpview (Fast, 1999b), an extension of the ArcView GIS software.

The second step in data preparation is to estimate the model parameters. The model parameters control the way in which the model transforms precipitation into runoff through processes such as interception, infiltration and snowmelt. These input data, together with physiographic data, are later saved in the command file. The command file can be updated each time the user runs SLURP. An example of the command file developed for the Sapochi River Basin is shown in Figure 4.1.

The first line in the command file explains that the SLURP model is run for one

ASA with two landcover types for the period of April to October 1994. The following characters define a series of run control options. The evaporation method and the type of model output are included in this part. Line two defines the ASA's parameters and landcover percentages. Line three specifies the ASA's properties such as canopy and snowmelt rates. Line four and line five contain data for within ASA routing of each landcover type. Line six consists of data related to the between ASA routing. Line seven accommodates data for evapotranspiration calculations, and line eight consists of Leaf Area Index (LAI) data for certain types of land cover. Line nine and line ten have the same function as line seven and line eight, respectively. The next record, line 11 to line 41, specify the watershed parameters used in SLURP.

For the SLURP application in the Sapochi River Basin, the command file was developed using the Slurpview command file editor with initial data described as follows:

1. **Date selection** (from sample data)

First year	1994
Last year	1994
First month	April
Last Month	October

2. **SLURP data option** (from sample data)

Running option	Simulation
Evapotranspiration model options	Spittelhouse/Black
Evaporation data options 1	Relative humidity data
Evaporation data options 2	Radiation data

3. **ASA attributes** (generated by SlurpView)

ASA area (km^2)	444.12
Mean latitude	56.40
Mean elevation (m)	261.51
Lapse rate (°C/100m)	0.75

Rate of change of precipitation with elevation (%/100m)	5.00

4. **Landcover percentages of ASA** (generated by SlurpView)

# of ASA	1
# of Landcover	2
Impervious (%)	5.60
Forest (%)	96.40

5. **Properties of canopy and snow melt rates** (from sample data)

	Impervious	Forest
Canopy capacity (mm)	0.10	10.00
No of snowmelt January	8.00	8.00
No of snowmelt July	0.70	0.70
Interception coefficient A	1.00	1.00
Interception coefficient B	1.00	1.00

6. **Leaf Area Index (LAI) data** (from sample data)

Month	Impervious	Forest
January	0.00	0.20
February	0.20	0.30
March	0.30	1.50
April	0.40	1.50
May	0.40	1.80
June	0.50	2.00
July	0.50	2.00
August	0.50	4.00
September	0.40	4.00
October	0.40	4.00
November	0.30	0.30
December	0.20	0.20

7. **Surface and snow albedo and properties of soil heat flux** (from sample data)

	Impervious	Forest
Surface albedo	0.05	0.10
Max snow albedo	0.80	0.80
Min snow albedo	0.40	0.40
Date of peak flux	August 1	August 1
Max heat flux	0.10	0.10

8. **Evaporation data** (from SLURP Manual)

	Impervious	Forest
WP	0.10	0.10
FC	0.50	0.50
Alpha water	1.00	1.00
Alpha soil	1.26	1.00
Beta	15.00	12.00

9. **Model parameters** (from sample data)

	Impervious	Forest
Initial contents of snow store (mm)	105.00	105.00
Initial contents of slow store (%)	0.00	0.00
Maximum infiltration rate (mm/d)	60.00	60.00
Manning roughness	0.02	0.02
Retent. constant for fast store (d)	17.00	17.00
Max. capacity of fast store (mm)	200.00	200.00
Retent. constant for slow store (d)	3000.00	3000.00
Max. capacity of fast slow (mm)	150.00	150.00
Precipitation factor	1.00	1.00
Rain/snow division temp. (° C)	0.00	0.00

10. **Data for within ASA routing** (generated by SlurpView)

	Impervious	Forest
Mean elevation (m)	261.00	261.00
To-stream mean (km)	1.558	1.63
STD to-stream mean	1.214	1.162
Mean dH (m)	2.00	2.00
Down-stream mean (km)	18.83	19.73
STD down-stream mean	8.015	8.939
Mean dH (m)	18.00	18.00

11. **Routing, diversion and intervension** (from sample data)

Route to which ASA?	Outlet
Routing method	Muskingum
Output from ASA1?	Yes
Is there any flow data?	Yes

12. Data for channel routing (generated by SlurpView)

Weighting constant, x	0.15
Travel time, K	1.00
Channel roughness	0.001
Average channel width (m)	20.00
Average channel depth (m)	2.00

Once the command file is developed, the next step in data preparation is to prepare the climate data. Climate data must be formatted into SLURP data format and saved into a certain file format with specific extension The operation of SLURP in this research is undertaken using selected climate data as follows: <Sapochi.pcp> for daily precipitation, <Sapochi.tav> for daily average temperature, <Sapochi.rhu> for daily relative humidity, and <Sapochi.net> for net radiation. Appendices 1 through 4 illustrate the precipitation data, temperature data, relative humidity data, and net radiation data used in the Sapochi River Basin. Appendix 5 also shows an example of the SLURP climate data.

4.1.2 Sensitivity Analysis

A sensitivity analysis is conducted in order to investigate the influence of each model parameter on hydrograph simulation. The sensitivity analysis of the SLURP parameters is undertaken on 12 parameters. The basis of comparison (BOC) is the hydrograph resulting from a simulation using example values of model parameters shown in section 4.1.1. The investigation is undertaken by observing the change of the simulated hydrograph when increasing or decreasing the values of parameters by 5% increments. The object of comparison in this sensitivity analysis is the discharge rate of the simulated hydrograph. Data used in the sensitivity analysis is the data collected for May 1994.

Table 4.1 presents the results of the sensitivity analysis. Results shows that the initial content of snow store, the maximum capacity of slow store, the precipitation factor, the maximum capacity of canopy store, and the interception coefficient are the most influential parameters in the SLURP simulation. Every 5% change in these parameters affects the discharge average by 6.53%, 2.36%, 2.14%, 1.04%, and 5.37%, respectively. Manning's roughness is the least sensitive parameter in the analysis. The category of sensitivity in this analysis is divided into two categories, high and low sensitivity. The parameters are considered to have a high sensitivity if their change of discharge rate per 5% is more than 0.5%. This was an arbitrary decision based on the relative differences in the average change.

4.1.3 Calibration and Verification

Archived data for 1994 and 1995 were used to calibrate and verify the SLURP model in the Sapochi River Basin. The basin has been applied as one ASA for initial calibration and validation. The model is first calibrated with 1994 data and then verified with 1995 data. Furthermore, 1995 data will be used as a calibration year and 1994 data as the verification year. The calibration is conducted by trial and error. The calibration parameters are changed manually to find the maximum value of Nash and Sutcliffe (NS) efficiency for the model. This was necessary because the optimization method provided with SLURP tended to force the mean computed discharge value to be equal to the mean recorded computed value regardless of the shape of the computed hydrograph. Table 4.2 shows the total volumes of precipitation, runoff, and losses for all of the simulation in this thesis.

The results of the first calibration are given in Figure 4.2, which compares the calculated hydrograph and the observed hydrograph. The maximum efficiency obtained was 91.4%. There is an agreement on the timing and peak flow between the two hydrographs mainly in the spring season. The calculated peak discharge is 16.069 m^3/s and the observed peak discharge is 16.900 m^3/s. The difference between the calculated and observed discharge average is 0.370 m^3/s. Using the same set of parameters, the model was verified on 1995 data and a comparison between the calculated hydrograph and the observed hydrograph is shown in Figure 4.3. The result produced a Nash and Sutcllife efficiency of–148.0% indicated by the lack of agreement on the timing and peak flow between two hydrographs in the spring and in the fall season. The calculated peak discharge is 27.155 m^3/s and the observed peak discharge is 9.500 m^3/s. The difference between the calculated and observed discharge average is 2.312 m^3/s. Based on this, this set of parameters can not necessarily be recommended as standard parameters for simulating runoff in the Sapochi River Basin. The set of parameters used for the first calibration is given in Table 4.3.

The model was then calibrated on 1995 data. Figure 4.4 shows the calculated hydrograph using the new calibrated parameter set and the observed hydrograph. The maximum NS value achieved in 1995 was 85.9%. The difference between the spring time computed and observed peak is about 15 days and this is quite significant. The calculated peak discharge is 8.667 m^3/s and the observed peak discharge is 9.500 m^3/s. The difference between the calculated and observed discharge average is 0.007 m^3/s. Model validation is carried out again by implementing the 1995 calibrated parameters on the 1994 data set. This resulted in an NS value of 31.1%. Although the difference in time to peak is not significant between the two hydrographs, peak flows in the spring season from those hydrographs show a lack of agreement. The calculated peak discharge is 4.642 m^3/s and the observed peak discharge is 16.900 m^3/s. the difference between the calculated and observed discharge average is 0.934 m^3/s. Again the calibrated parameters of 1995 are not considered as standard parameters the Sapochi River Basin. Figure 4.5 shows the calculated hydrograph using 1995 calibrated parameter set and the observed hydrograph from the Sapochi River Basin in 1994. The set of parameter used for the second calibration process is given in Table 4.4.

An effort was made to find the best set of parameters that would result in a good NS value for both 1994 and 1995. By considering both data sets in a calibration process, a compromise was reached in achieving high NS values in both years. Figure 4.6 and Figure 4.7 show hydrograph comparisons between the calculated hydrograph using the best parameter set and the observed hydrograph for 1994 and 1995, respectively. With the set of parameters obtained by considering both data sets in a calibration process, the optimum NS value achieved was 85.4% for 1994 and 81.7% for 1995. For the 1994 data, the calculated peak discharge is 16.280 m^3/s and the observed peak discharge is 16.900 m^3/s. The difference between the calculated and observed discharge average is 0.947 m^3/s. The application of these parameters to the 1995 data produced the calculated peak discharge of 12.669 m^3/s and the observed peak discharge for 9.500 m^3/s. The difference between calculated and observed discharge average is 1.140 m^3/s. The set of parameters used for this calibration process is given in Table 4.5.

4.1.4 Assessment and Discussion

In general, the third calibration parameter set for runoff simulation in the Sapochi River Basin gave satisfactory results and resulted in high NS values for both years. The NS values are not very different from others produced by previous SLURP applications in Canadian river basins. The application of SLURP to the Kootenay River Basin, for instance, resulted in approximately a 79% to 85% NS value when using either ground truth data or satellite data, respectively.

In examining Tables 4.3, 4.4, and 4.5, there is definite parameter interaction between the calibrated parameters of each table. This is illustrated by the fact that maximum capacity of the fast store was the same for 1994 (Table 4.3) and 1995 (Table 4.4) but was reduced for the optimized set that maximized the NS value for both years. The recommended parameter set show in table 4.5 shows similar values for both the impervious and forested areas. This is primarily because the forest area comprises such as large percentage of the basin and therefore, the impervious component had little effect. There was only a differentiation in the maximum capacity of the canopy store between the impervious and pervious area. In Table 4.5, the maximum capacity of the slow stores are roughly similar; however due to the lack of physical basis in this model, it is not possible to state the physical meaning of these parameters. What is interesting to note is that the retention constant of the slow store is high and listed as 1200 days long. This implies that moisture held in this slow storage is released over a very long period of time.

As a northern boreal-forested area, the Sapochi River Basin receives long snow fall periods. The snowmelt proved to be a dominant factor affecting the amount of flow recorded in the watershed outlet. Snowpack melts in the period between May and June, but naturally the depth of snowpack covering the basin is not uniform every year. The streamflow data of 1994 and 1995 in Figure 4.8 implies that the depth of snowpack accumulated in year 1994 was much higher than the depth accumulated in year 1995. Based on the BOREAS website data, 1994 and 1995 had roughly similar initial snow stores. Prior to the start of the melt season, year 1994 had 105mm of recorded snowpack depth while 1995 had an 81mm depth. Rationally, by using the same watershed parameters and ignoring the small amount of total precipitation in the Sapochi River Basin in the spring season (which was 81.4mm for 1994 and 44.0mm for 1995), 1995 should generate about 77.1% of the 1994 runoff volume. In fact, data show that 1995 only produced about 23.2% of the 1994 runoff volume. This is basically caused by the initial content of slow store in the initial simulation. Initial content of slow store, given as a percentage of slow storage maximum capacity, describes how much water is contained in slow storage before the start of the simulation. Initial content of slow store plays an important role in SLURP simulations by driving the discharge volume in the spring season and the beginning of summer. This research recommends an initial slow store of 90.0% of 1994 maximum slow store and 0.00% of 1995 maximum slow store.

4.1.5 Distributed Approaches

Increasing the number of ASAs in the applications was conducted in order to observe the effect of watershed division to the SLURP simulation results. Without changing the land cover, dividing the watershed into more ASAs would not be expected to provide any significant change to NS. This is understandable because the Sapochi River Basin is very flat. The flatness of the area makes every ASA, for any number of

ASAs in the basin, to have similar physiographic characteristics. However, the SLURP simulations using a variety of ASAs indicates that the topography of the watershed does have a role in SLURP simulations in this area. Figure 4.9 to Figure 4.11 show watershed sub-division for two, three, and five ASAs in the Sapochi River Basin. Results displaying hydrograph comparisons between calculated and observed hydrographs for two, three, and five ASAs are presented in Figure 4.12 to Figure 4.17. Simulations using two ASAs result in NS values of 83.0% and 77.2% for 1994 and 1995, respectively. Simulations using three and five ASAs produce NS value of 84.7% and 83.5% for 1994 and 84.7% and 87.2% for 1995, respectively. The increase in the NS value from one to five ASAs is significant (roughly 7%) and may be attributed to a better representation of catchment physiography. The relative lack of increase in NS value for 1994 but good increase for 1995 may indicate that importance of the catchment physiography in non-snowmelt related runoff.

4.2 WATFLOOD Model Application in the Sapochi River Basin

4.2.1 Data Preparation

Deriving watershed physiographic data is the first step to initiating runoff simulations using WATFLOOD. In this research watershed physiographic derivation was undertaken using Maputil. A 1km resolution DEM and landcover map of the Sapochi River Basin are the input data. For the first simulation the basin is divided into 64 GRUs where each of them has an area of 5km x 5km (see Figure 4.18). Results obtained from the derivation is the <Sapochi.MAP> file that contains GRU characteristics as follows:

a) River elevation
b) Drainage direction

c) Element drainage area
d) River type
e) Contour density
f) Channel number
g) Percentage of landcover type

The watershed physiographic data are saved in the MAP file and then imported as a SHD file for use in WATFLOOD. Once the physiographic data are prepared, the watershed parametric data are collected. A set of standard values of parametric data are provided with WATFLOOD. All of the watershed parametric data for the Sapochi River Basin were copied from the Grand River Basin in Ontario data. The data are considered as initial data to start the simulations. In order to obtain the best simulation results, the data will be optimized by WATFLOOD in the calibration process.

The third step in data preparation is compiling the time series climate data. Every file of the data contains the name and location of the climate station and the time series data in a specific interval of measurement. Finally, all of the data are organized and activated by what is known as an event file. The event file lists the files that are used in the simulation. An example of event file is given in Figure 4.19. Lines 1 to 6 define a series of run control options such as the initial date of the simulation and the interval of time series data. Lines 6 to 10 list the watershed physiographic data and parameter data files. The remaining lines list the climate time series data files. Appendix 6,7, and 8 show examples of the WATFLOOD Map, SHD, and climate data files.

4.2.2 Sensitivity Analysis

The parameters used in WATFLOOD calibration can be divided into two categories: runoff parameters and snow parameters. Runoff parameters lead the processes of rainfall transformation into runoff. These parameters are very dominant in affecting runoff in the summer and the fall season. On the other hand, snow parameters play important role in runoff calculations in the winter and spring period. A sensitivity analysis has been undertaken to identify the sensitivity of each parameter in the WATFLOOD model. The sensitivity analysis of the WATFLOOD parameters is undertaken on 20 parameters. Data collected for May 1994 was used in this sensitivity analysis.

Table 4.6 presents the result of the sensitivity analysis. The table indicates that the runoff parameters such as interflow depletion (REC), upper zone specific retention (RETN), lower zone drainage resistance factor (AK2), lower zone drainage resistance factor (AKfs2), lower zone drainage function parameter (LZF), and lower zone drainage function parameter (PWR) are the most sensitive parameters. Every 5% change in these parameters affect the discharge average by 1.01%, 0.73%, 0.53%, 2.49%, 1.43%, and 5.38%, respectively. For snow parameters, melt factor (MF) is the most sensitive parameter. Every 5% of change of this parameter changes the discharge average by 0.39 %. Other parameters from both groups are categorized as low sensitive parameters. Every 5% of change of these parameters only affects the discharge average by up to 0.10%. The parameters affecting evapotranspiration, interception, and depression storage were revealed to be parameters of low sensitivity for the model

4.2.3 Calibration and Verification

1994 and 1995 data were again used to investigate the performance of the WATFLOOD model in the Sapochi River Basin. In the first simulation of the model, optimization parameters were set to the standard parameters given by Kouwen (1998) as a suitable parameter set in previous WATFLOOD applications in several regions of Canada. A 5km x 5km grid was used for physiographical analysis as suggested in the WATFLOOD manual. WATFLOOD simulation in this thesis is started by using 1994 as the calibration year and 1995 as the verification year. Further tests use 1995 as the calibration year and 1994 as the verification year. The results of those simulations will be examined to determine the optimum set of parameters to produce the best calculated runoff.

Figure 4.20 shows the results of the calibration on 1994 data. The calibration NS is 81.1%. The calculated hydrograph modeled observed hydrograph well in the spring season but not in the fall season. The calculated peak discharge is 14.600 m^3/s and the observed peak discharge is 16.900 m^3/s. The difference between the calculated and observed discharge average is 1.121 m^3/s. Model validation is carried out by implementing the calibrated parameters to the 1995 data. Figure 4.21 shows the results for 1995 data when using 1994 optimized parameters. However, the result is poor indicated by an NS value of –31.7%. There is poor agreement in spring season peak. The calculated peak discharge is 11.200 m^3/s and the observed peak discharge is 9.500 m^3/s. The difference between the calculated and observed average discharge is 1.446 m^3/s. Results of the calibration and validation indicate that this set of optimized parameters are not recommended as standard parameters for simulating runoff in the Sapochi River Basin using WATFLOOD. The set of parameters used for the 1994 calibration process is given in Table 4.7.

The results of the calibration using 1995 data are shown in Figure 4.22. The maximum NS value that can be reached from calibrating on 1995 data is 70.8%. The calculated peak discharge is 7.850 m^3/s and the observed peak discharge is 9.500 m^3/s. The difference between the calculated and observed average discharge is 0.123 m^3/s. Validation of the model is accomplished by applying the calibrated parameters to the 1994 data and this is shown in Figure 4.23. This resulted in an NS value of 27.1%. The calculated peak discharge is 5.900 m^3/s and the observed peak discharge is 16.900 m^3/s. the difference between the calculated and observed average discharge is 0.382 m^3/s. This indicates that the set of 1995 optimized parameters should probably not be considered as standard parameters for simulating runoff in the Sapochi River Basin. The set of parameters used for the 1995 calibration process is given in Table 4.6.

To cope with the poor verification efficiencies, an optimum parameter set is sought that will provide good NS values on both 1994 and 1995. Figure 4.24 and Figure 4.25 show hydrograph comparisons between the calculated hydrographs using an optimized set of parameters and the observed hydrograph for both 1994 and 1995, respectively. The optimum NS value reached by the calibration was 58.6% for 1994 and 57.9% for 1995. When applied to 1994 data, the optimized parameter set resulted in the calculated peak discharge of 8.100 m^3/s and the observed peak discharge of 16.900 m^3/s. The difference between the calculated and observed average discharge is 1.446 m^3/s. The optimized parameter set produced the calculated peak discharge of 6.100 m^3/s and the observed peak discharge is 9.500 m^3/s when applied to 1995 data. The difference between the calculated and observed average discharge is 0.358 m^3/s. So far, the WATFLOOD optimized parameter set has not produced very satisfactory results, primarily in modeling runoff in the spring season. The set of WATFLOOD optimized parameters is given in Table 4.6.

In examining the parameters in Table 4.7, it is noted that the parameters relating to the depression storage, interflow depletion, saturated conductivity, upper zone drainage resistance factor, lower zone drainage function exponent, and the melt factor, changed significantly between the 1994 and 1995 calibrated parameter sets. The optimized parameter set sometimes indicated that a median value of certain parameters that were different between 1994 and 1995 was most suitable. With regard to the optimized parameter set that involved both 1994 and 1995 data, the upper zone specific retention (**RETN**) which governs the division between slow and fast moving water (i.e. surface runoff and interflow/base flow) was one parameter that is very different than the values that were in the standard parameter set provided by Kouwen (1998). It is a full order of magnitude higher and almost five times the "standard" value. This high **RETN** value indicates that less water is becoming discharge or fast runoff and more water is going into the slower zone that governs interflow and base flow.

4.2.4 Assessment and Discussion

For the most part, the calibration of WATFLOOD parameters in order to find the best runoff simulation on the Sapochi River Basin have not been satisfactory. The fundamental problem causing the low simulation efficiency is the variation of discharge in the spring season. The adjustment of snow parameters to find the most appropriate calculation of runoff volume in the spring season does not provide any improvement. The adjustment of snow parameters also affects the calculation of runoff in the summer and fall season. This condition will decrease the efficiency for the entire year. The variation of initial subsurface area store, either upper zone or lower zone, in the start of simulation can be a factor affecting runoff in the spring season. Unfortunately, the variation of initial subsurface area store can not be changed because WATFLOOD does not include these parameters in its set of optimization parameters. Improving the efficiency of the simulation either in 1994 or in 1995 can be reached by optimizing the depth of snow cover data. In this case the snow cover data for each year is optimized in order to find the appropriate parameter set that is best able to produce a good NS efficiency for both years. Result obtained by undertaking this method show an increase in efficiency. The maximum efficiency is acquired by changing the depth of snow cover from 105 mm to 210 mm for 1994. The efficiency of the simulation improves to 74.3% for year 1994 and 70.8% for year 1995. Figure 4.26 and Figure 4.27 show comparisons between the calculated hydrographs using optimized snow cover and observed hydrographs for 1994 and 1995, respectively.

Based on the results above, conducting optimization on the depth of snow cover is potentially able to increase the efficiency of WATFLOOD simulations in the Sapochi River Basin. However, optimizing the depth of snow covers means ignoring the field data existence and moreover, may reduce the deterministic quality of the model. The optimization of snow cover depth maybe appropriate when the optimized snow covers data does not really represent the actual condition in the basin. When the optimized snow cover depth deviates greatly from the observed snow cover depth, then modeler should question the validity of the model.

4.2.5 Distributed Approaches

Grid size of the Group Response Unit (GRU) is an important factor that influences WATFLOOD simulations. Varying the grid size will change the values of several parameters of watershed physiography, such as the number of GRUs, river elevation, drainage direction, and river characteristics. The optimum parameter set was tested in several simulations using various grid sizes. Two new watershed sub-divisions of 10km x 10km and 20km x 20 km are shown in Figure 4.28 and 4.29, respectively. Figure 4.30 to Figure 4.35 show the changes in the hydrograph based on the variability of grid size. The grid size 5km x 5km gave the highest value of NS when compared with 10km x 10km size and 20km x 20km size. For a grid size of 5km x 5km, the efficiency of the simulation is 58.6% for year 1994 and 57.9% for year 1995, respectively. A 10km x 10km grid results in 23.2% and 51.3% efficiencies; and a 20km x 20km grid produces 11.0% and 32.2% for 1994 and 1995, respectively. Based on the results above, it seems that the smaller the grid size the better the representation of spatial heterogeneity by the model. However, making the grid size as small as possible is not practical. Too many GRUs will create difficulties in data preparation and data management. So far, a 5km x 5km grid size is a good size for WATFLOOD watershed subdivision and recommended for use in small basins such as the Sapochi River Basin. Finally, because of a large part of the physiographical data analysis in WATFLOOD is determined manually in the MAP file development using Maputil, the subjectivity of the modeler plays an important role in developing the SHD file in WATFLOOD simulations.

4.3 Comparison and Evaluation

4.3.1 Theory and Mathematical Development

The SLURP and WATFLOOD models belong to a relatively recent generation of hydrological models developed for deterministic watershed runoff prediction. Using GIS and remotely sensed data, the models are able to provide a relatively detailed and realistic picture of watershed behavior as a consequence of the spatial variability that naturally occurs in meteorological input data, land cover, and watershed physiographic data. Both models are considered conceptual models as indicated by the mathematical equations used to represent the runoff processes. Many of the equations are standard mathematical representations of hydrological processes that have existed in the literature for decades including Philip's equation for infiltration, Hargreaves and Spittelhouse/Black equations for evaporation, and the Muskingum method for routing.

Rainfall and snowmelt are the most important hydrological input for the models. The snowmelt rate, actual temperature, and critical temperature are dominant parameters driving the snowmelt process in both models. Vertical water movement involves processes such as precipitation, snowmelt, interception, evaporation, and infiltration. Runoff generation is a combination of vertical water movement and lateral runoff. Lateral runoff such as surface runoff and interflow, play an important role in quick runoff generation, while groundwater flow or base flow together with vertical water movement drive long-term runoff generation. Routing is accomplished using storage routing techniques such as the Muskingum routing method, which is used in both SLURP and WATFLOOD.

The primary difference between the SLURP and WATFLOOD models is in the way they conceptualize the physical watershed as a medium for runoff generation. In the SLURP model, every ASA in the watershed consists of a vertical series of tanks that can receive, store, and release water due to precipitation. Processes that occur in the ASA are related to the amount of water being stored in the tanks. If the maximum capacity of a tank has not yet been reached, the water flowing to the tank will be stored in the tank until the maximum capacity is exceeded. Vertical and lateral flow will occur when the amount of water stored in the tank exceeds the maximum capacity of the tank. Excess water will flow to a lower tank and follow the same process as in the previous tank. Discharge to the outlet of the watershed is a combination of discharges produced by every ASA in the watershed. This concept makes the runoff generation processes in the SLURP model easy to understand. By determining the initial storage of each tank prior to a simulation, very good results can be obtained. The weakness in this concept is its inability to describe the runoff generation processes in physically based way. Consequently, not every process in the subsurface region of the watershed can be explained using mathematical equations involving subsurface parameters such as soil moisture content, soil porosity, and soil permeability. Model deviations from observed results as a consequence of the variability in the subsurface area could not be corrected in this concept. Based on these circumstances, SLURP cannot be considered a very physically based model because it uses black box concepts in key calculations. This makes it difficult to translate the watershed to nearby watersheds.

Unlike the SLURP model, the WATFLOOD model is more physically based in its approach to conceptualizing the watershed. WATFLOOD considers each GRU in the watershed as a vertical series of soil zones. The zones do not necessarily function as stores of water. Zones instead describe the soil condition and determine which mathematical equations are appropriate for that condition. Watershed discharge is combined from every GRU which result from the physical processes occurring in each zone. Initial storage of a watershed is described from the initial moisture contents of the soil zones. A large number of parameters are required in computing runoff in WATFLOOD, thus making the calibration process in WATFLOOD much more complicated than that of SLURP.

4.3.2 Model Performance

The SLURP and WATFLOOD model were applied to the Sapochi River Basin to investigate the performance of each model in modeling runoff. Results indicate that in general both models, with optimization, will successfully simulate runoff in the Sapochi River Basin. SLURP reaches an efficiency of about 80% and WATFLOOD produces an efficiency of about 70% for 1994 and 1995. Snowmelt drives the fluctuations of runoff. Also for SLURP, the initial content of the slow store is an important factor in simulating runoff. WATFLOOD unfortunately does not allow changes to the initial contents of the upper soil zone which is assumed as zero, and which can affect the simulation of runoff for such a short series. This fact affects the simulation efficiency of the WATFLOOD model. Sensitive parameters, either in SLURP or in WATFLOOD, play an important role in driving the volume of runoff in the simulation. The coefficients of fast and slow store for SLURP and the specific retention of the soil in the upper zone and lower zone drainage function for WATFLOOD, for instance, are highly influencing parameters, but mostly in the summer and in the beginning of the fall season.

Both SLURP and WATFLOOD are simple to operate. Input data on a daily basis for the SLURP model can be organized using a text editor or MS Excel spreadsheet. Computation speeds are very quick in SLURP. It requires only seconds to produce hydrographs and water balance descriptions. Unfortunately, SLURP does not provide a good Graphical User Interface (GUI). A better GUI is obtained when SlurpView assists SLURP in runoff simulations. On the other hand, with a better GUI than that of SLURP alone, WATFLOOD uses a Windows operating system and input data organization can be undertaken using a text editor, MS Excel spreadsheet, or directly within the GUI. Input data for WATFLOOD is organized on an hourly basis. Due to the conversion of hourly computations to daily values WATFLOOD requires greater computational times than SLURP. A seven-month period of simulation required approximately 23 seconds to produce a hydrograph. However, WATFLOOD provides a very detailed presentation of the whole runoff process on a daily basis while SLURP only provides a presentation of daily discharge on a daily basis.

4.3.3 Distributed Modeling

The concept of watershed sub-division is the primary issue in distributed modeling. Watershed sub-division determines how far the model goes to representing the natural conditions in a watershed. Scale plays an important role in SLURP and WATFLOOD simulations. The smaller the scale the better the presentation of watershed physiography. Unfortunately, the Sapochi River Basin is a flat area and has almost uniform land cover. The effect of the watershed subdivision might only be slightly noticeable from the simulation result. However, the research indicates that conducting simulations using smaller scales tends to result in better simulations. But making the scale as small as possible is not the best path to take. Too many ASAs in the SLURP model or too many GRUs in the WATFLOOD model will cause difficulties in data preparation and data management. For the SLURP model, watershed subdivision is recommended by considering the uniformity of the aerial topography. It is suggested that each ASA area have uniform topography. For the WATFLOOD model, the physiographical data is determined from the size of each GRU. Grid sizes of 5km x 5km are the most recommended size for watershed subdivision in the WATFLOOD model for a small watershed like the Sapochi River Basin.

This research also indicates that the ASA concept from the SLURP model is more representative than the GRU concept in depicting the natural condition of a watershed. The ASA is based on stream networks derived from topographic characteristics in the watershed, thus providing a more natural representation of runoff movement in the watershed than the GRU concept used in WATFLOOD. A change in ASA size that does not cause a change in topographic characteristics of the ASA, will not affect the simulated runoff response of the ASA.WATFLOOD does not devise the GRU as a system that relies on the movement of water in the watershed. GRU is only a calculation unit. The format of GRU ignores the topographical characteristic of the area. The direction of water movement in a GRU system is determined manually by the WATFLOOD modeler using the MAPUTIL facility. A change in GRU's size affects the GRU characteristics such as river class, slope, and drainage direction. The best way to maximize the advantages of using the GRU concept is to make the size of the GRU as small as possible. By this method, the GRU will provide a more natural representation of runoff movement in the watershed. This method allows WATFLOOD to be applied in a fully distributed manner, thus producing good results, but requiring greater computer power.

Table 4.1 Result of Sensitivity Analysis for SLURP Parameters

No.	Parameter with BOC value	Change of mean computed flow based on the change of parameter value							Average change (%)	Sensitivity
		-15%	-10%	-5%	BOC	+5%	+10%	+15%		
1	Initial content of snow store (310mm)	2.195	2.355	2.518	2.688	2.855	3.027	3.208	6.53	HIGH
2	Initial content of slow store (5%)	2.66	2.669	2.678	2.688	2.697	2.706	2.715	0.34	LOW
3	Maximum infiltration rate (40mm/d)	2.717	2.702	2.688	2.688	2.687	2.686	2.685	-0.20	LOW
4	Manning roughness (0.02)	2.688	2.688	2.688	2.688	2.688	2.688	2.688	0.00	LOW
5	Retention constant for fast store (12 day)	2.691	2.69	2.689	2.688	2.687	2.686	2.685	-0.04	LOW
6	Maximum capacity of fast store (200mm)	2.717	2.701	2.688	2.688	2.687	2.686	2.685	-0.12	LOW
7	Retention constant for slow store (4000 day)	2.732	2.715	2.701	2.688	2.676	2.665	2.655	-0.50	LOW
8	Maximum capacity of slow store (350mm)	2.909	2.825	2.746	2.688	2.633	2.581	2.532	-2.36	HIGH
9	Precipitation factor (1)	2.533	2.58	2.631	2.688	2.745	2.804	2.876	2.14	HIGH
10	Rain/snow division temperature ($0^{o}C$)	2.69	2.688	2.688	2.688	2.687	2.687	2.686	-0.02	LOW
11	Max. capacity of canopy store (10mm)	2.778	2.746	2.716	2.688	2.659	2.631	2.609	-1.04	HIGH
12	Interception coefficients (1)	3.172	3.006	2.844	2.688	2.688	2.688	2.688	-5.37*	HIGH

Table 4.2 Water Balance Volumes for All Simulations

SIMULATION		Precipitation (mm)	Runoff (mm)	Losses (mm)
SLURP	1994 calibration set on 1994 data	232.00	115.20	116.80
	1994 calibration set on 1995 data	290.00	178.20	111.80
	1995 calibration set on 1994 data	232.00	60.90	171.10
	1995 calibration set on 1995 data	290.00	81.70	208.30
	Optimum set on 1994 data	232.00	139.20	92.80
	Optimum set on 1995 data	290.00	77.30	212.70
WATFLOOD	1994 calibration set on 1994 data	232.00	142.80	89.20
	1994 calibration set on 1995 data	290.00	142.10	147.90
	1995 calibration set on 1994 data	232.00	72.60	159.40
	1995 calibration set on 1995 data	290.00	86.70	203.30
	Optimum set on 1994 data	232.00	98.00	134.00
	Optimum set on 1995 data	290.00	96.40	193.60

Table 4.3 SLURP 1994 Calibrated Parameters

No.	Parameter	SLURP 1994 Calibrated Parameters			
		Applied for 1994 data		Applied for 1995 data	
		Impervious	Forest	Impervious	Forest
1	Initial content of snow store (mm)	105.0	105.0	81.0	81.0
2	Initial content of slow store (%)	10.0	10.0	10.0	10.0
3	Maximum infiltration rate (mm/d)	40.0	40.0	40.0	40.0
4	Manning roughness	0.02	0.02	0.02	0.02
5	Retention constant for fast store (days)	15.5	15.5	15.5	15.5
6	Maximum capacity of fast store (mm)	200.0	200.0	200.0	200.0
7	Retention constant for slow store (days)	85.0	85.0	85.0	85.0
8	Maximum capacity of slow store (mm)	22.0	22.0	22.0	22.0
9	Precipitation factor	1.0	1.0	1.0	1.0
10	Rain/snow division temperature (oC)	0.0	0.0	0.0	0.0
11	Max. capacity of canopy store (mm)	0.1	10.0	0.1	10.0
12	Interception coefficients (A,B)	1.0	1.0	1.0	1.0

Table 4.4 SLURP 1995 Calibrated Parameters

No.	Parameter	SLURP 1995 Calibrated Parameters			
		Applied for 1994 data		Applied for 1995 data	
		Impervious	Forest	Impervious	Forest
1	Initial content of snow store (mm)	105.0	105.0	81.0	81.0
2	Initial content of slow store (%)	10.0	10.0	10.0	10.0
3	Maximum infiltration rate (mm/d)	60.0	60.0	60.0	60.0
4	Manning roughness	0.02	0.02	0.02	0.02
5	Retention constant for fast store (days)	16.0	16.0	16.0	16.0
6	Maximum capacity of fast store (mm)	200.0	200.0	200.0	200.0
7	Retention constant for slow store (days)	1200.0	1200.0	1200.0	1200.0
8	Maximum capacity of slow store (mm)	140.0	140.0	140.0	140.0
9	Precipitation factor	1.0	1.0	1.0	1.0
10	Rain/snow division temperature (oC)	0.0	0.0	0.0	0.0
11	Max. capacity of canopy store (mm)	0.1	10.0	0.1	10.0
12	Interception coefficients (*A*,*B*)	1.0	1.0	1.0	1.0

Table 4.5 SLURP 1994-1995 Optimized Parameters

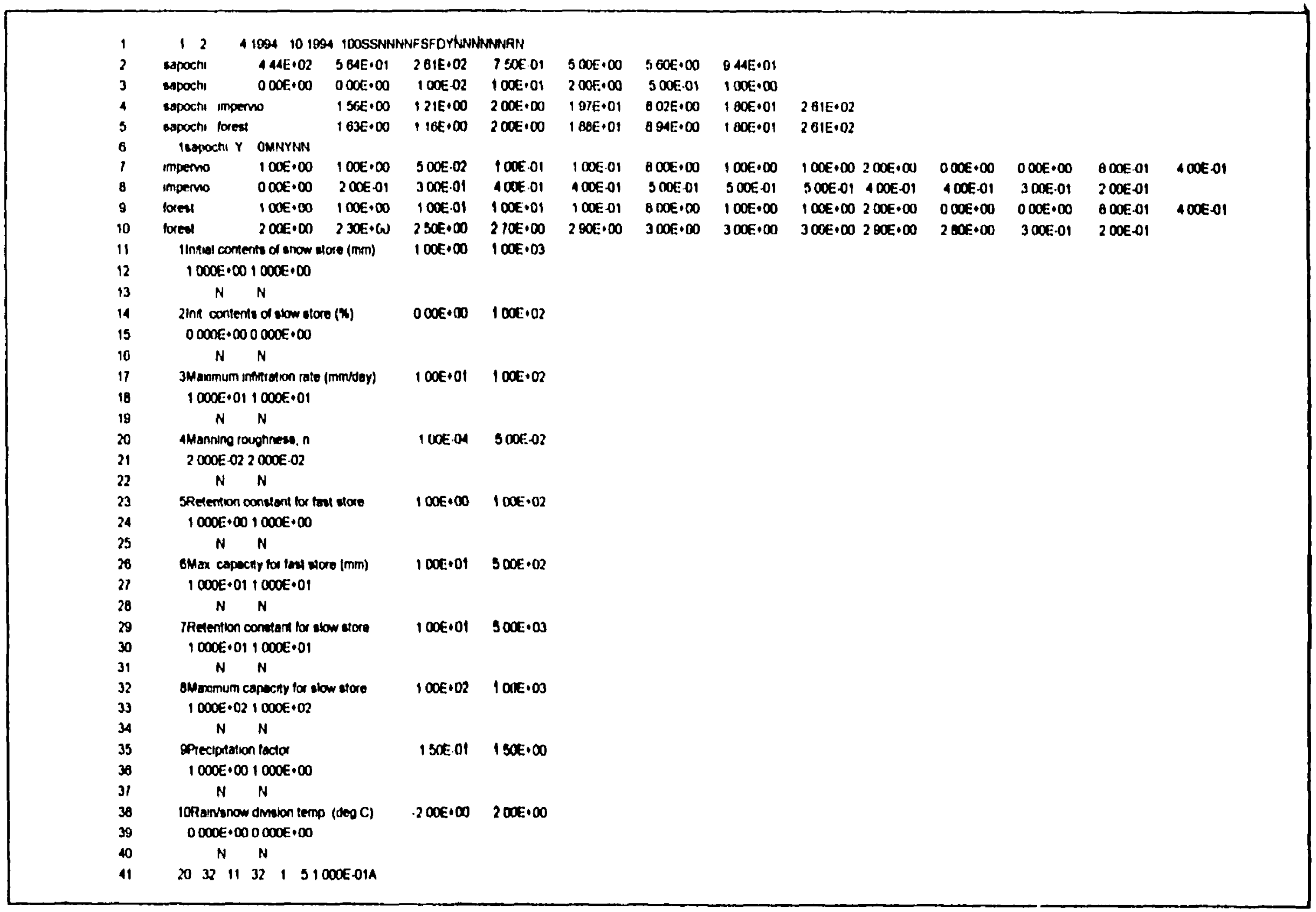
No.	Parameter	SLURP Optimized Calibrated Parameters			
		Applied for 1994 data		Applied for 1995 data	
		Impervious	Forest	Impervious	Forest
1	Initial content of snow store (mm)	105.0	105.0	81.0	81.0
2	Initial content of slow store (%)	90.0	90.0	0.0	0.0
3	Maximum infiltration rate (mm/d)	60.0	60.0	60.0	60.0
4	Manning roughness	0.02	0.02	0.02	0.02
5	Retention constant for fast store (days)	15.0	15.0	15.0	15.0
6	Maximum capacity of fast store (mm)	100.0	100.0	100.0	100.0
7	Retention constant for slow store (days)	1200.0	1200.0	1200.0	1200.0
8	Maximum capacity of slow store (mm)	130.0	130.0	130.0	130.0
9	Precipitation factor	1.0	1.0	1.0	1.0
10	Rain/snow division temperature (oC)	0.0	0.0	0.0	0.0
11	Max. capacity of canopy store (mm)	0.1	10.0	0.1	10.0
12	Interception coefficients (A,B)	1.0	1.0	1.0	1.0

Table 4.6 Results of Sensitivity Analysis for WATFLOOD Parameters

No	Parameter with BOC Value		Change of mean computed flow based on the change of parameter value							Average change (%)	Sensitivity
			-15%	-10%	-5%	BOC	+5%	+10%	+15%		
1	D_s	Depression storage (2mm)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
2	D_{sc}	Depression storage capacity (10mm)	3.287	3.286	3.285	3.284	3.283	3.282	3.281	-0.03	LOW
3	REC	Interflow depletion coefficient (2.4)	3.184	3.219	3.252	3.284	3.316	3.342	3.381	1.01	HIGH
4	K_s	Saturated conductivity (70mm/s)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
5	RETN	Upper zone spesific retention (0.035)	3.361	3.332	3.306	3.284	3.258	3.239	3.216	-0.73	HIGH
6	AK2	Upper zone drainage resistance factor (0.0035)	3.226	3.242	3.261	3.284	3.300	3.319	3.329	0.53	HIGH
7	LZF	Lower zone drainage function parameter (0.0001)	3.139	3.194	3.235	3.284	3.332	3.384	3.419	1.43	HIGH
8	PWR	Lower zone drainage function exponent (0.8)	2.855	2.974	3.123	3.284	3.471	3.671	3.910	5.38	HIGH
9	n	River channel roughness (0.486)	3.297	3.290	3.290	3.284	3.284	3.281	3.281	-0.08	LOW
10	MF	Melt factor (0.057mm/deg/hr)	3.252	3.265	3.271	3.284	3.297	3.313	3.329	0.39	LOW
11	TBASE	Critical temperature (0° C)	3.290	3.290	3.294	3.284	3.274	3.265	3.271	-0.10	LOW
12	f_{pet}	The increase of IET for all vegetation (2)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
13	FTALL	The reduction in PET for all vegetation (1)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
14	FCAP	The field capacity (15%)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
15	FFCAP	The permanent wilting point (10%)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
16	SPORE	The soil porosity (30%)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
17	Temp1	Lower limit in degree-day function (40° C/day)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
18	Temp2	Degree day function parameter (50° C/day)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
19	Temp3	Upper limit in degree-day function (500° C/day)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW
20	TTO	Initial total number of degree-days at the start of simulation (0° C/day)	3.284	3.284	3.284	3.284	3.284	3.284	3.284	0.00	LOW

Table 4.7 WATFLOOD Calibrated and Optimized Parameters

No	WATFLOOD Parameter		1994 Calibrated Parameters		1995 Calibrated Parameters		Optimized Parameters	
			Imperv.	Forest	Imperv.	Forest	Imperv.	Forest
1	D_s	Depression storage (mm)	2.000	2.000	20.000	20.000	2.000	2.000
2	D_{sc}	Depression storage capacity (mm)	10.000	10.000	200.000	200.000	10.000	10.000
3	REC	Interflow depletion coefficient	2.400	2.400	0.160	0.160	1.120	1.120
4	K_s	Saturated conductivity (mm/s)	70.000	70.000	5.000	5.000	70.000	70.000
5	RETN	Upper zone spesific retention	0.035	0.035	62.000	62.000	0.150	0.150
6	AK2	Upper zone drainage resistance factor	0.004	0.004	0.035	0.035	0.035	0.035
7	LZF	Lower zone drainage function parameter	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001
8	PWR	Lower zone drainage function exponent	0.800	0.800	0.100	0.100	0.800	0.800
9	n	River channel roughness	0.486	0.486	0.486	0.486	0.486	0.486
10	MF	Melt factor (\mm/deg/hr)	0.057	0.057	0.350	0.350	0.057	0.057
11	TBASE	Critical temperature (° C)	0.000	0.000	0.000	0.000	0.000	0.000
12	f_{pet}	The increase of IET for all vegetation	2.000	2.000	2.000	2.000	2.000	2.000
13	FTALL	The reduction in PET for all vegetation	1.000	1.000	1.000	1.000	1.000	1.000
14	FCAP	The field capacity (%)	15.000	15.000	15.000	15.000	15.000	15.000
15	FFCAP	The permanent wilting point (%)	10.000	10.000	10.000	10.000	10.000	10.000
16	SPORE	The soil porosity (%)	30.000	30.000	30.000	30.000	30.000	30.000
17	Temp1	Lower limit in degree-day function (°C/day)	40.000	40.000	40.000	40.000	40.000	40.000
18	Temp2	Degree day function parameter (° C/day)	50.000	50.000	50.000	50.000	50.000	50.000
19	Temp3	Upper limit in degree-day function (° C/day)	500.000	500.000	500.000	500.000	500.000	500.000
20	TTO	Initial total number of degree-days at the start of simulation (°C/day)	0.000	0.000	0.000	0.000	0.000	0.000



```
  1  2    4 1994  10 1994  100SSNNNNFSFDYNNNNNNRN
sapochi       4.44E+02  5.64E+01  2.61E+02  7.50E-01  5.00E+00  5.60E+00  9.44E+01
sapochi       0.00E+00  0.00E+00  1.00E-02  1.00E+01  2.00E+00  5.00E-01  1.00E+00
sapochi  impervio       1.56E+00  1.21E+00  2.00E+00  1.97E+01  8.02E+00  1.80E+01  2.61E+02
sapochi  forest         1.63E+00  1.16E+00  2.00E+00  1.88E+01  8.94E+00  1.80E+01  2.61E+02
  1sapochi Y   0MNYNN
impervio      1.00E+00  1.00E+00  5.00E-02  1.00E-01  1.00E-01  8.00E+00  1.00E+00  1.00E+00 2.00E+00  0.00E+00  0.00E+00  8.00E-01  4.00E-01
impervio      0.00E+00  2.00E-01  3.00E-01  4.00E-01  4.00E-01  5.00E-01  5.00E-01  5.00E-01 4.00E-01  4.00E-01  3.00E-01  2.00E-01
forest        1.00E+00  1.00E+00  1.00E-01  1.00E+01  1.00E-01  8.00E+00  1.00E+00  1.00E+00 2.00E+00  0.00E+00  0.00E+00  8.00E-01  4.00E-01
forest        2.00E+00  2.30E+00  2.50E+00  2.70E+00  2.90E+00  3.00E+00  3.00E+00  3.00E+00 2.90E+00  2.80E+00  3.00E-01  2.00E-01
  1Initial contents of snow store (mm)    1.00E+00  1.00E+03
   1.000E+00 1.000E+00
       N     N
  2Init. contents of slow store (%)       0.00E+00  1.00E+02
   0.000E+00 0.000E+00
       N     N
  3Maximum infiltration rate (mm/day)     1.00E+01  1.00E+02
   1.000E+01 1.000E+01
       N     N
  4Manning roughness, n                   1.00E-04  5.00E-02
   2.000E-02 2.000E-02
       N     N
  5Retention constant for fast store      1.00E+00  1.00E+02
   1.000E+00 1.000E+00
       N     N
  6Max. capacity for fast store (mm)      1.00E+01  5.00E+02
   1.000E+01 1.000E+01
       N     N
  7Retention constant for slow store      1.00E+01  5.00E+03
   1.000E+01 1.000E+01
       N     N
  8Maximum capacity for slow store        1.00E+02  1.00E+03
   1.000E+02 1.000E+02
       N     N
  9Precipitation factor                   1.50E-01  1.50E+00
   1.000E+00 1.000E+00
       N     N
  10Rain/snow division temp. (deg C)     -2.00E+00  2.00E+00
   0.000E+00 0.000E+00
       N     N
  20  32  11  32   1   5 1.000E-01A
```

Figure 4.1 Example of SLURP command file (modified from Kite, 1997)

"

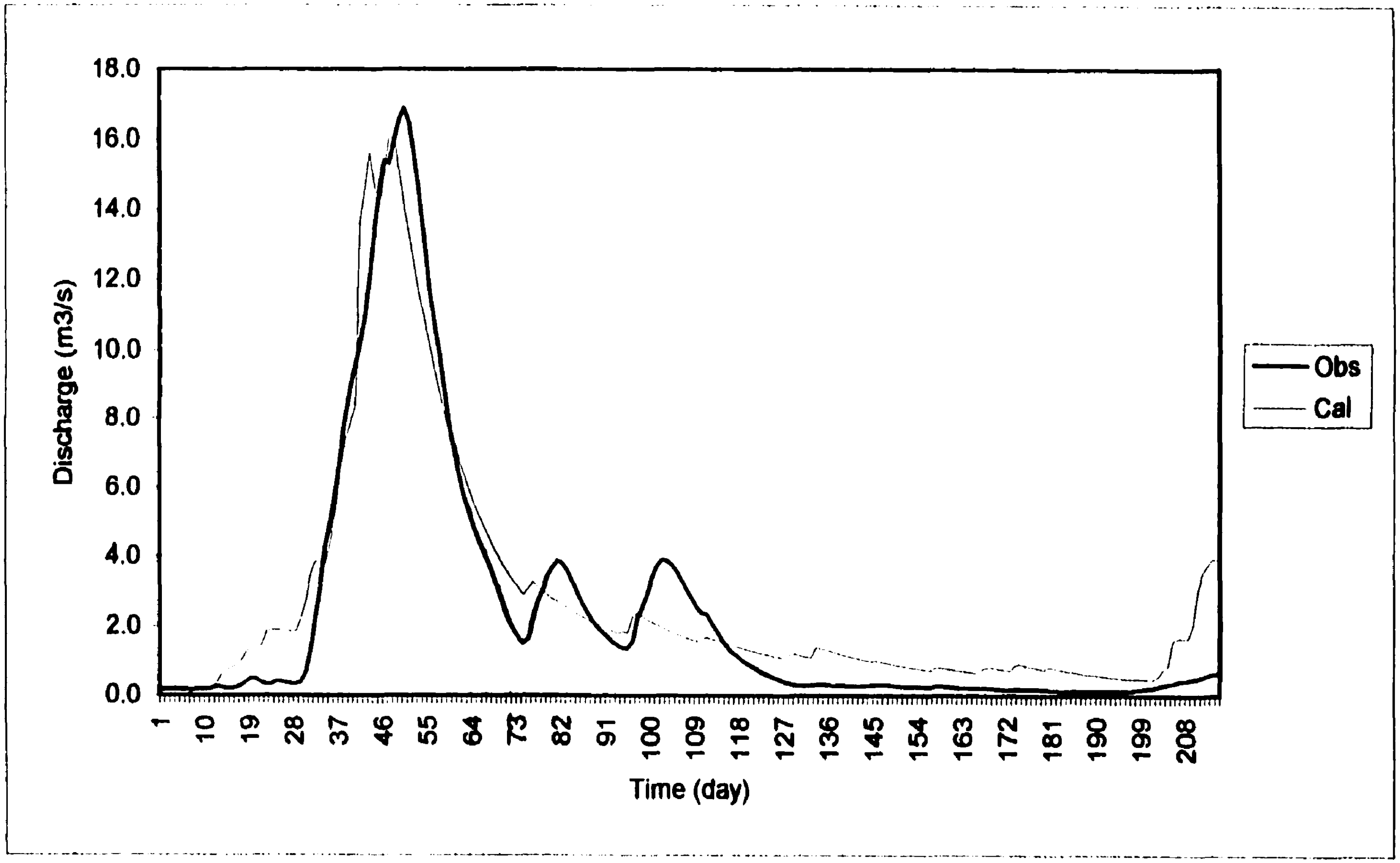


Figure 4.2 Hydrograph Comparison for the Sapochi River Basin Using SLURP 1994 Calibrated Parameters on 1994 Data

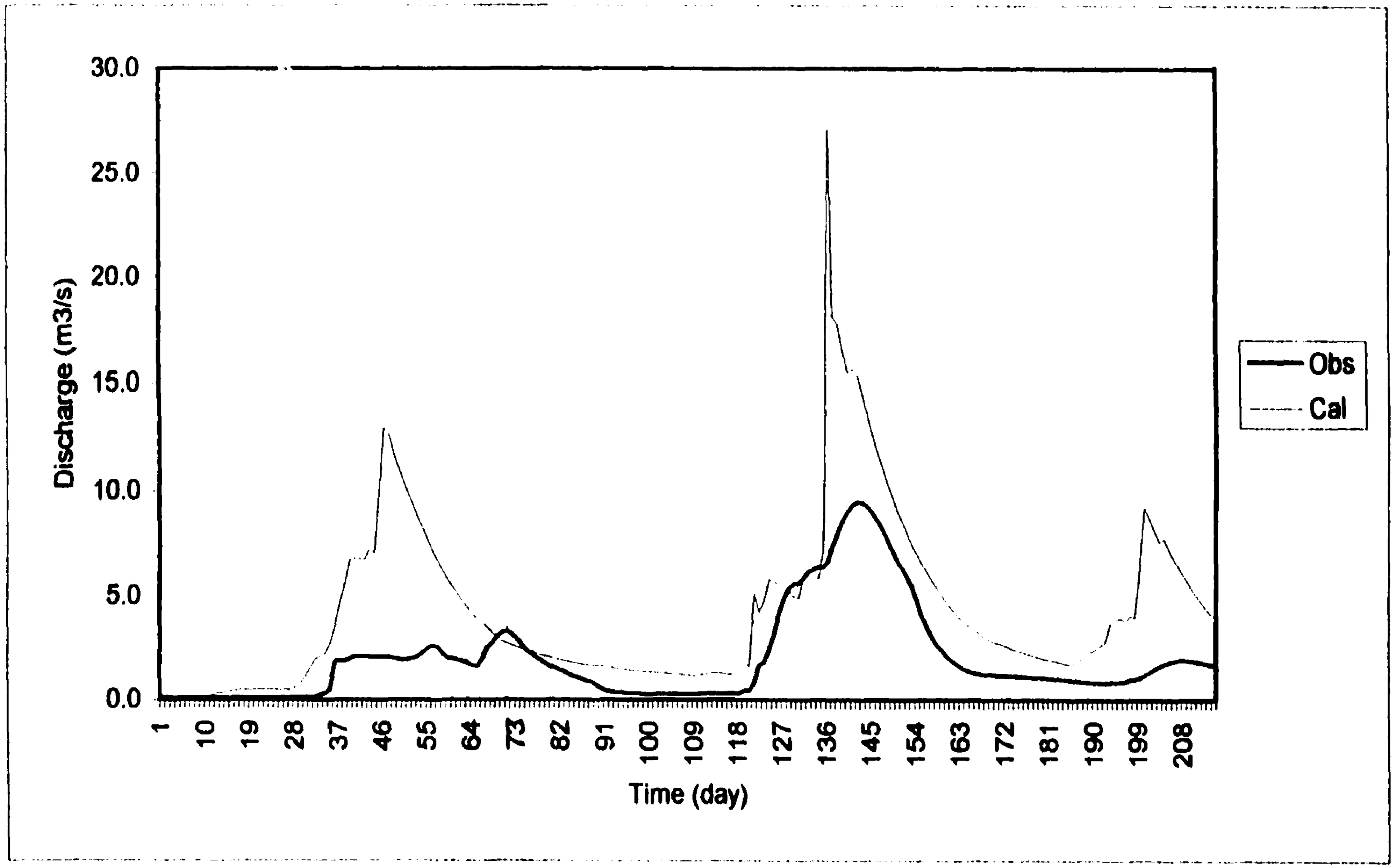


Figure 4.3 Hydrograph Comparison for the Sapochi River Basin Using SLURP 1994 Calibrated Parameters on 1995 Data

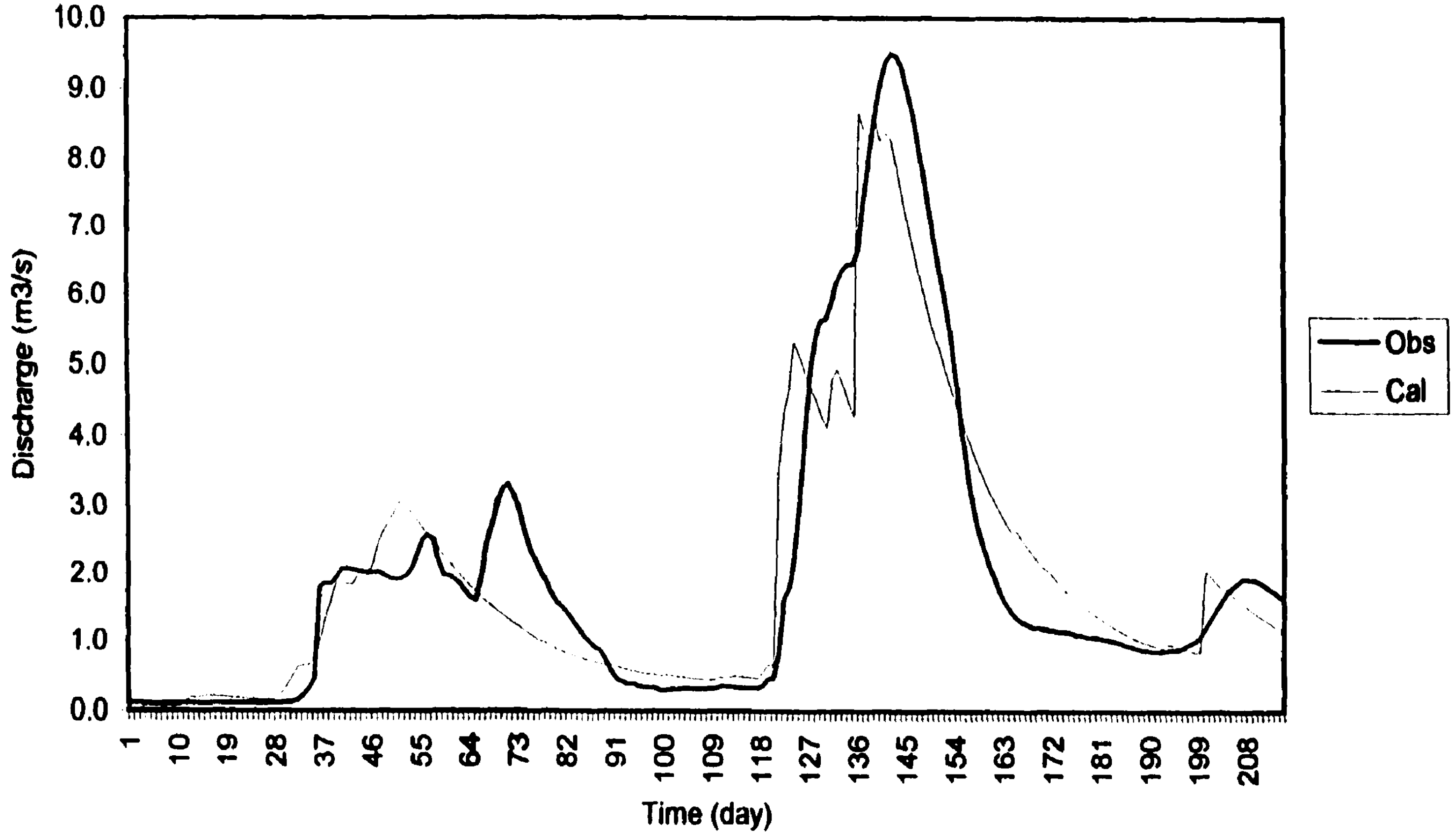


Figure 4.4 Hydrograph Comparison for the Sapochi River Basin Using SLURP 1995 Calibrated Parameters on 1995 Data

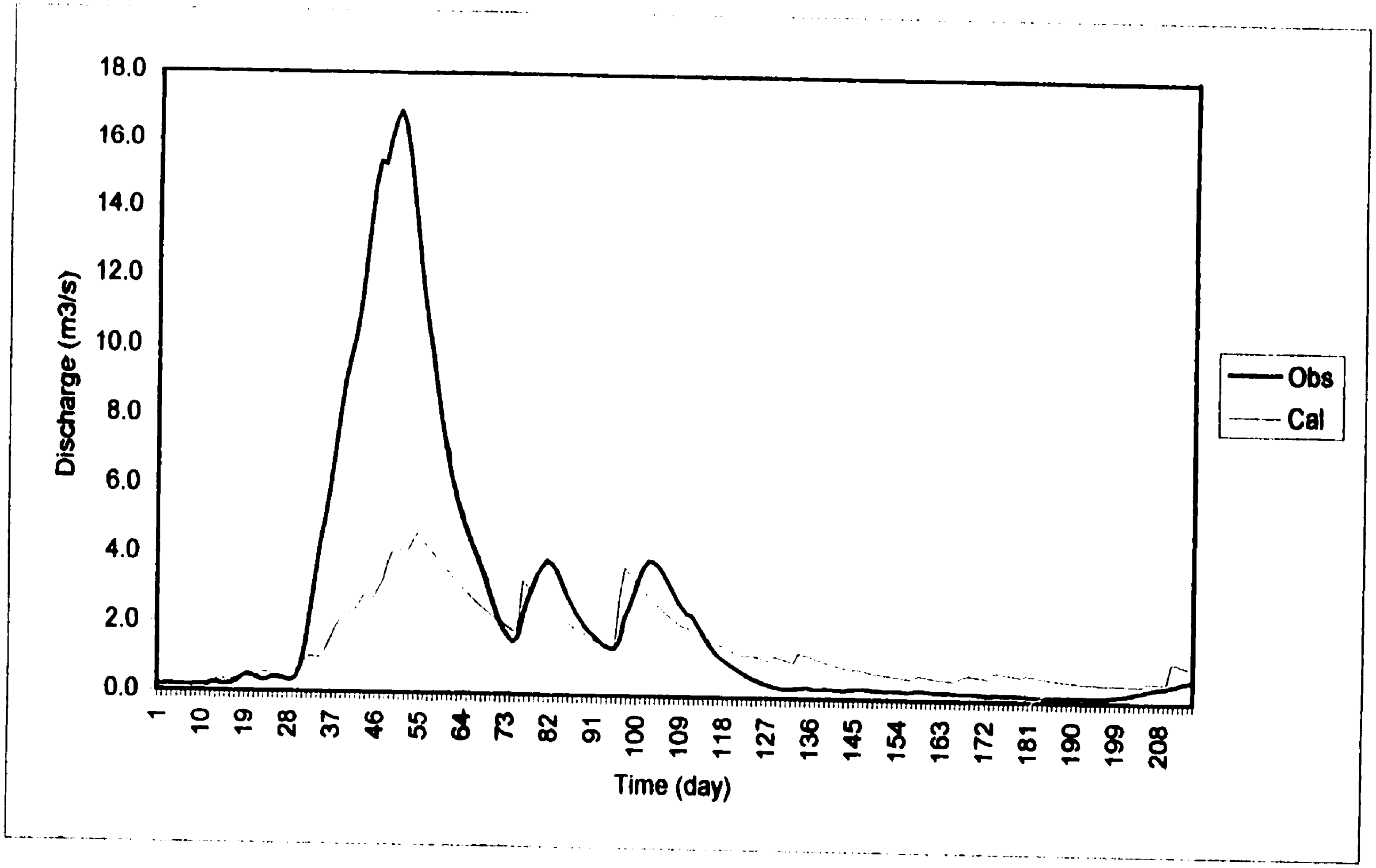


Figure 4.5 Hydrograph Comparison for the Sapochi River Basin Using SLURP 1995 Calibrated Parameters on 1994 Data

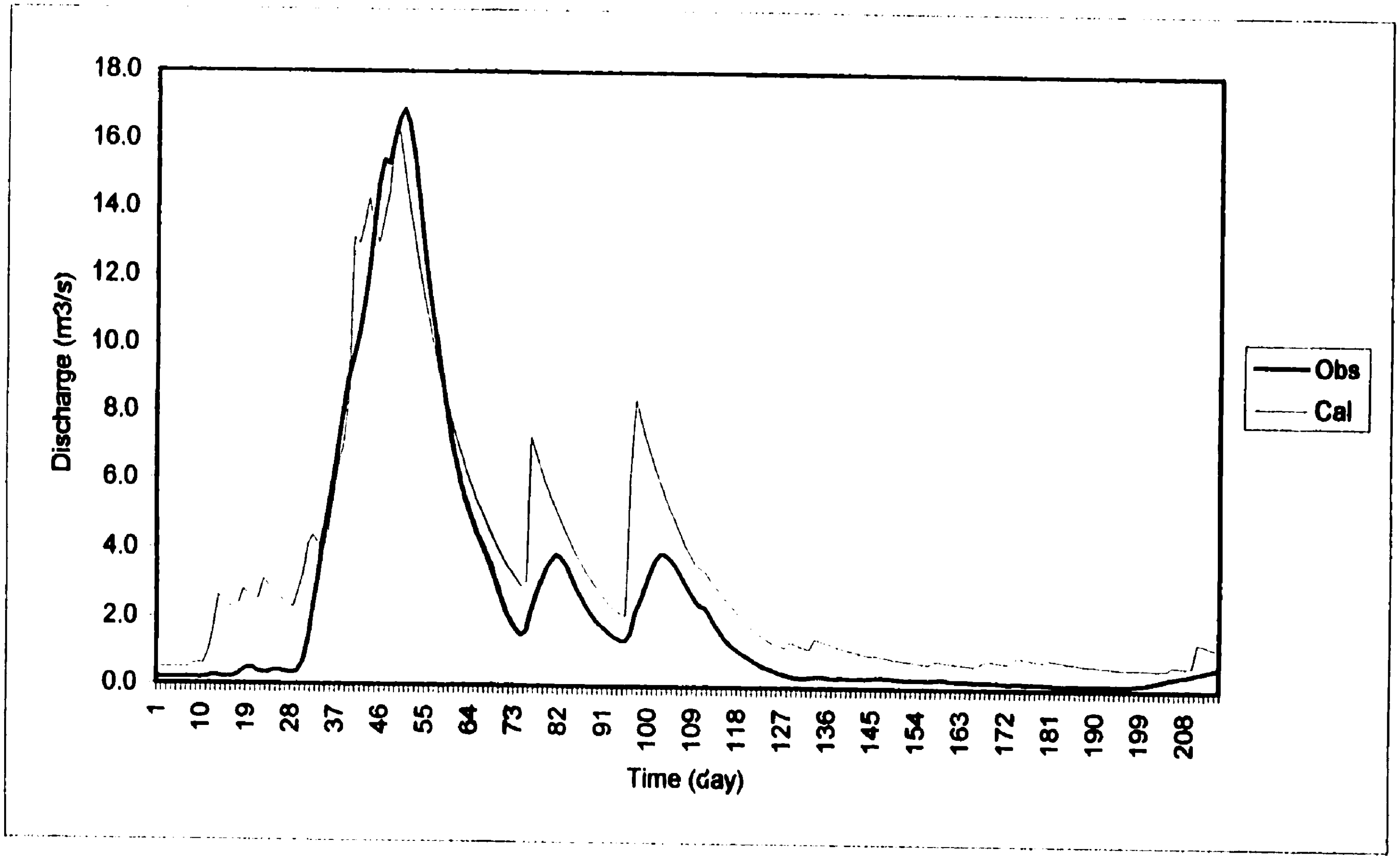


Figure 4.6 Hydrograph Comparison of the Sapochi River Basin Using SLURP 1994-1995 Optimized Parameters on 1994 Data

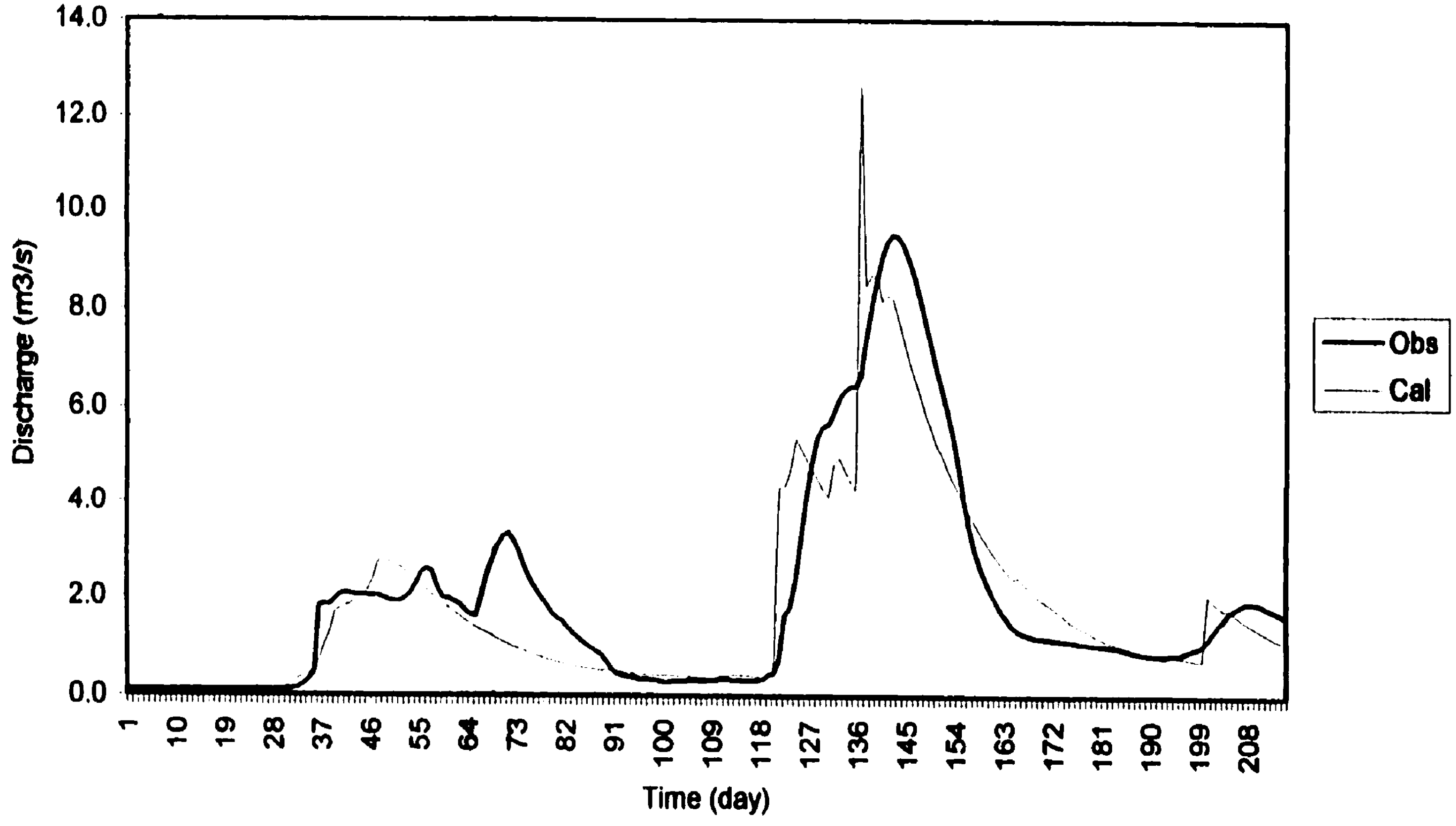


Figure 4.7 Hydrograph Comparison of the Sapochi River Basin Using SLURP 1994-1995 Optimized Parameters on 1995 Data

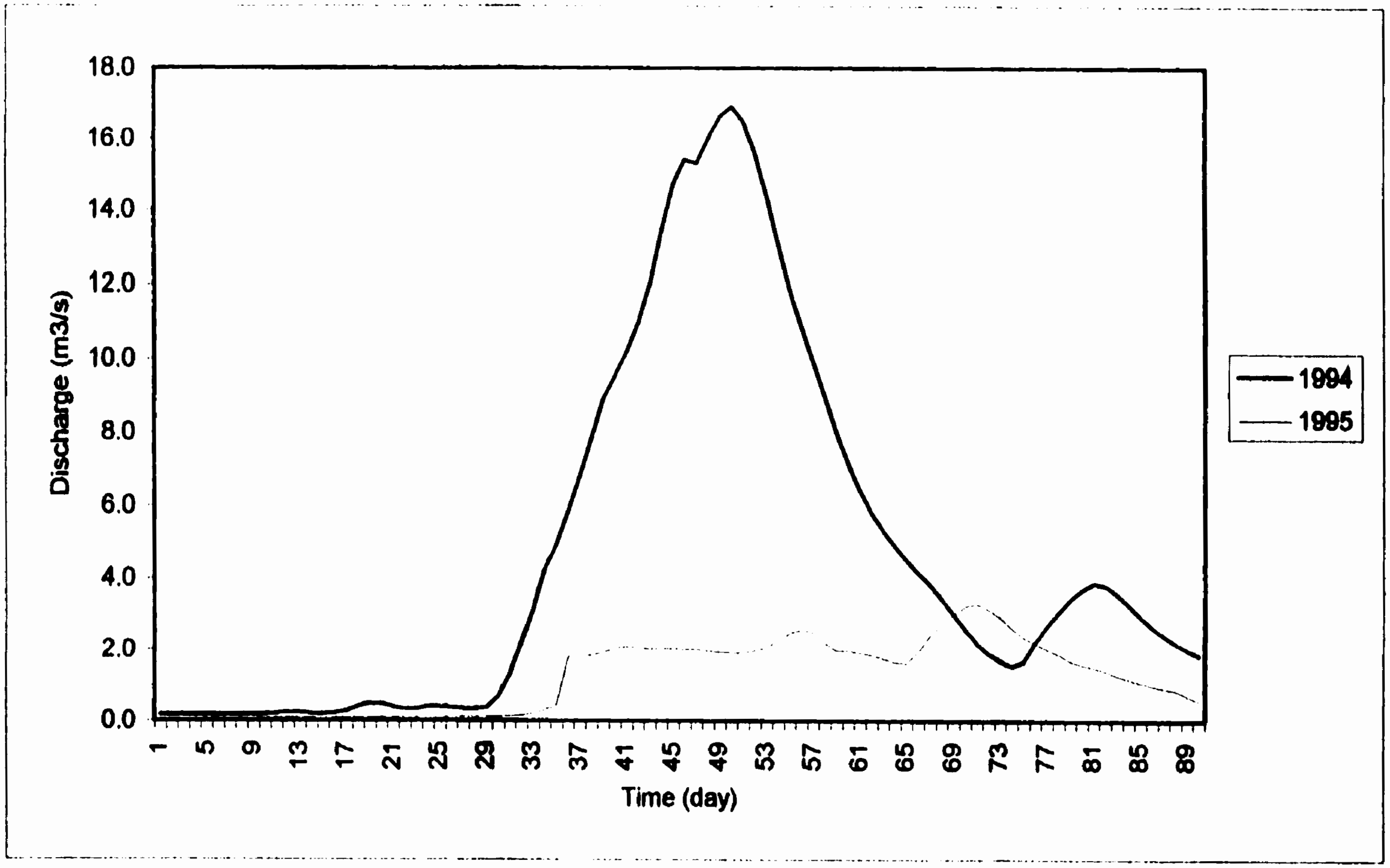


Figure 4.8 **Spring Discharge Comparison of the Sapochi River Basin For Year 1994 and 1995**

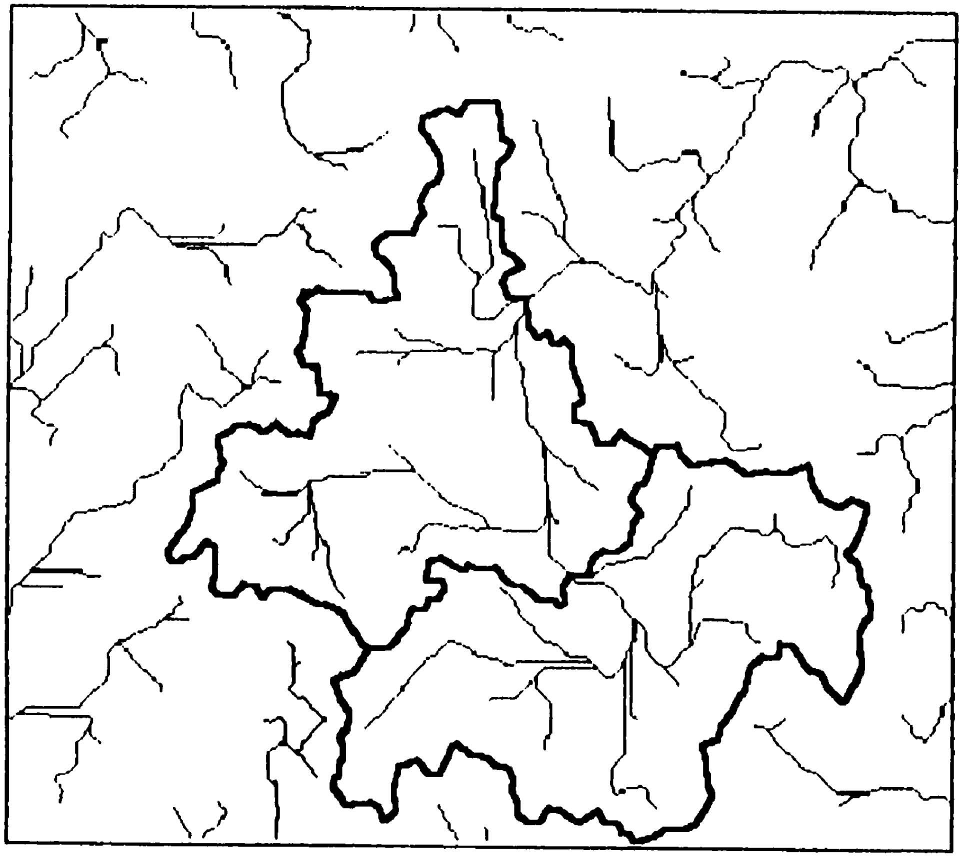


Figure 4.9 SLURP Watershed Sub-division for 2 ASAs

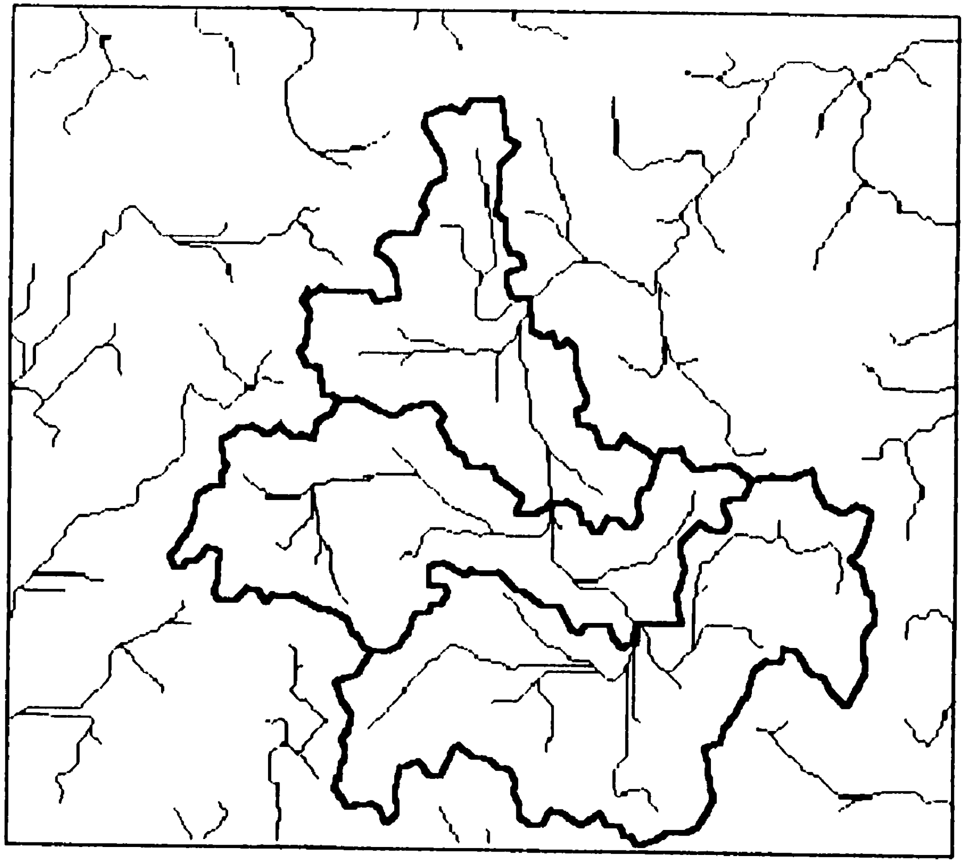


Figure 4.10 SLURP Watershed Sub-division for 3 ASAs

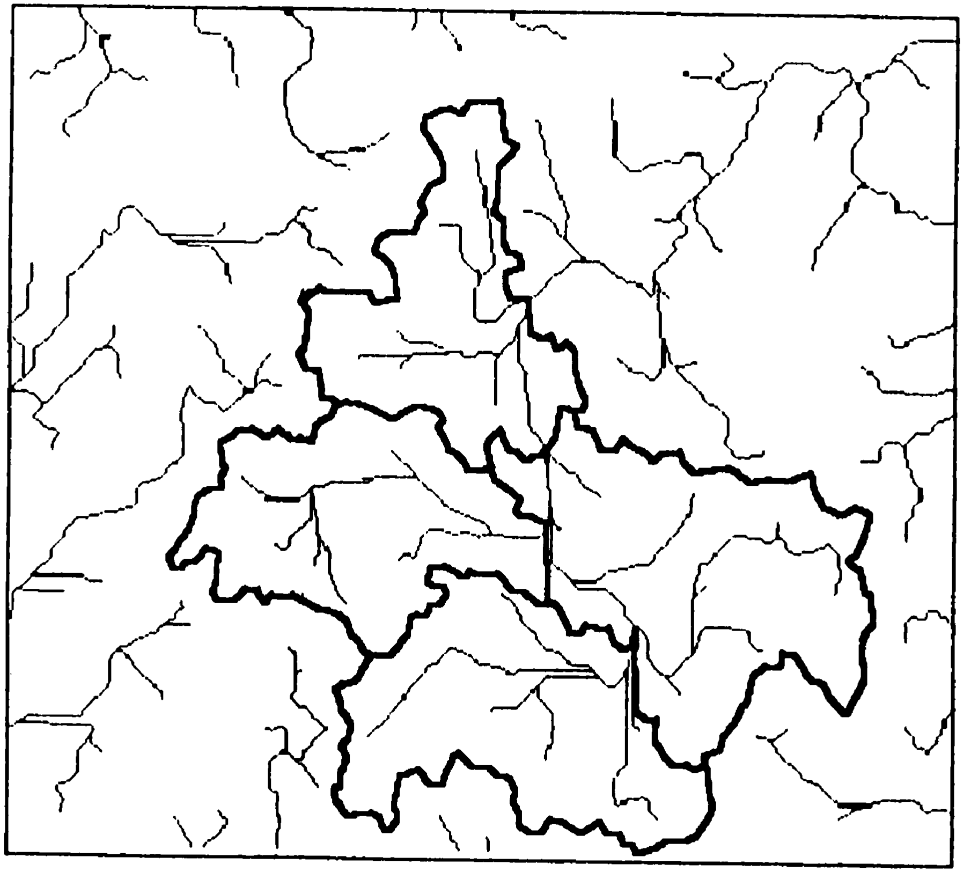


Figure 4.11 SLURP Watershed Sub-division for 5 ASAs

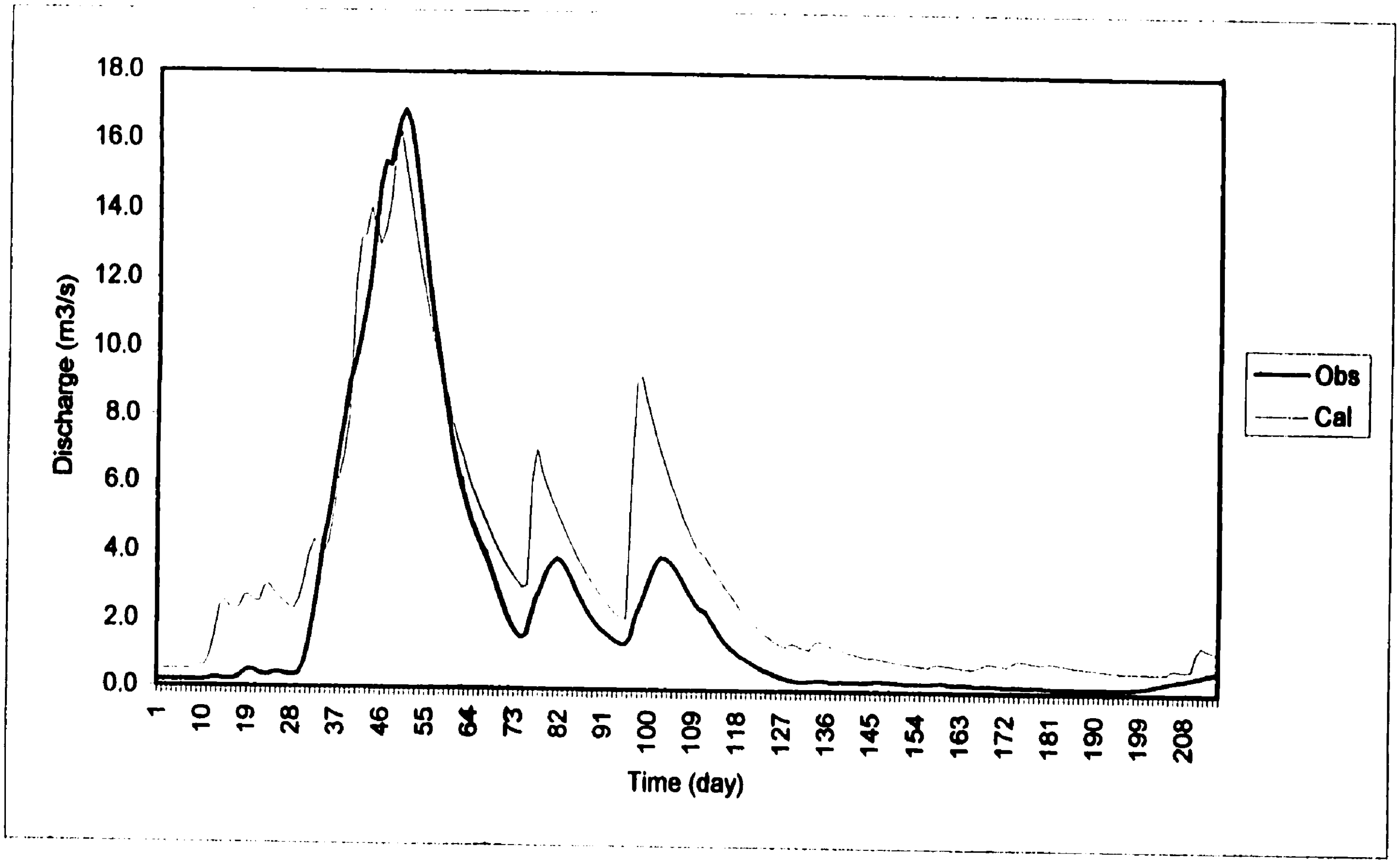


Figure 4.12 Hydrograph Comparison of the Sapochi River Basin Using Two ASAs for Year 1994

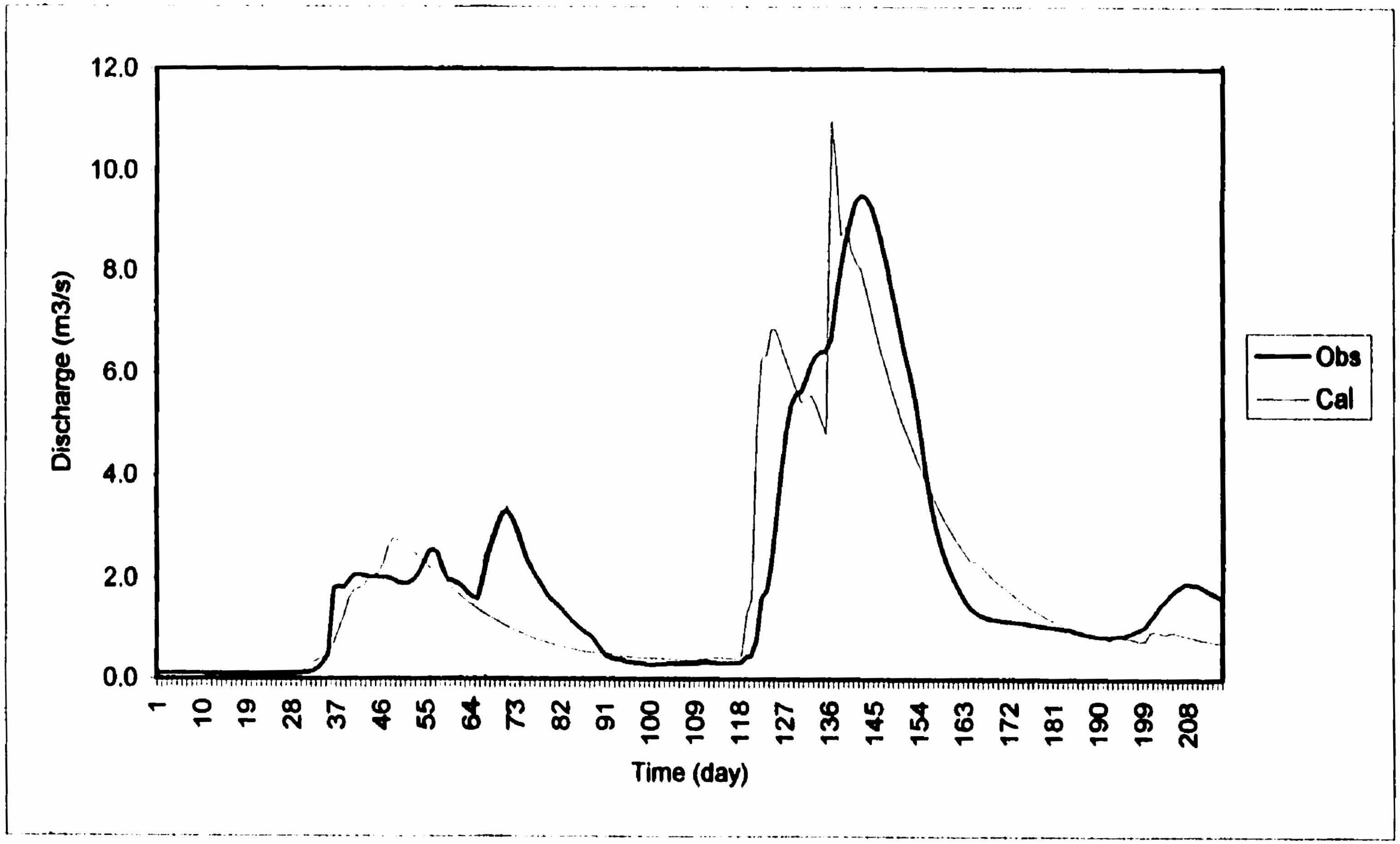


Figure 4.13 Hydrograph Comparison of the Sapochi River Basin Using Two ASAs for Year 1995

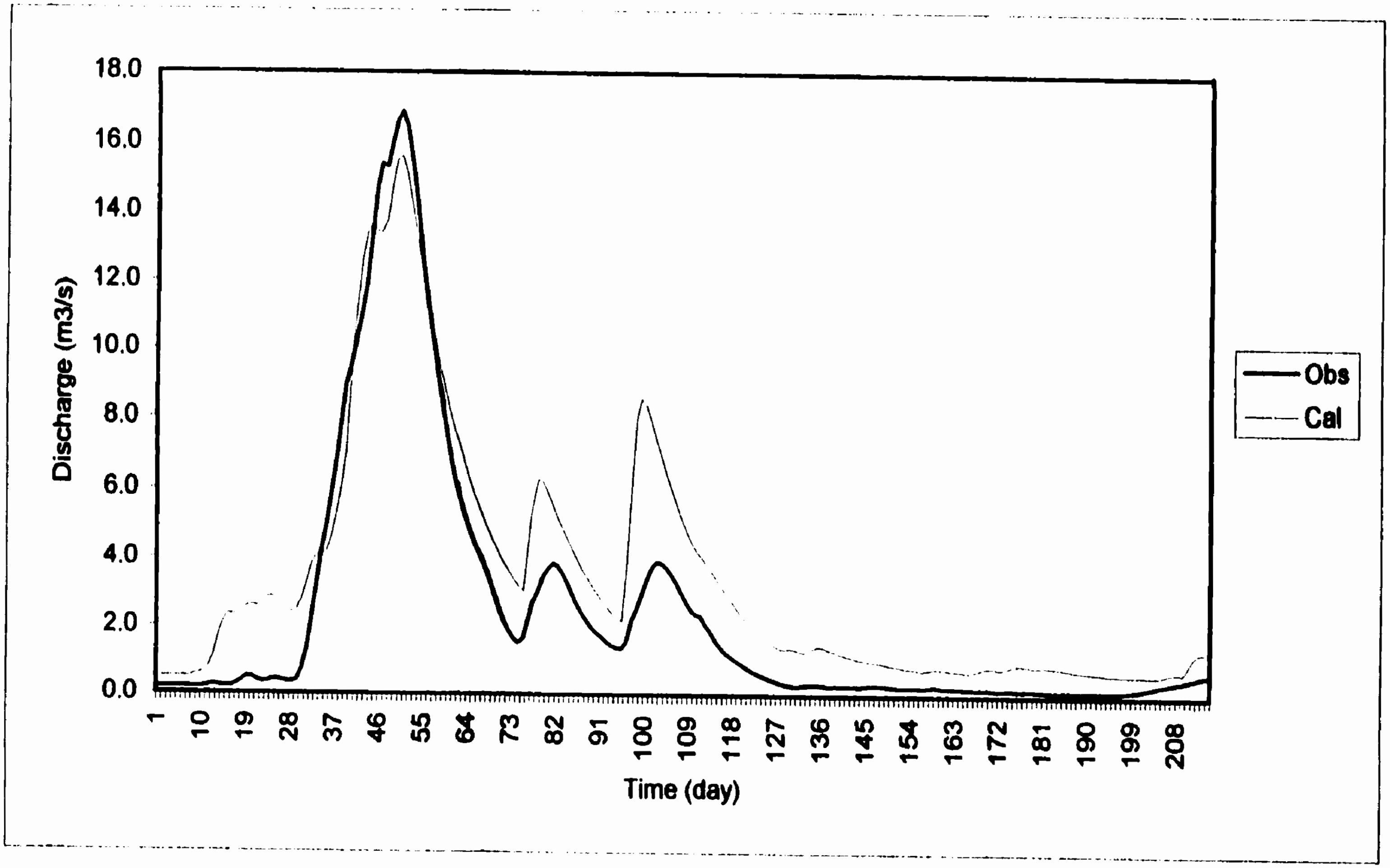


Figure 4.14 Hydrograph Comparison of the Sapochi River Basin Using Three ASAs for Year 1994

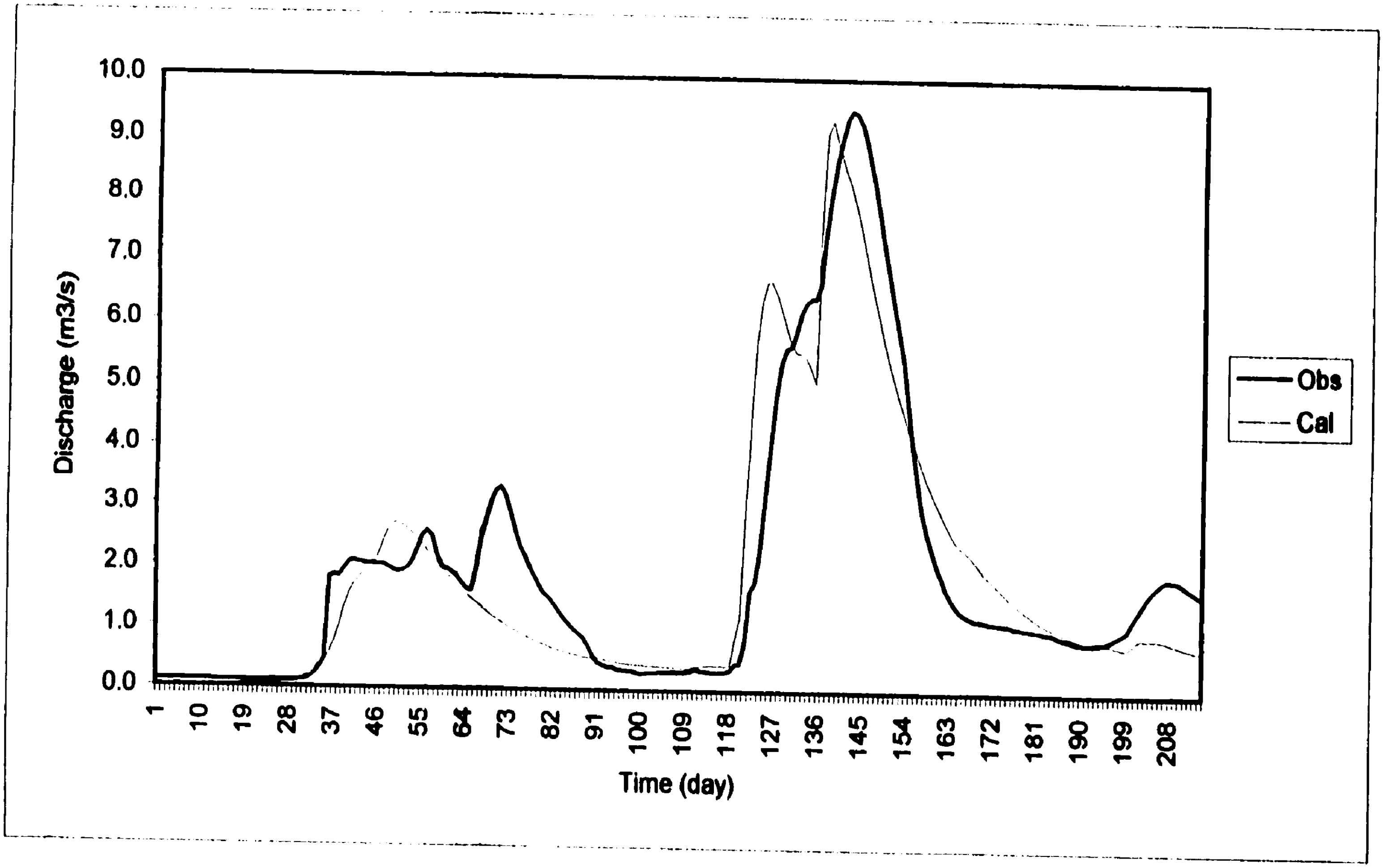


Figure 4.15 Hydrograph Comparison of the Sapochi River Basin Using Three ASAs for Year 1995

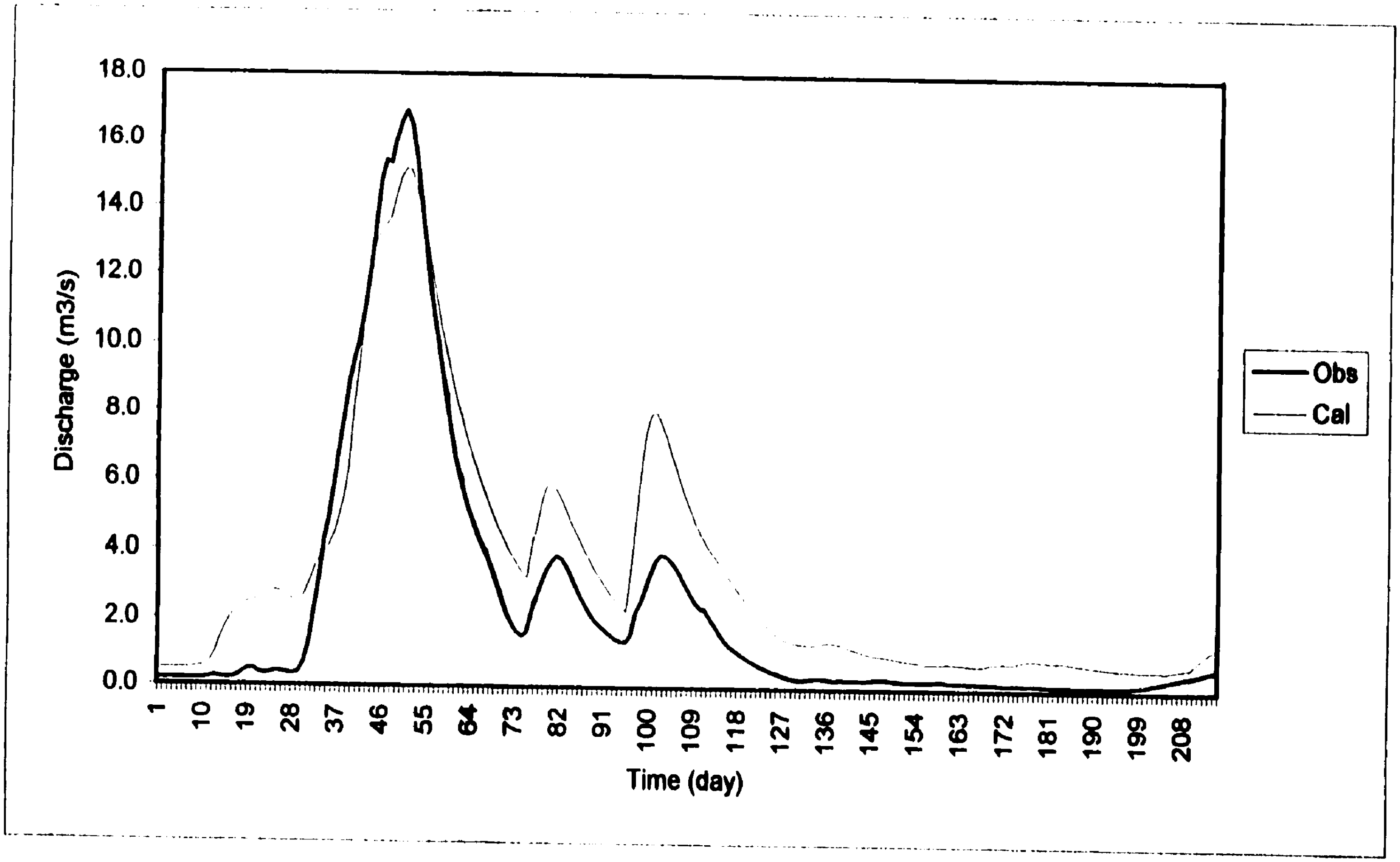


Figure 4.16 Hydrograph Comparison of the Sapochi River Basin Using Five ASAs for Year 1994

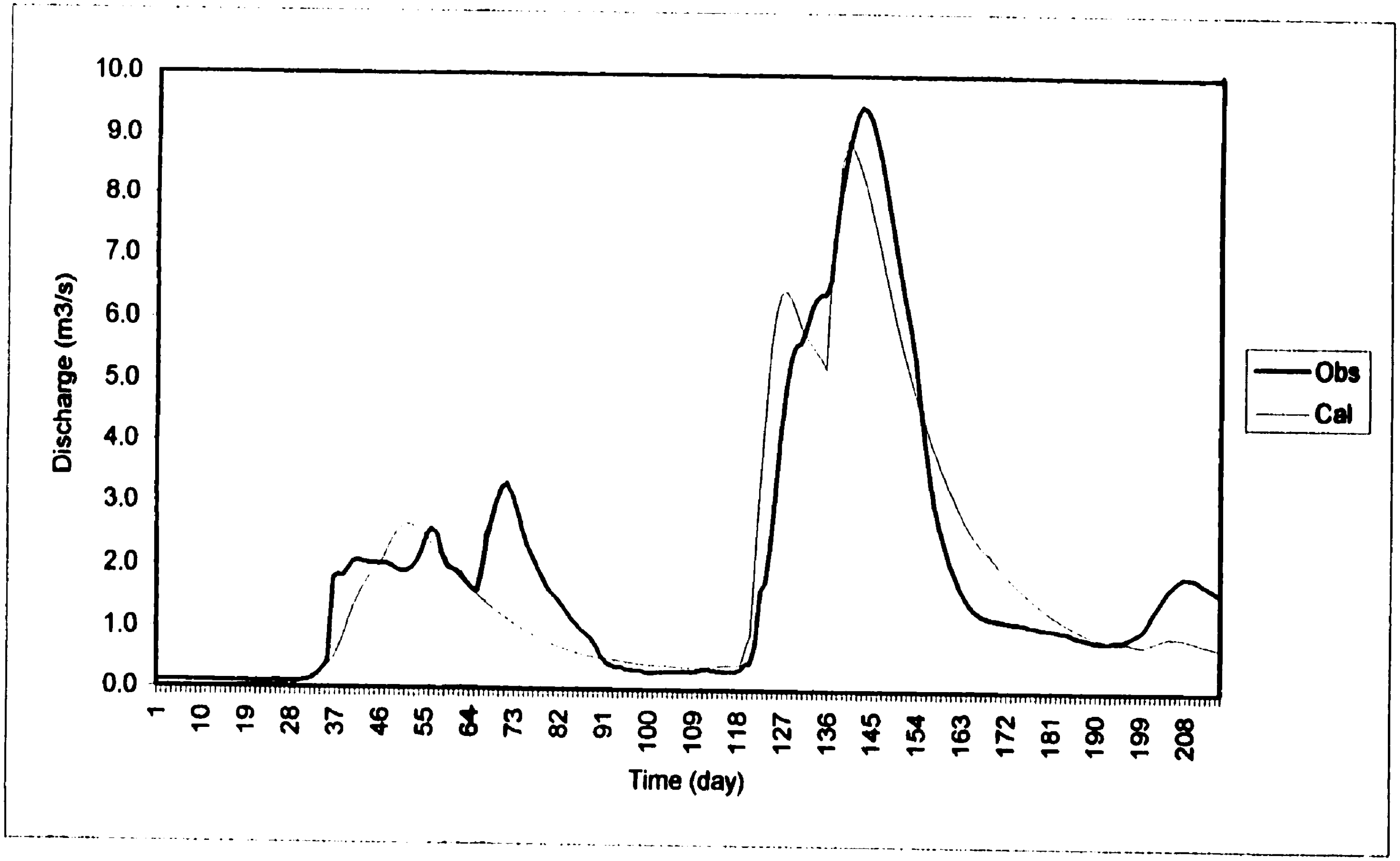


Figure 4.17 Hydrograph Comparison of the Sapochi River Basin Using Five ASAs for Year 1995

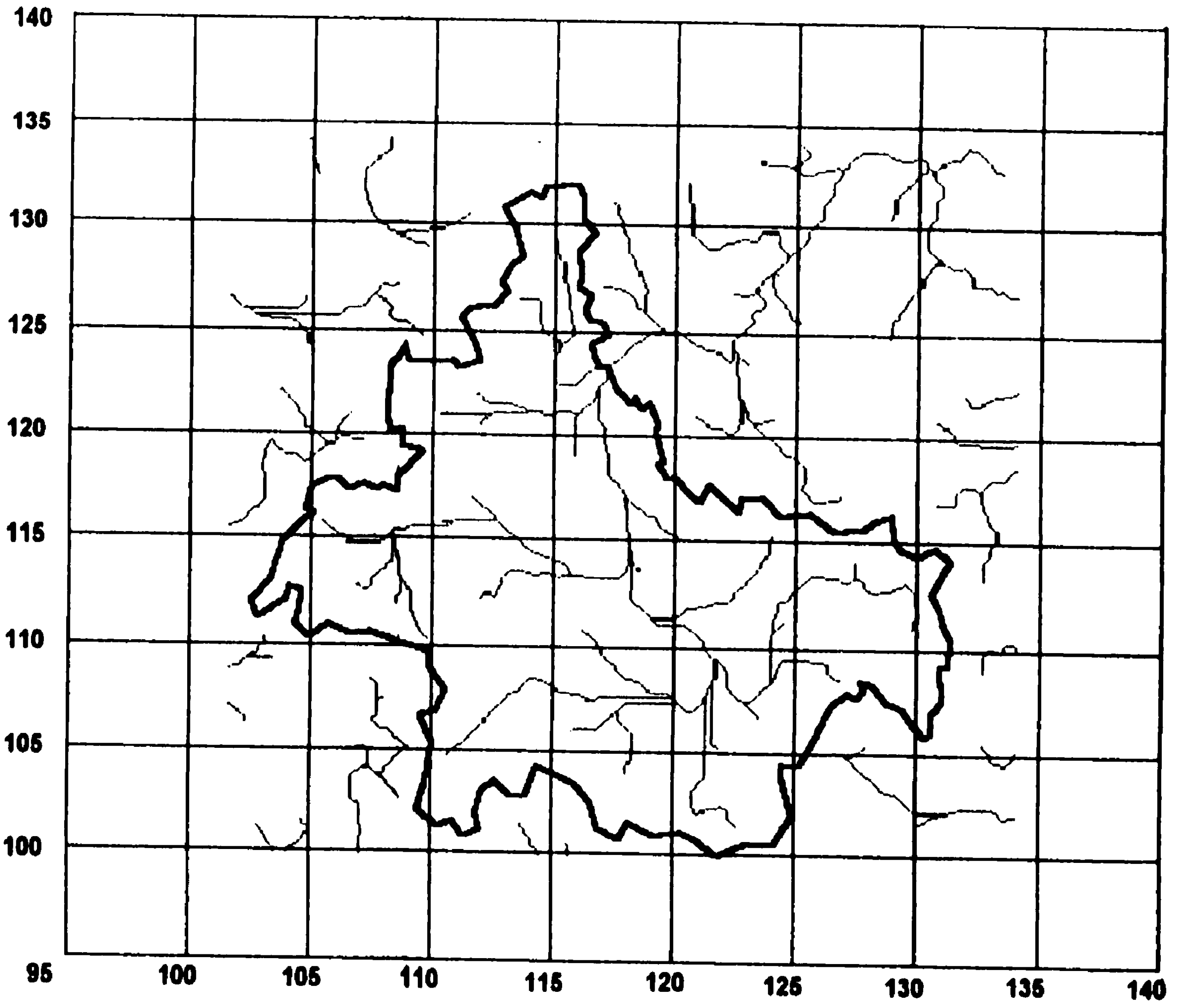
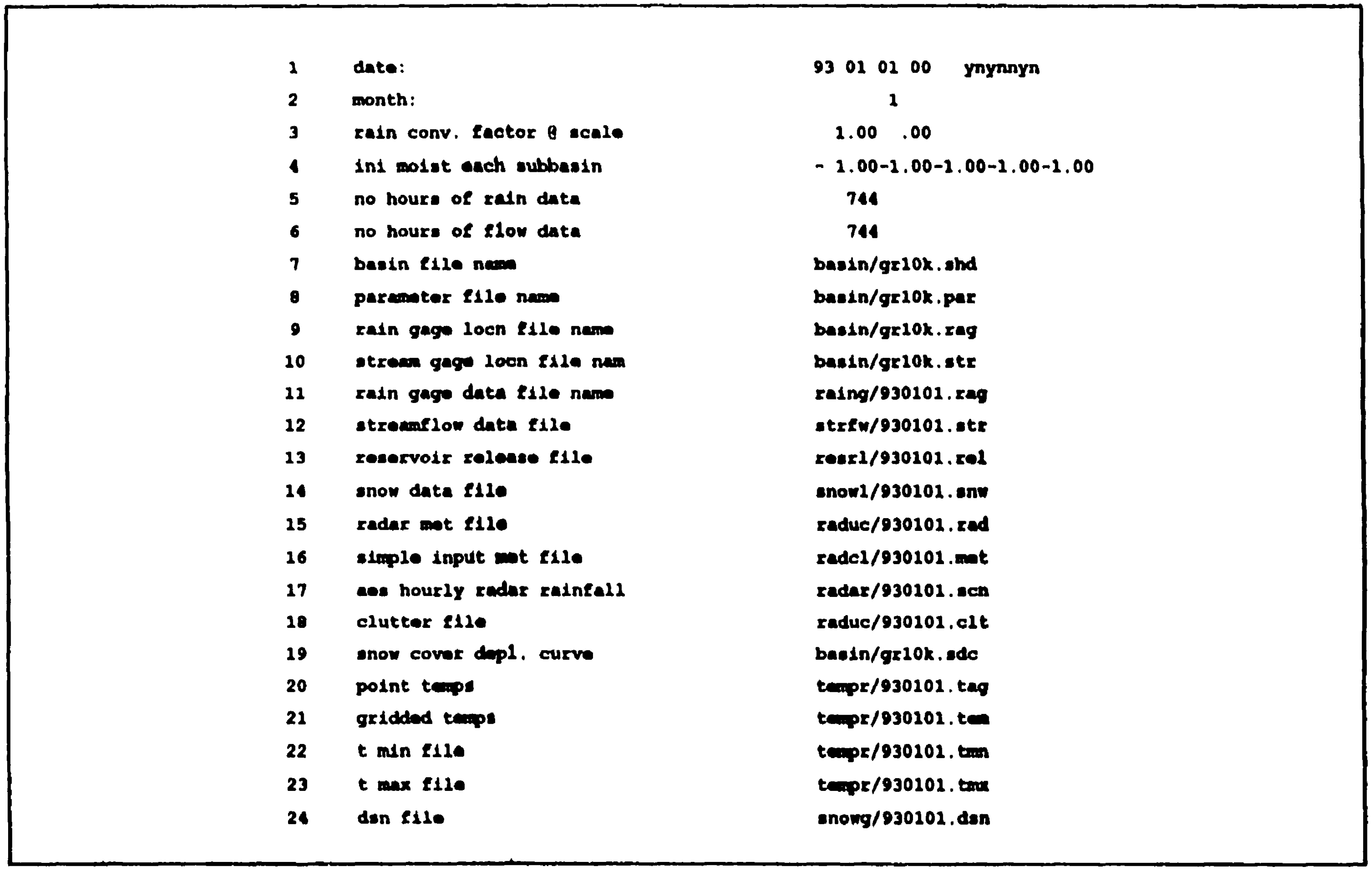


Figure 4.18 WATFLOOD Watershed Sub-division for 5km x 5 km GRU



```
1    date:                          93 01 01 00   ynynnyn
2    month:                               1
3    rain conv. factor @ scale        1.00  .00
4    ini moist each subbasin        - 1.00-1.00-1.00-1.00-1.00
5    no hours of rain data             744
6    no hours of flow data             744
7    basin file name                basin/gr10k.shd
8    parameter file name            basin/gr10k.par
9    rain gage locn file name       basin/gr10k.rag
10   stream gage locn file nam      basin/gr10k.str
11   rain gage data file name       raing/930101.rag
12   streamflow data file           strfw/930101.str
13   reservoir release file         resrl/930101.rel
14   snow data file                 snow1/930101.snw
15   radar met file                 raduc/930101.rad
16   simple input met file          radcl/930101.met
17   aes hourly radar rainfall      radar/930101.scn
18   clutter file                   raduc/930101.clt
19   snow cover depl. curve         basin/gr10k.sdc
20   point temps                    tempr/930101.tag
21   gridded temps                  tempr/930101.tem
22   t min file                     tempr/930101.tmn
23   t max file                     tempr/930101.tmx
24   dsn file                       snowg/930101.dsn
```

Figure 4.19 Example of Event File for WATFLOOD

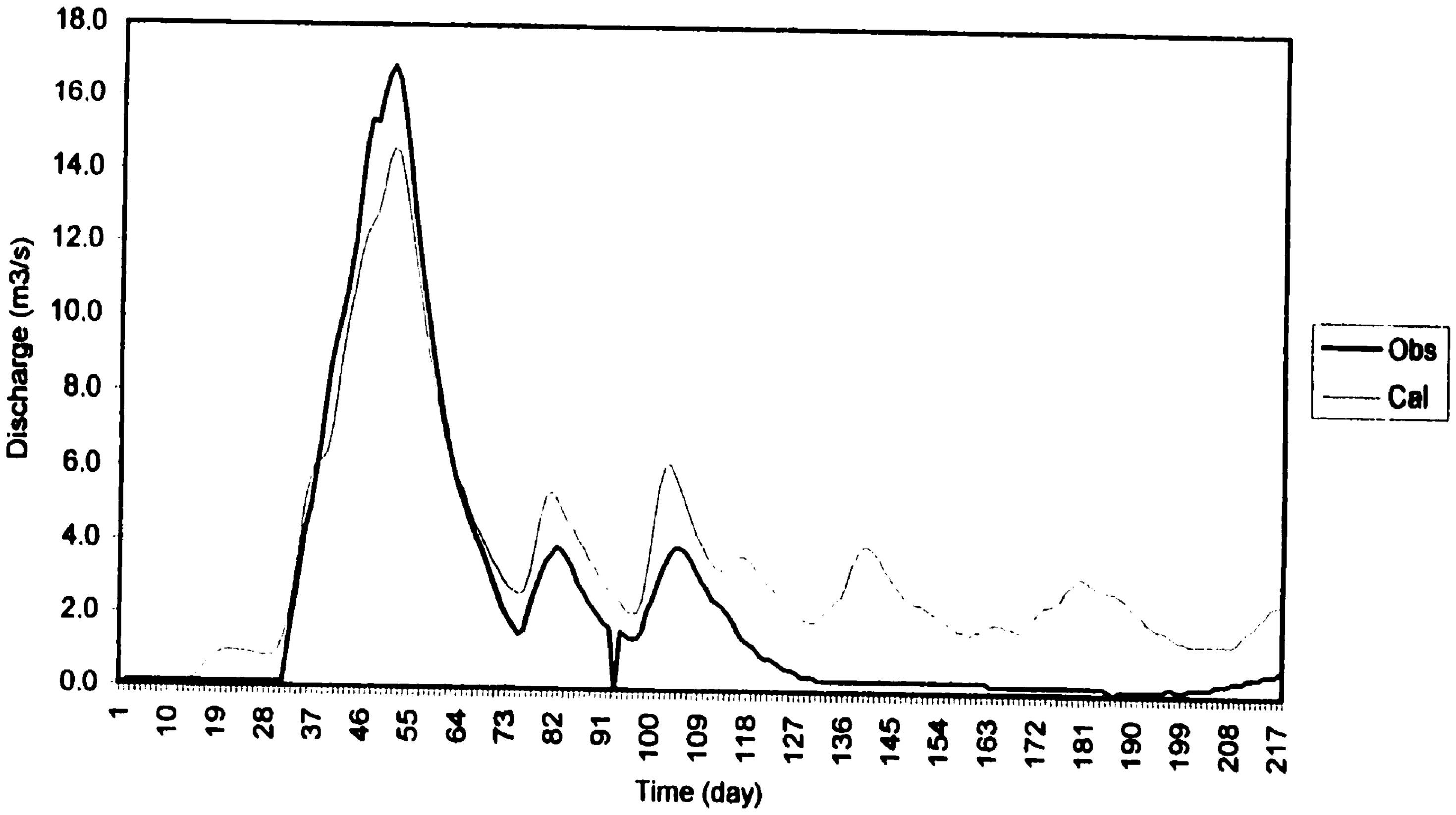


Figure 4.20 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD 1994 Calibrated Parameters on 1994 Data

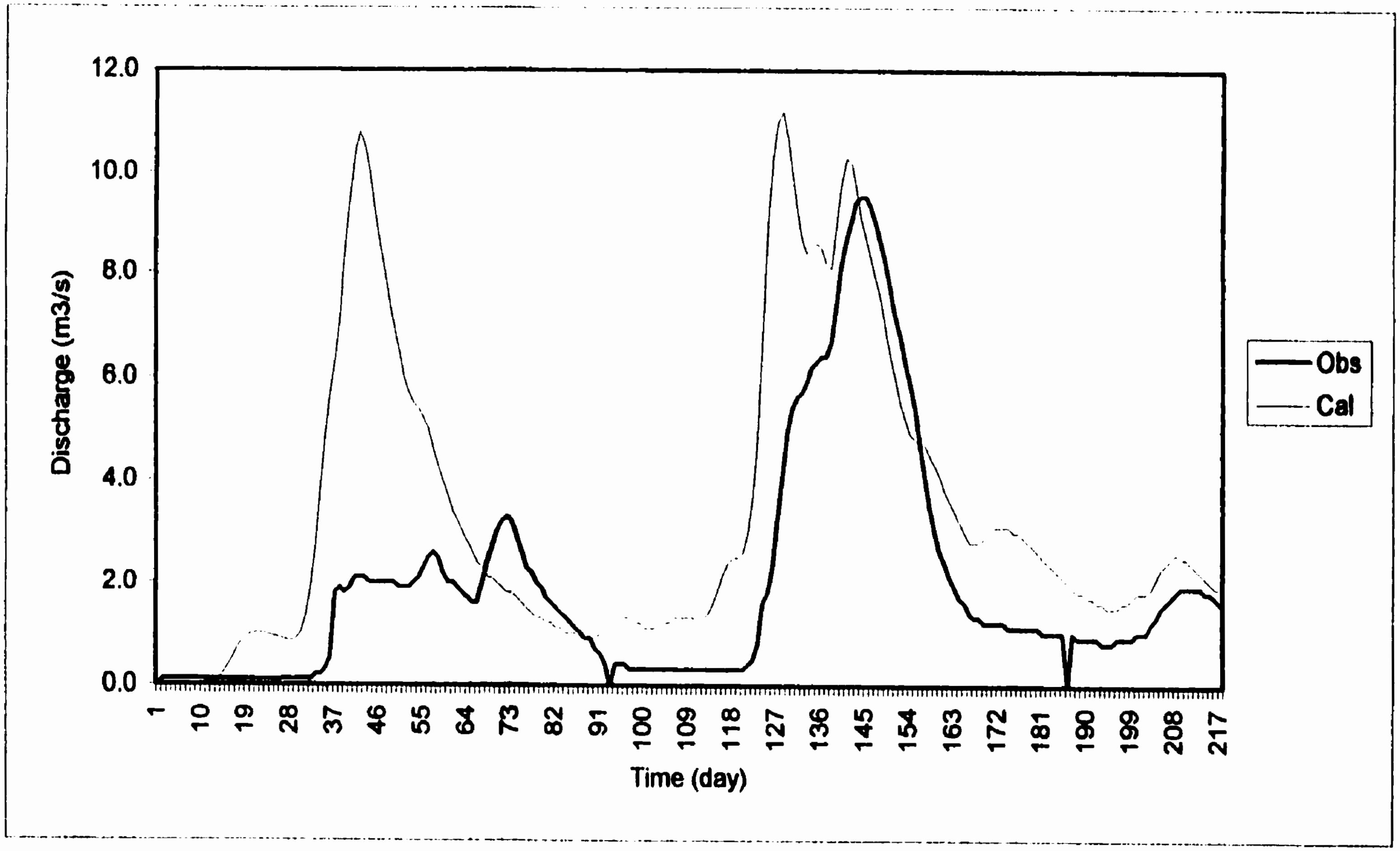


Figure 4.21 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD 1994 Calibrated Parameters on 1995 Data

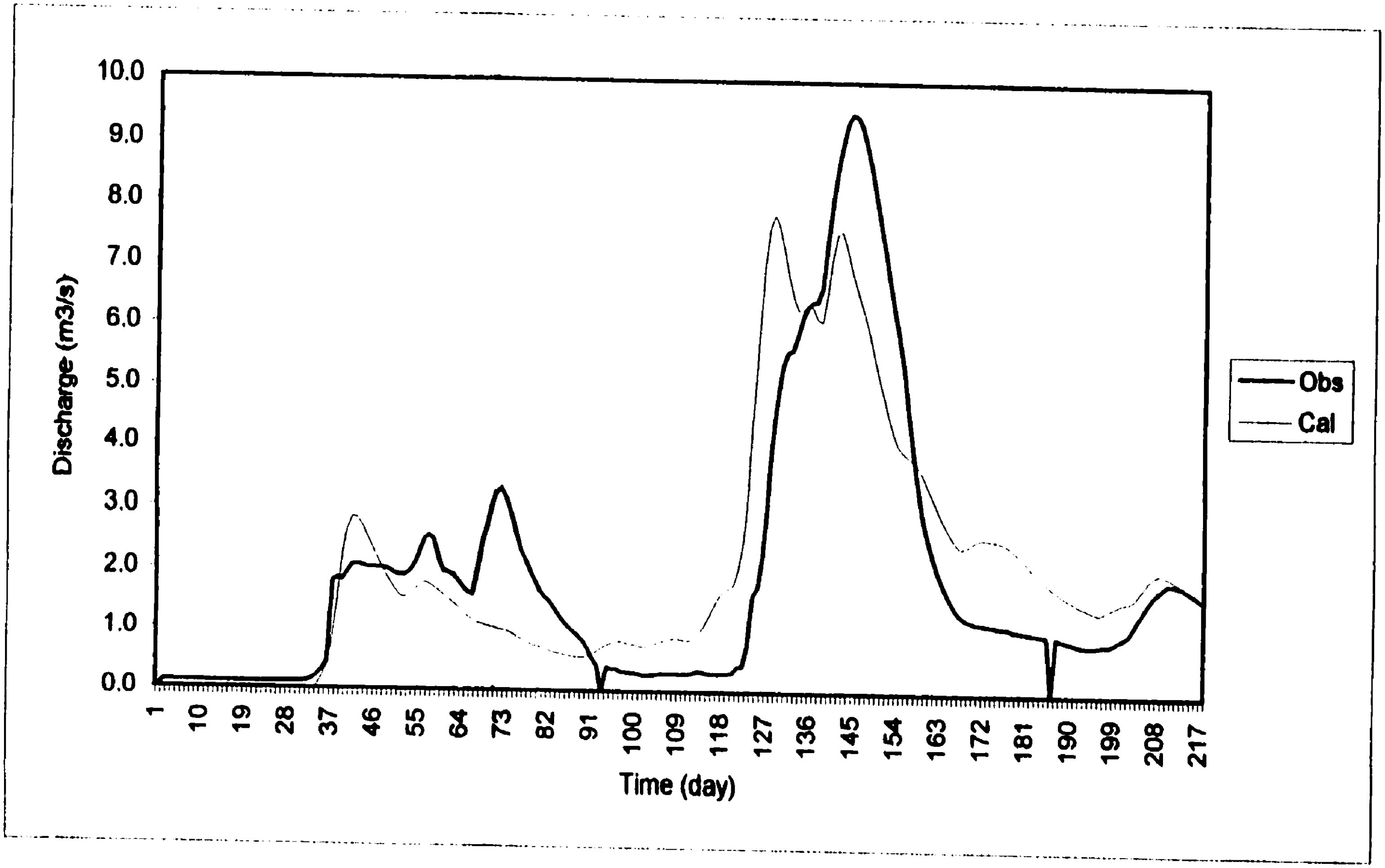


Figure 4.22 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD 1995 Calibrated Parameters on 1995 Data

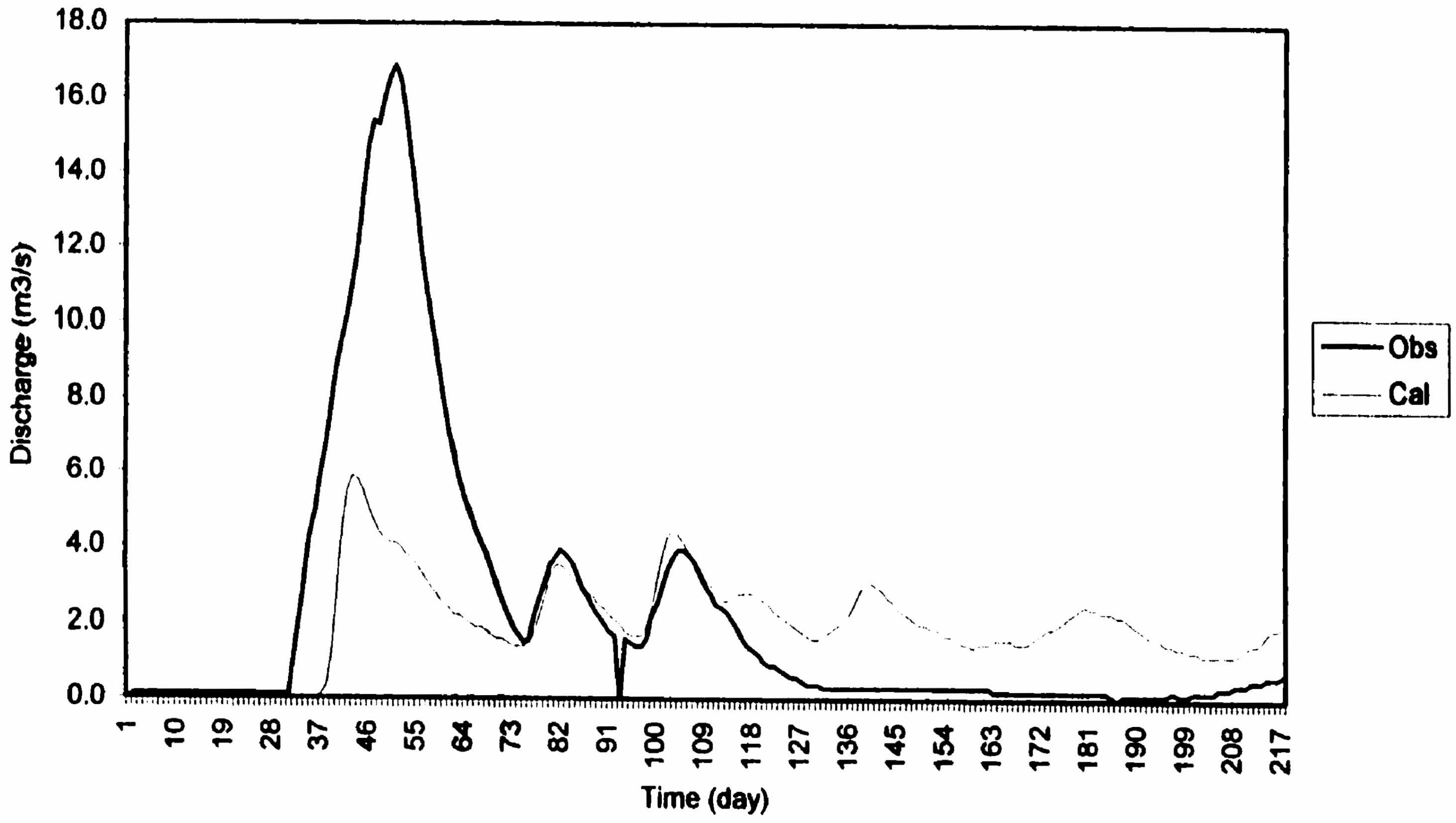


Figure 4.23 **Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD 1995 Calibrated Parameters on 1994 Data**

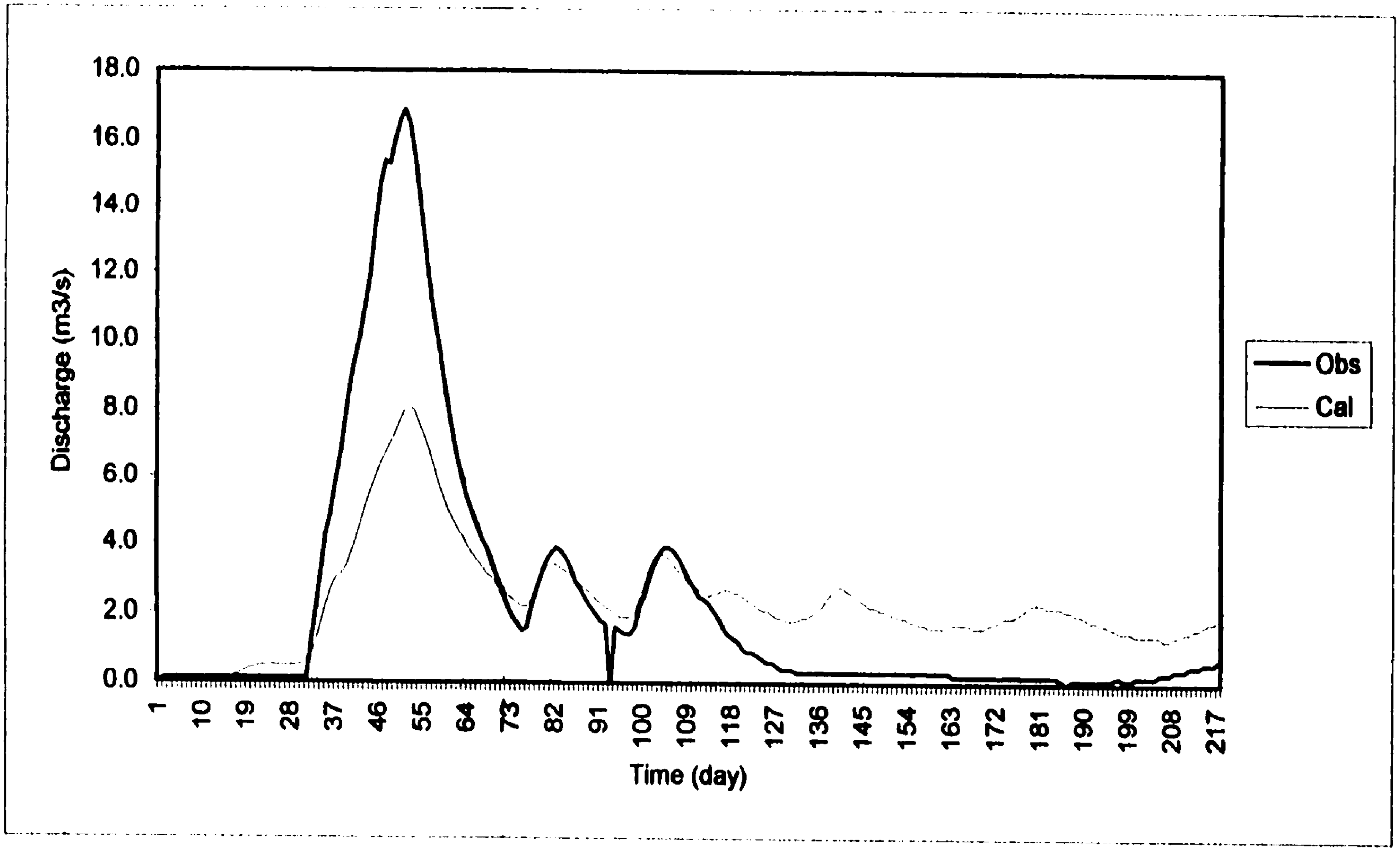


Figure 4.24 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD Optimized Parameters on 1994 Data

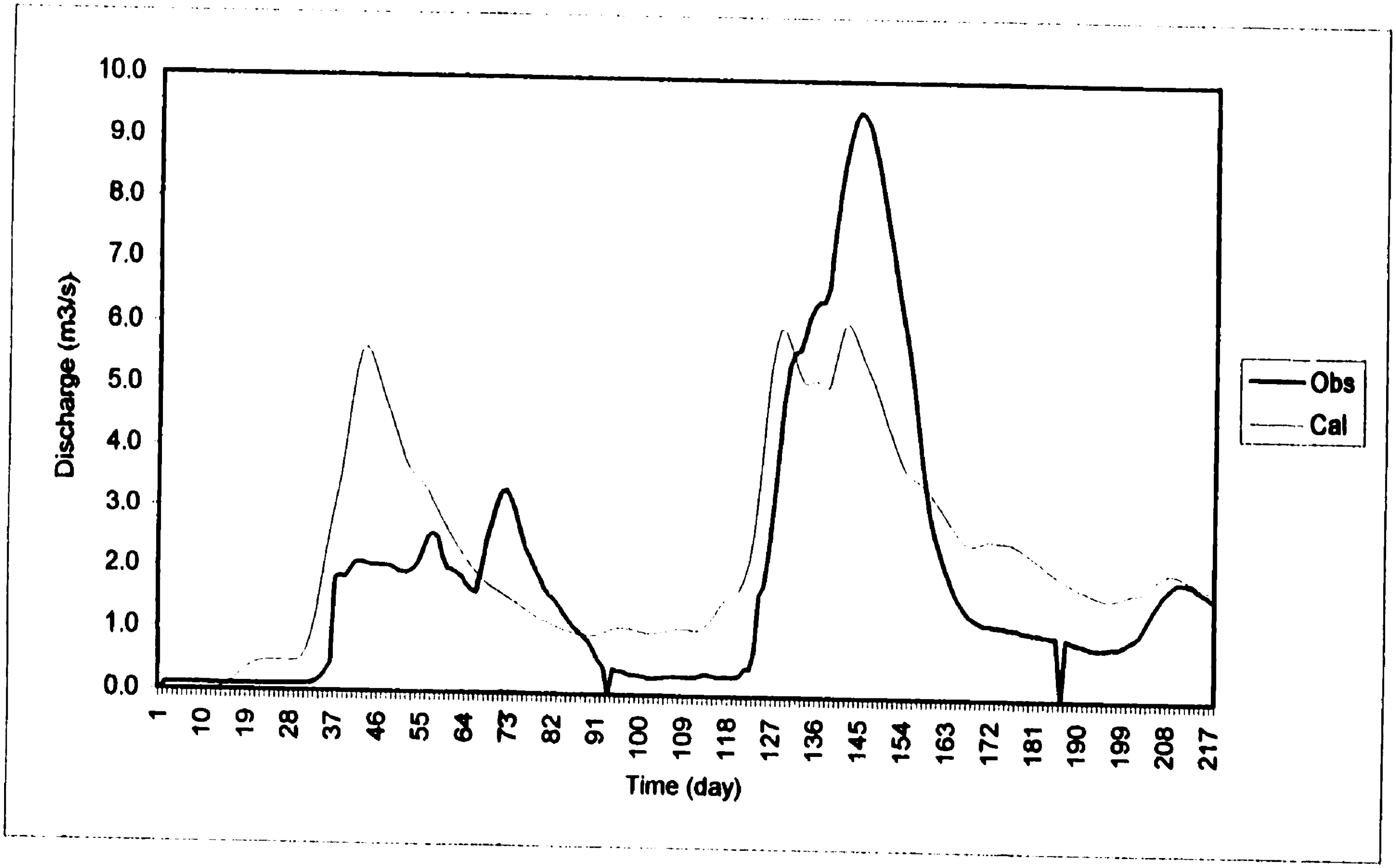


Figure 4.25 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD Optimized Parameters on 1995 Data

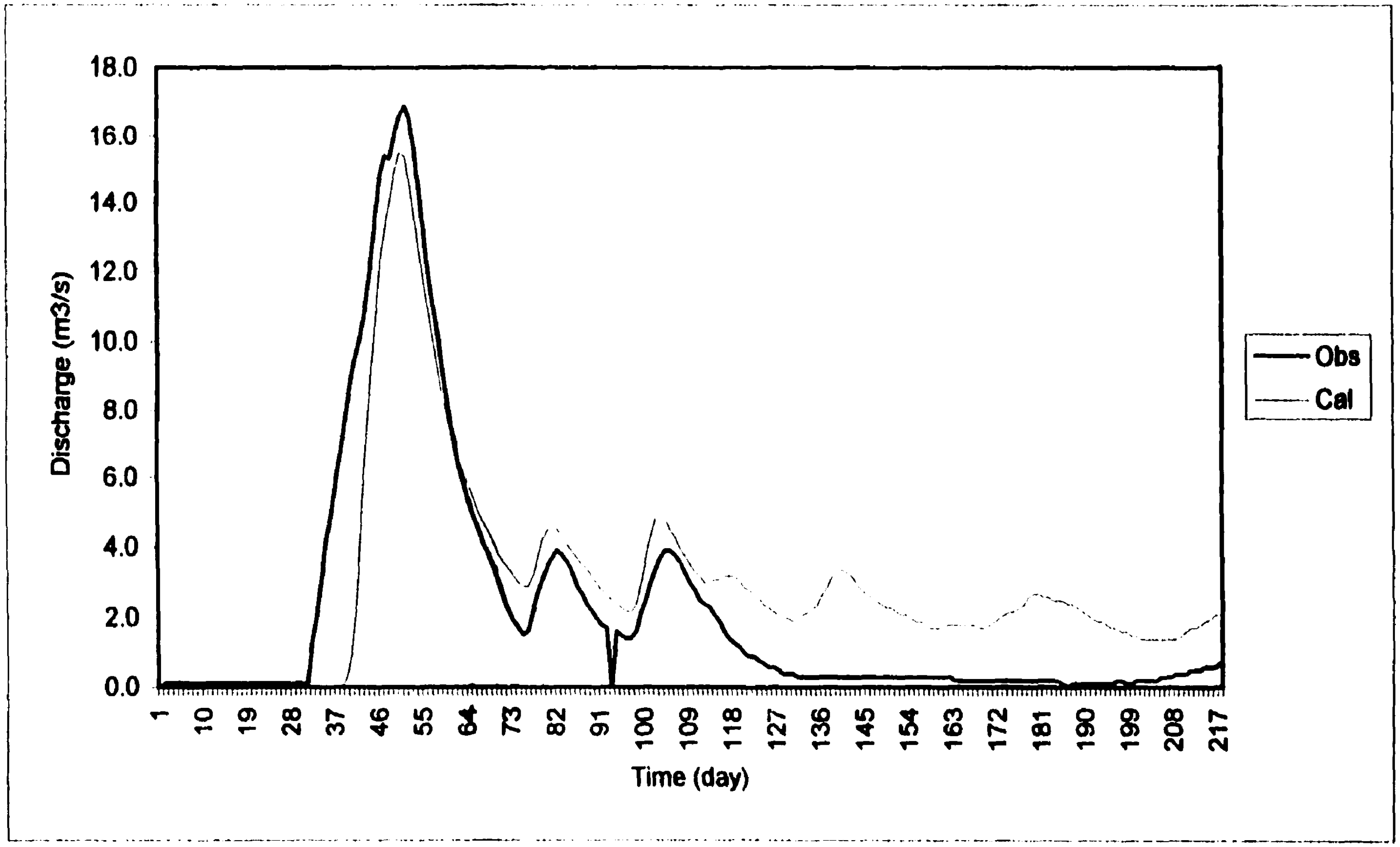


Figure 4.26 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD Snow Cover Optimization on 1994 Data

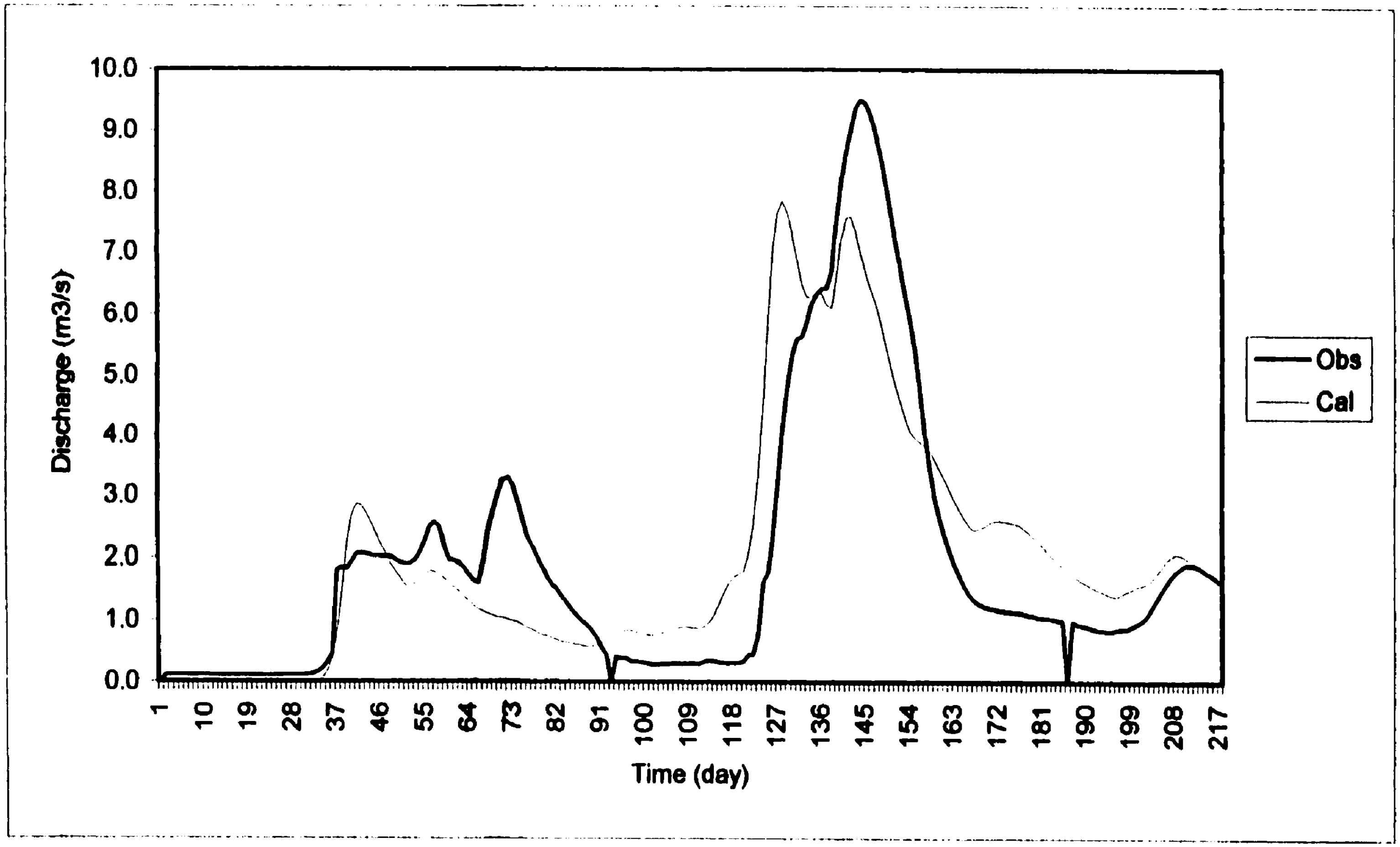


Figure 4.27 Hydrograph Comparison of the Sapochi River Basin Using WATFLOOD Snow Cover Optimization on 1995 Data

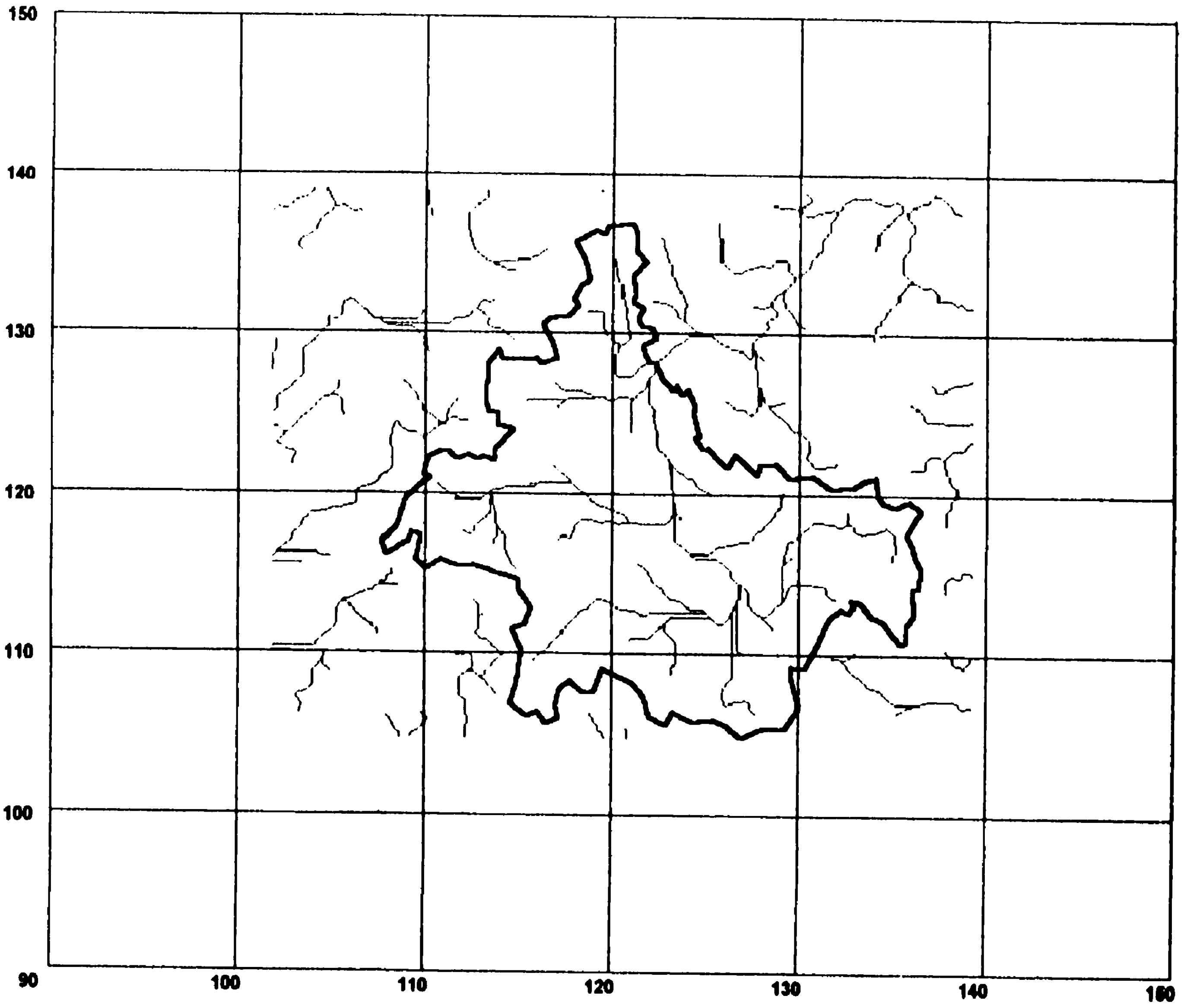


Figure 4.28 WATFLOOD Watershed Sub-division for 10km x 10km GRU

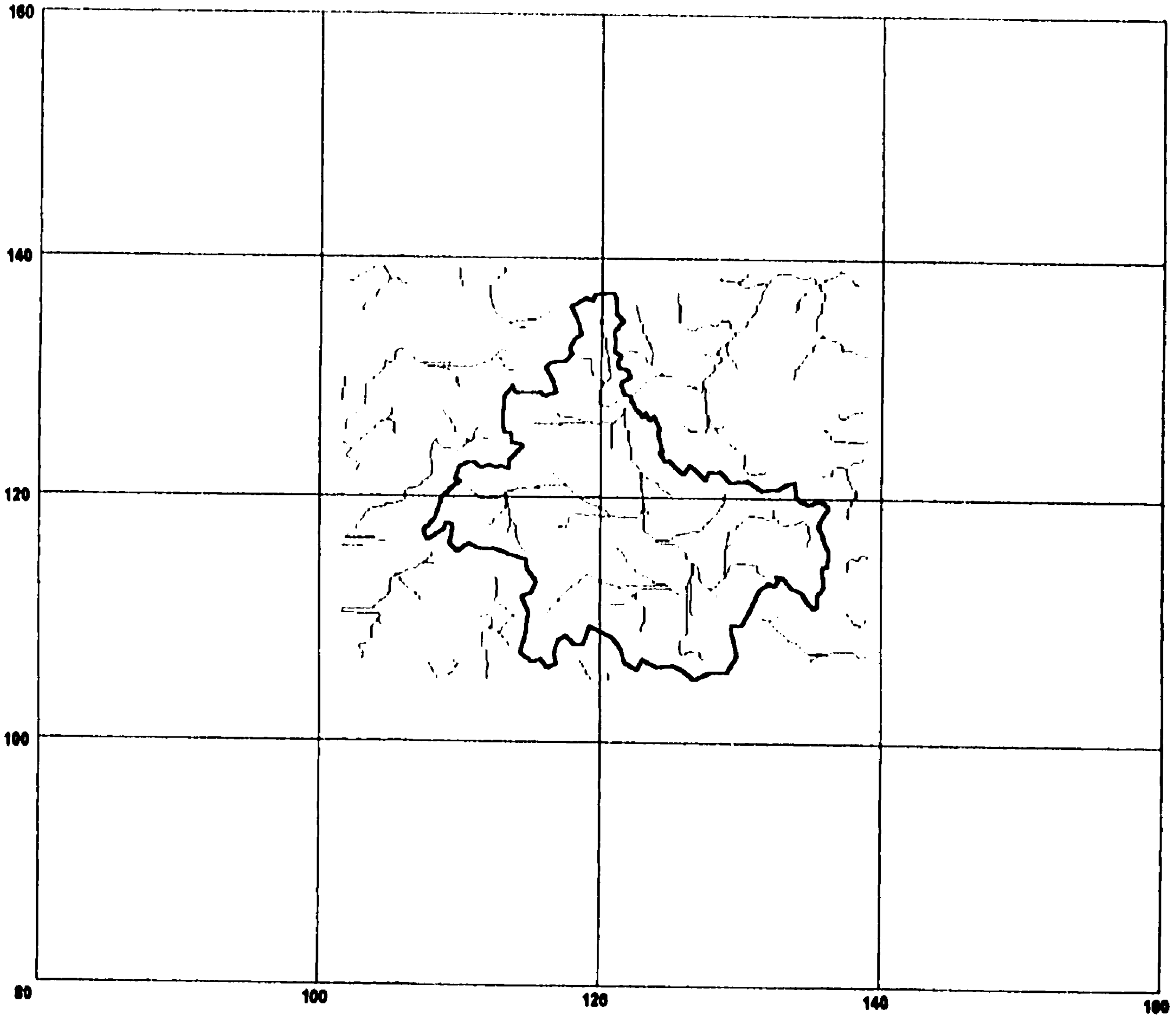


Figure 4.29 WATFLOOD Watersheed Sub-division for 20km x 20km GRU

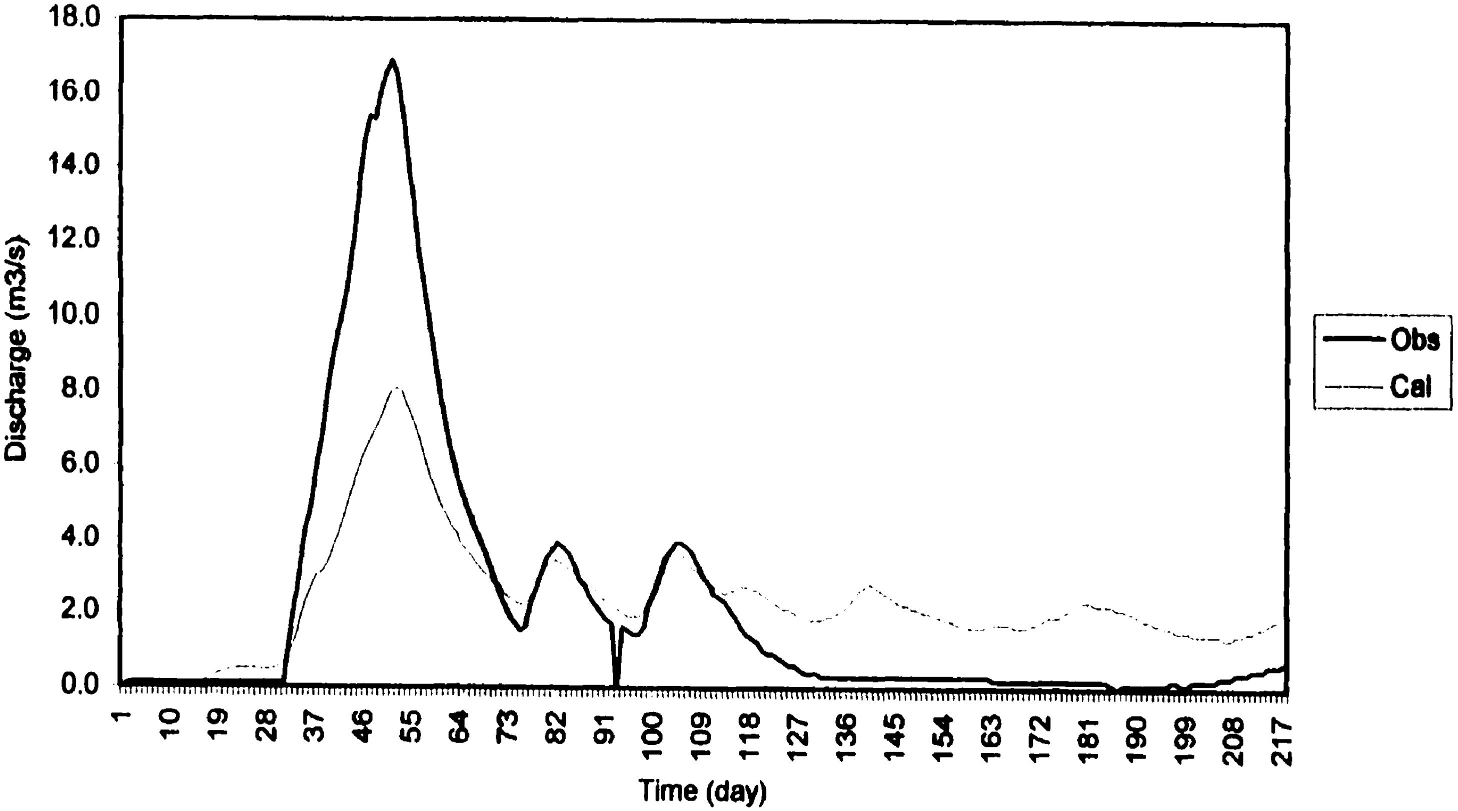


Figure 4.30 Hydrograph Comparison of the Sapochi River Basin Using 5km x 5km Grid Size of GRU for Year 1994

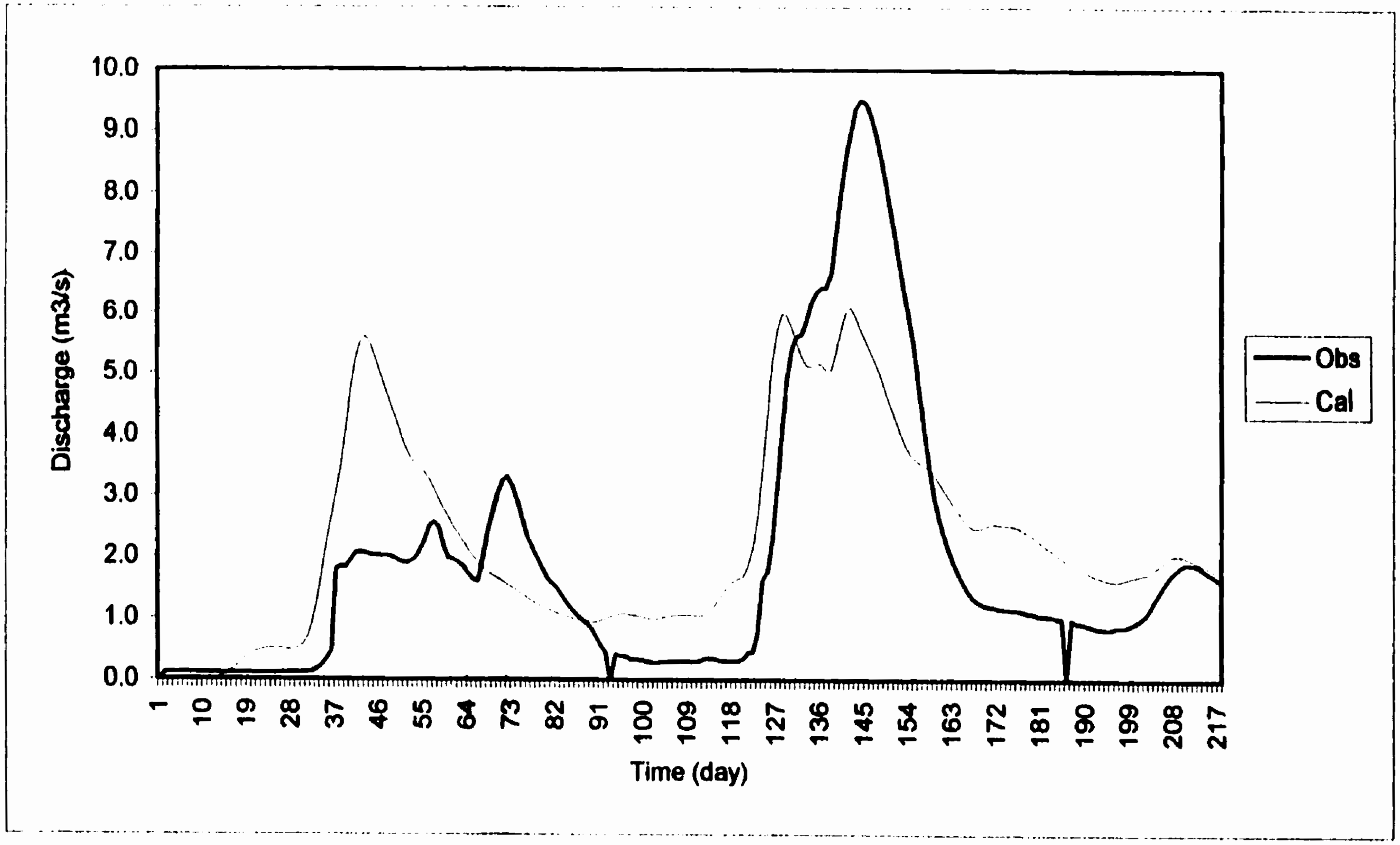


Figure 4.31 Hydrograph Comparison of the Sapochi River Basin Using 5km x 5km Grid Size of GRU for Year 1995

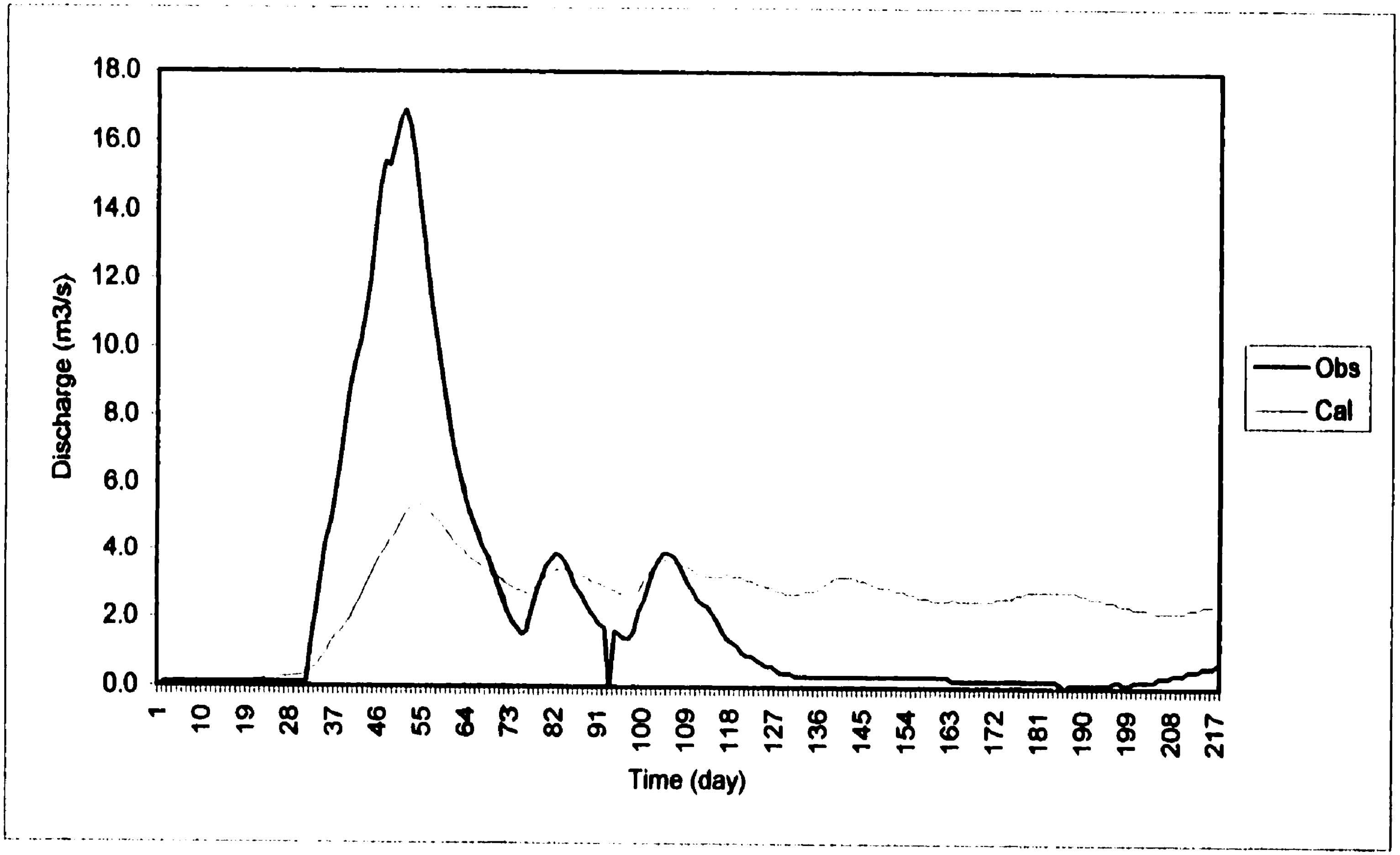


Figure 4.32 Hydrograph Comparison of the Sapochi River Basin Using 10km x 10km Grid Size of GRU for Year 1994

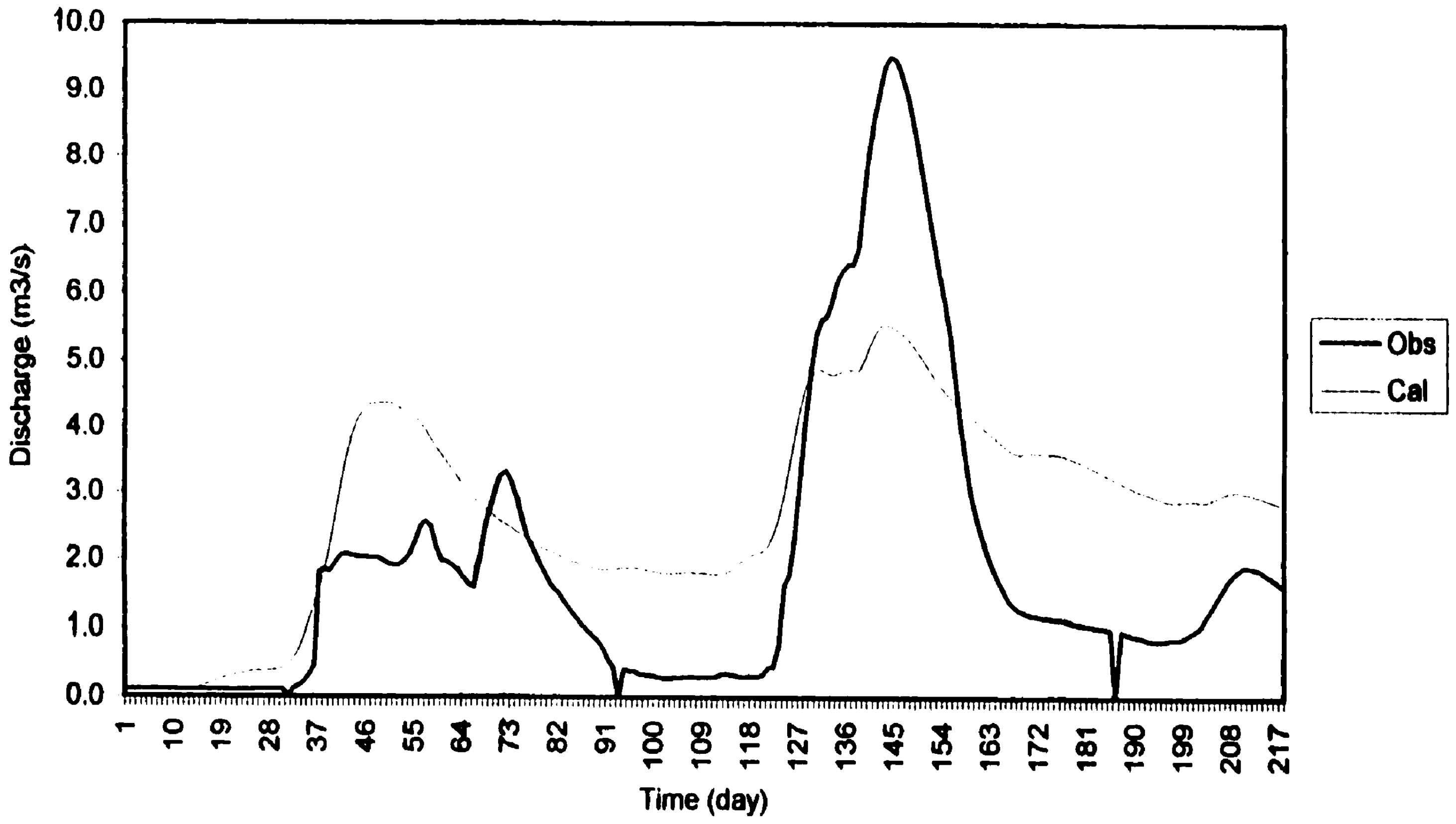


Figure 4.33 Hydrograph Comparison of the Sapochi River Basin Using 10km x 10km Grid Size of GRU for Year 1995

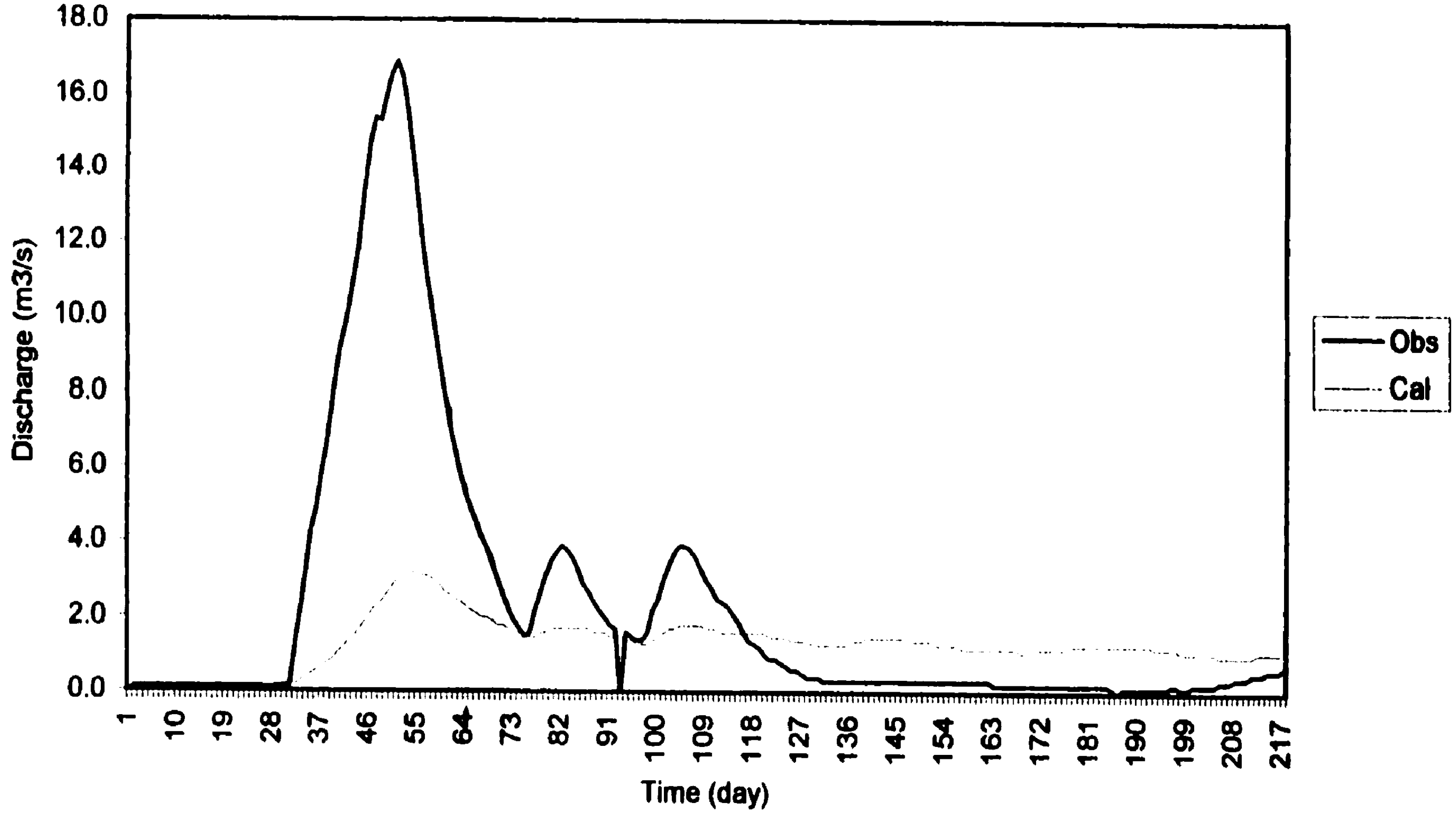


Figure 4.34 Hydrograph Comparison of the Sapochi River Basin Using 20km x 20km Grid Size of GRU for Year 1994

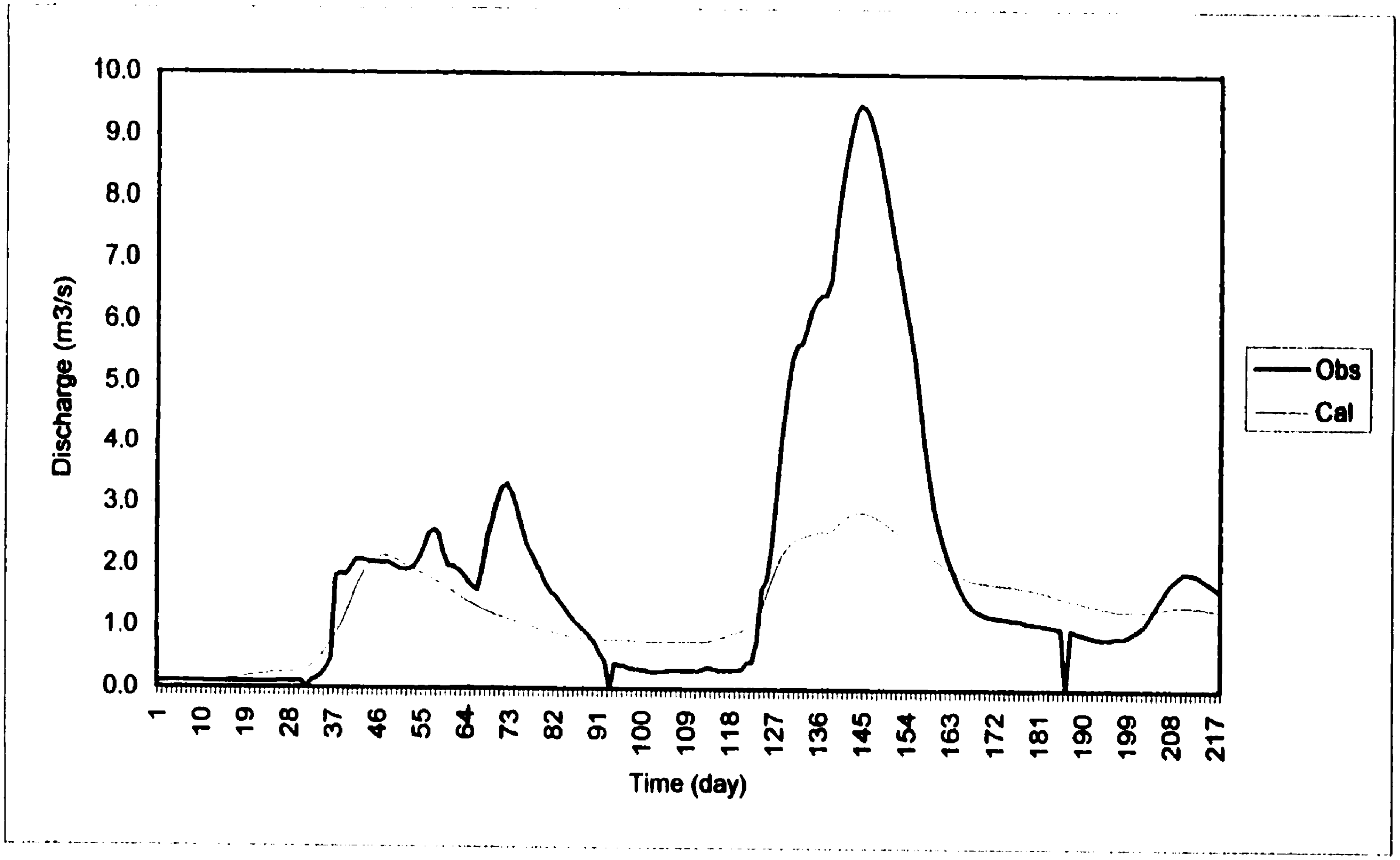


Figure 4.35 Hydrograph Comparison of the Sapochi River Basin Using 20km x 20km Grid Size of GRU for Year 1995

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

5.1 Conclusions

This research applied and evaluated two hydrological models, SLURP and WATFLOOD, to the Sapochi River Basin. Both models were calibrated and verified in 1994 and 1995. The applications and evaluations resulted in the following conclusions:

1. The application of each model in the Sapochi River Basin produced different results with the SLURP model achieving a Nash and Sutcliffe efficiency of 80% over the two year period of 1994 and 1995 while WATFLOOD produces about 70% for year 1994 and 1995.
2. The snowmelt drives the fluctuations of runoff in the spring in simulations using SLURP or WATFLOOD. Initial snow store and initial slow store are the most dominant parameters for SLURP in simulating the volume of runoff in the spring season and the beginning of summer. Coefficients of fast store and slow store for SLURP and the specific retention of the soil in the upper zone and lower zone drainage function for WATFLOOD are highly influential in the summer and in the beginning of fall season runoff. Other parameters had minor contributing effects to the fluctuations of runoff.
3. The research indicates that a single parameter set, either from SLURP or WATFLOOD, may be applied to produce good results for the Sapochi River Basin.

However this must be verified with additional data and simulations, and it is believed that the SLURP and WATFLOOD models are site specific.

4. This research indicates that the ASA concept from the SLURP model is more representative than the GRU concept in depicting the natural condition of a watershed. The ASA is based on stream networks derived from topographic characteristics in the watershed, thus providing a more natural representation of runoff movement in the watershed than the GRU concept used in the WATFLOOD
5. Due to the flatness of the Sapochi River Basin, applications of various ASA numbers applied for runoff simulation using SLURP did not affect the NS values significantly (less than 10%). However, this research indicates that with more ASA numbers the NS tends to be slightly higher. The more ASA numbers the better the presentation of watershed characteristics.
6. A change in GRU's size affects the GRU characteristics such as river class, slope, and drainage direction. A 5km x 5km GRU's size is a good size and recommended to be used in simulating runoff in the Sapochi River Basin.
7. SLURP model provides a better simulation. The modeler can change the value of initial slow store to drive the runoff volume in the spring and in the beginning of summer. This can not be undertaken in the WATFLOOD model. The only way to modify the runoff volume in the spring and in the beginning of the summer using WATFLOOD is by changing the depth of snow cover. However, this will reduce the physical quality of the model.

Finally, it is difficult to say that one model is better than another in this research. Each model has its advantages and weaknesses. The judgment about the quality of the model maybe more determined by the person who uses the model and where the model is applied. Experience is an important factor in modeling runoff. Short simulation periods also make judging the quality of a continuous model difficult.

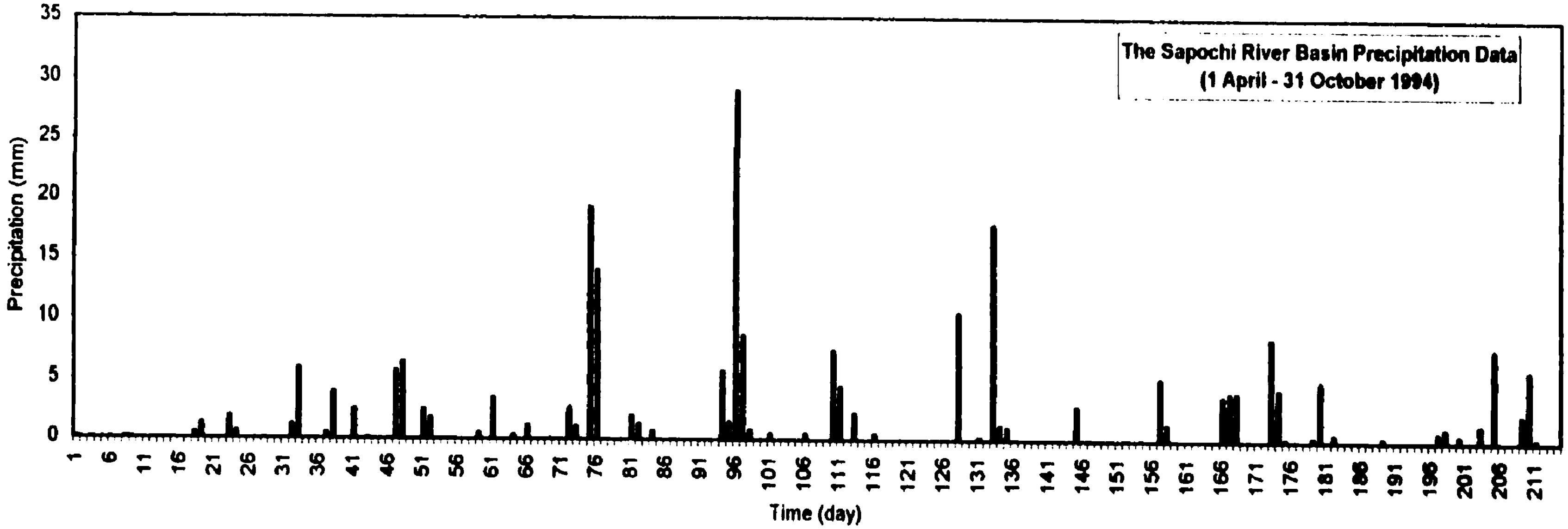
5.2 Recommendations for Future Study

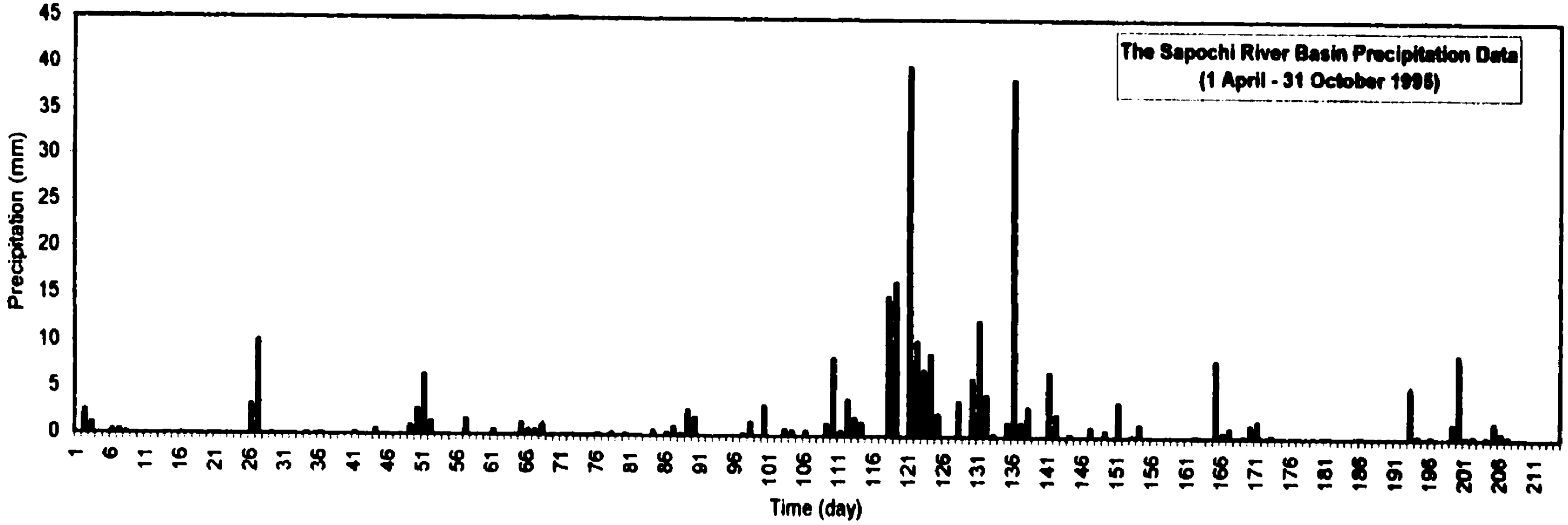
The following recommendations are made based on this research:

1. The efficiency of time and energy of the SLURP model simulation can be improved by using GIS support. SlurpView has proven to be able to support SLURP in developing a command file and is recommended for further development in supporting SLURP for future studies.
2. Runoff simulation using SLURP can be improved by providing a very detailed presentation of the whole runoff process on a daily basis. Efforts to improve the runoff process presentation should be taken into account in the future SLURP model.
3. The quality of watershed physiographic data derivation in WATFLOOD can be improved by using GIS support. The use of DEM and landcover data maybe useful to help the modeler to derive watershed physiographic data and to provide a better representation of the watershed.
4. The efficiency of simulations in the WATFLOOD model can be improved by managing the upper soil zone and lower soil zone parameters. The future WATFLOOD model should consider improving a facility to enable the modeler to change and control these parameters better.
5. The manuals of both SLURP and WATFLOOD must be improved in order to simplify the modeling process to the beginner in simulating runoff. The summary of

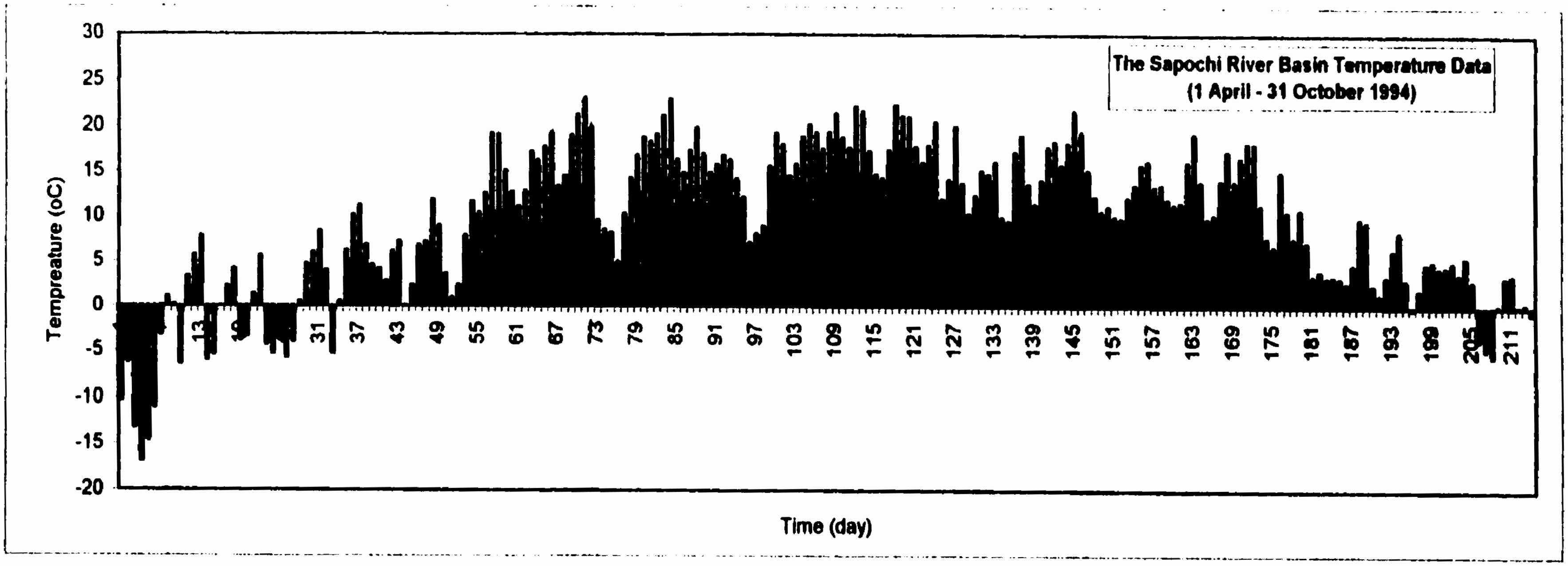
APPENDICES

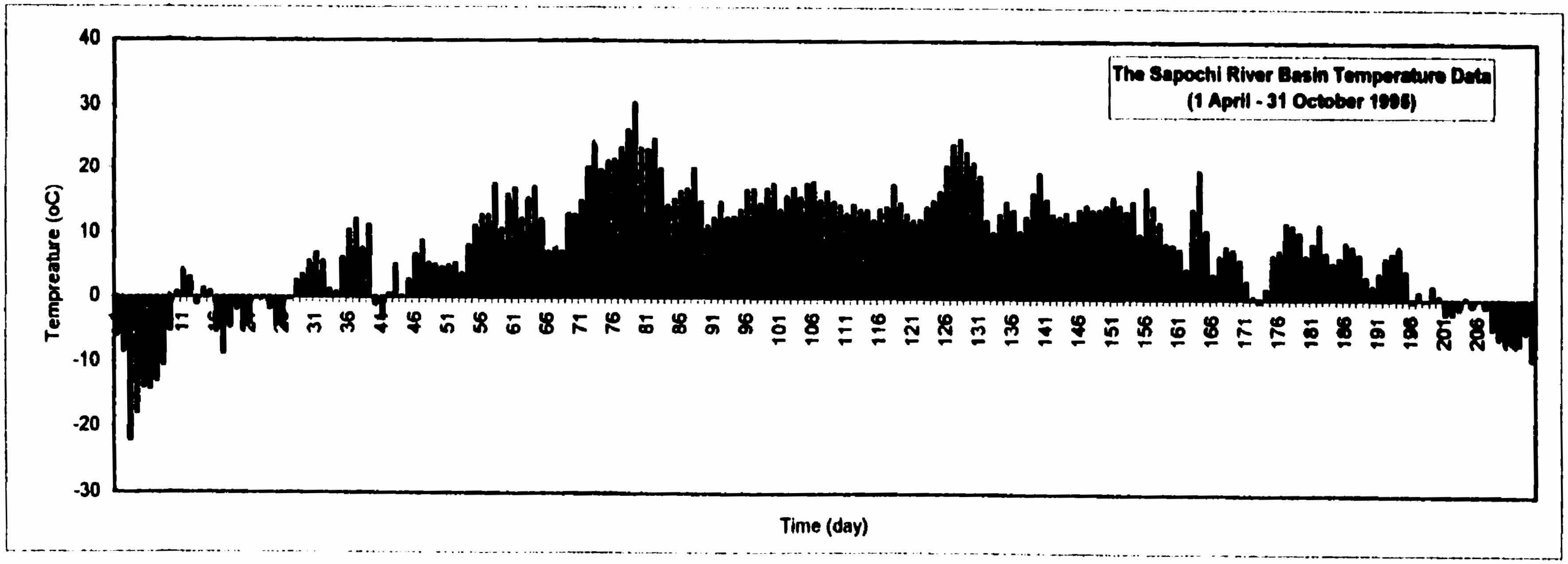
Appendix 1: The Sapochi River Basin Precipitation Data (1994 - 1995)



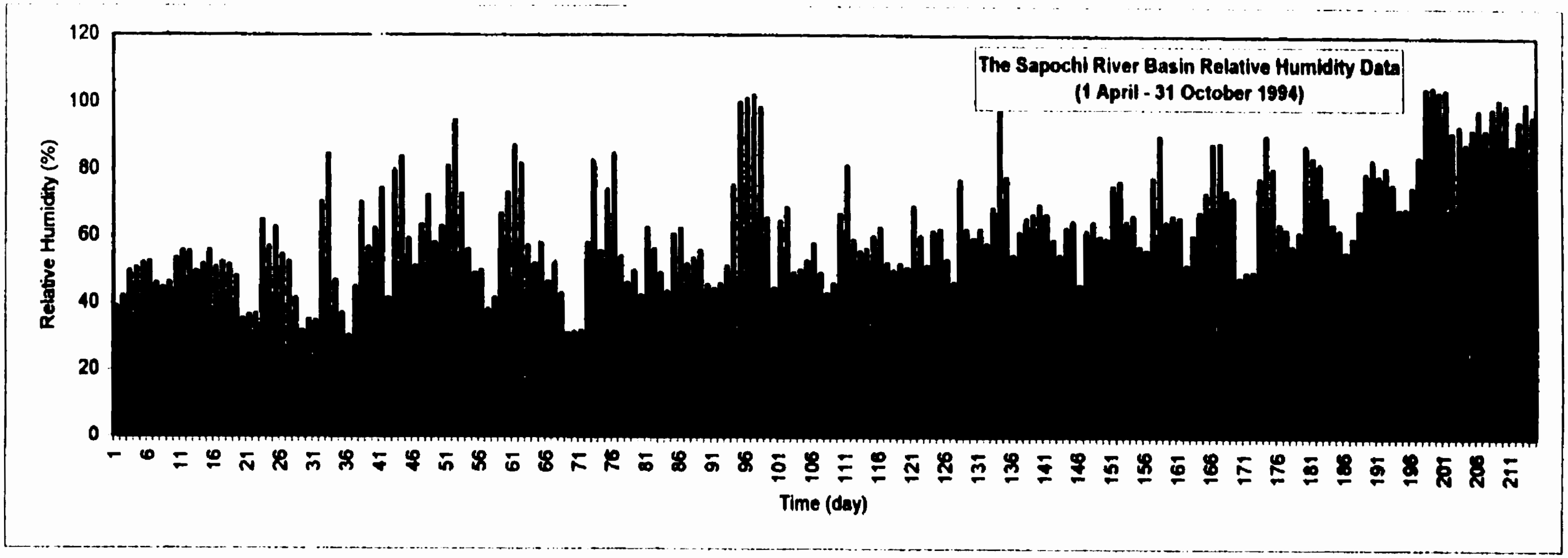


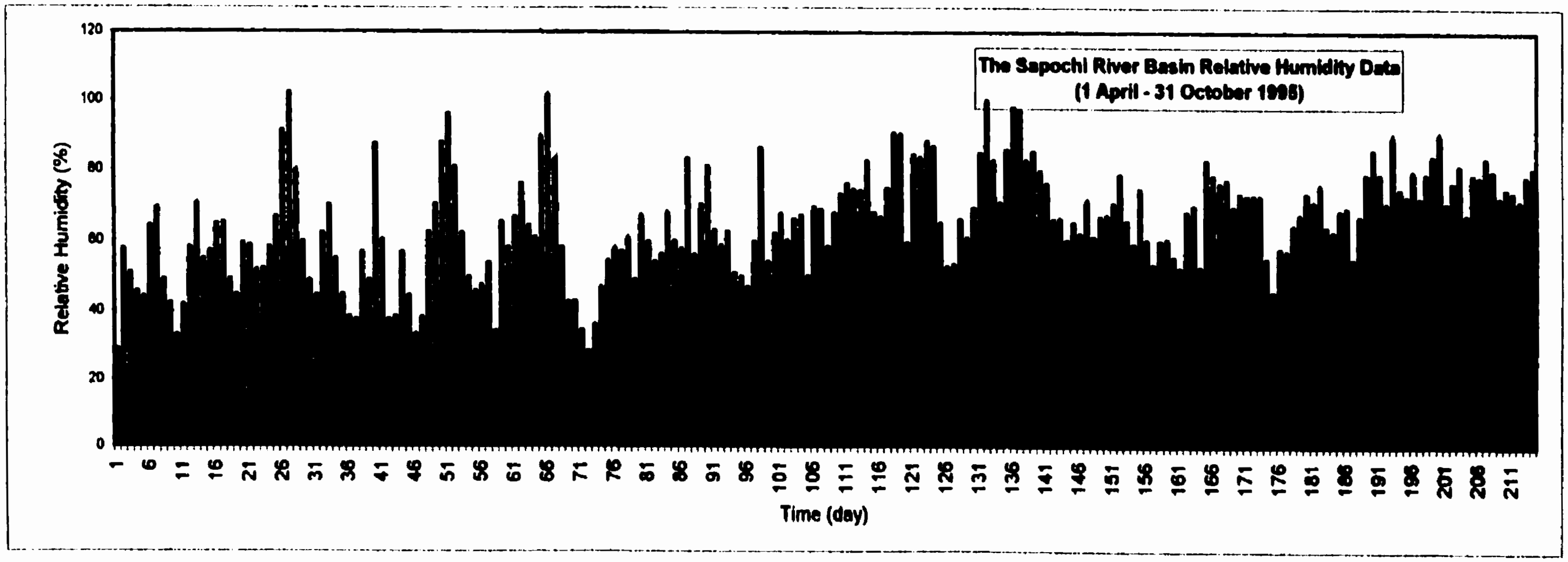
Appendix 2: The Sapochi River Basin Temperature Data (1994 - 1995)



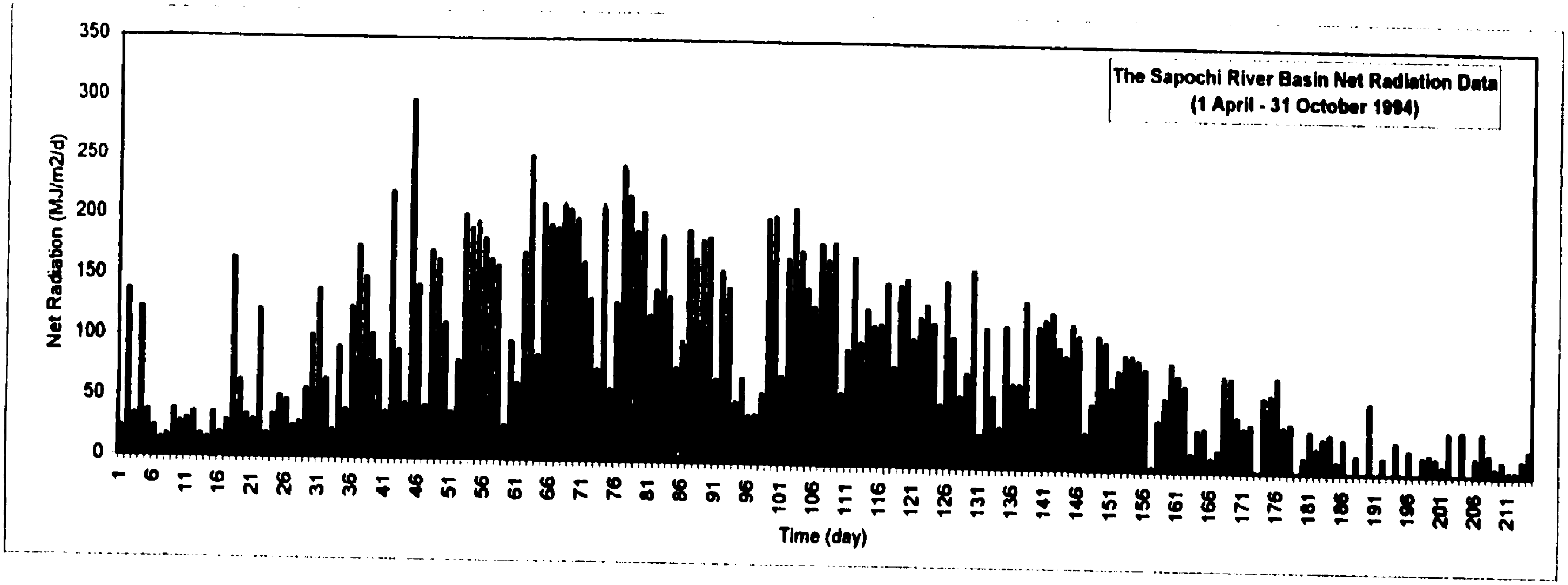


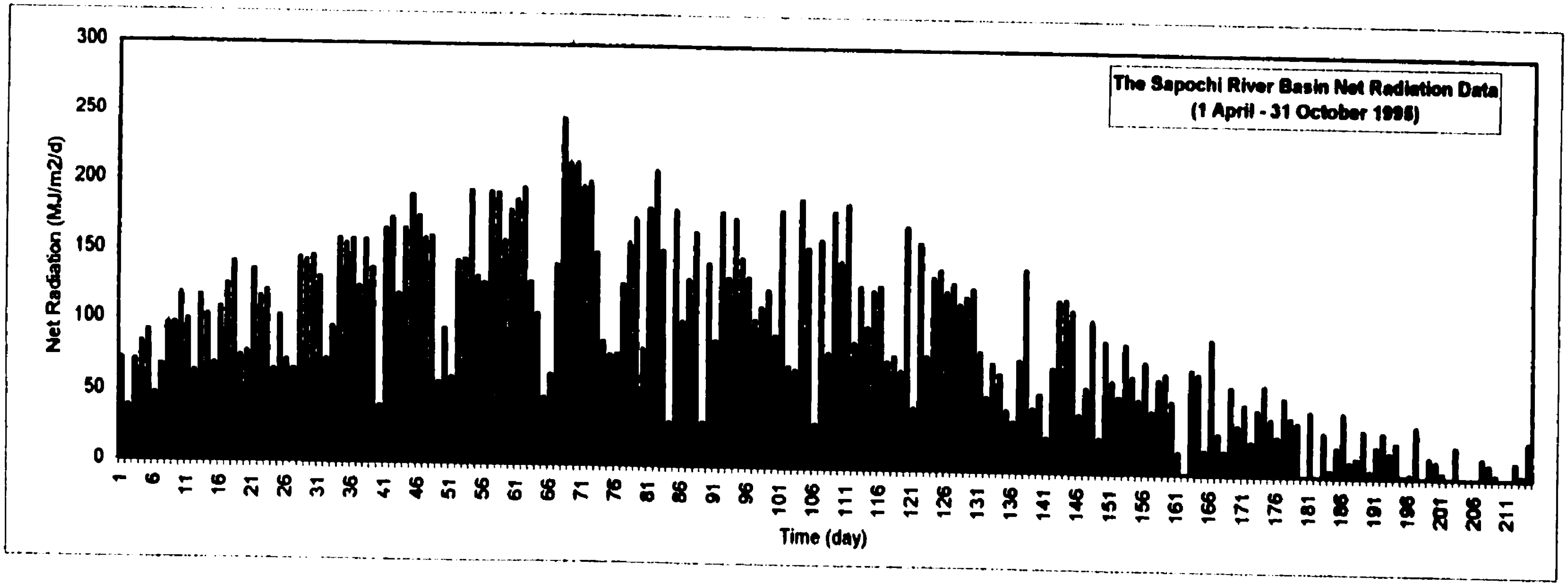
Appendix 3: The Sapochi River Basin Relative Humidity Data (1994 - 1995)





Appendix 4: The Sapochi River Basin Net Radiation Data (1994 - 1995)





Appendix 5: The Example of SLURP Climate Data File

```
1994   4      1      0.1
1994   4      2      0
1994   4      3      0
1994   4      4      0
1994   4      5      0
1994   4      6      0
1994   4      7      0
1994   4      8      0.1
1994   4      9      0
1994   4      10     0
1994   4      11     0
1994   4      12     0
1994   4      13     0
1994   4      14     0
1994   4      15     0
1994   4      16     0
1994   4      17     0
1994   4      18     0.5
1994   4      19     1.3
1994   4      20     0
1994   4      21     0
1994   4      22     0
1994   4      23     1.9
1994   4      24     0.6
1994   4      25     0
1994   4      26     0
1994   4      27     0
1994   4      28     0
1994   4      29     0
1994   4      30     0
1994   5      1      0
1994   5      2      1.2
1994   5      3      6
1994   5      4      0
1994   5      5      0
1994   5      6      0
1994   5      7      0.5
1994   5      8      4
1994   5      9      0
1994   5      10     0
1994   5      11     2.5
1994   5      12     0
1994   5      13     0.1
1994   5      14     0
1994   5      15     0
1994   5      16     0
1994   5      17     5.8
1994   5      18     6.5
1994   5      19     0
1994   5      20     0
1994   5      21     2.5
1994   5      22     1.8
1994   5      23     0
1994   5      24     0
1994   5      25     0
1994   5      26     0
1994   5      27     0
1994   5      28     0
1994   5      29     0.5
```

Appendix 6: The Example of WATFLOOD Map File

```
   3    1    1  745    0
     5000   20    0    3    1
  95  135   95  135
elevations
  0   0   0   0   0   0   0   0   0
  0   0   0 266 266   0   0   0   0
  0   0   0 261 265   0   0   0   0
  0   0 246 245 240 239   0   0   0
  0 248 247 244 241 245 252   0   0
  0 263 262 252 242 244 251 252   0
  0   0 252 251 244 243 246 247   0
  0   0 252 252 245 245 246   0   0
  0   0   0   0   0   0   0   0   0
element areas
  0   0   0   0   0   0   0   0   0
  0   0   0  19  13   0   0   0   0
  0   0   0  53  29   0   0   0   0
  0   0  37  93  56   0   0   0   0
  0  15  72 100  98  45  26   0   0
  0  38  98 100 100 100 100  40   0
  0   0  11  99 100 100  65  33   0
  0   0  13  48  63  89   8   0   0
  0   0   0   0   0   0   0   0   0
drainage directions
0 0 0 0 0 0 0 0 0
0 0 0 4 4 0 0 0 0
0 0 0 3 4 0 0 0 0
0 0 2 2 2 2 0 0 0
0 2 2 3 8 4 4 0 0
0 2 8 2 8 6 5 6 0
0 0 2 2 2 7 6 6 0
0 0 1 8 8 8 6 0 0
0 0 0 0 0 0 0 0 0
basin number
0 0 0 0 0 0 0 0 0
0 0 0 1 1 0 0 0 0
0 0 0 3 3 0 0 0 0
0 0 1 1 5 5 0 0 0
0 1 2 2 4 1 1 0 0
0 1 1 2 4 2 2 1 0
0 0 1 1 1 2 1 1 0
0 0 1 1 1 1 1 0 0
0 0 0 0 0 0 0 0 0
contour density
0 0 0 0 0 0 0 0 0
0 0 0 2 2 0 0 0 0
0 0 0 2 2 0 0 0 0
0 0 1 1 1 1 0 0 0
0 2 2 1 1 2 1 0 0
0 1 1 2 1 1 1 1 0
0 0 2 2 1 1 1 1 0
0 0 2 2 1 1 1 0 0
0 0 0 0 0 0 0 0 0
number of channels
0 0 0 0 0 0 0 0 0
0 0 0 3 4 0 0 0 0
0 0 0 2 1 0 0 0 0
```

```
  0 4 3 3 1 4 4 0 0
  0 4 4 3 1 3 3 4 0
  0 0 4 4 4 3 4 4 0
  0 0 4 4 4 4 4 0 0
  0 0 0 0 0 0 0 0 0
  routing reach number
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0
 Impervious Percentages
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
 Class 1
     0     0     0     0     0     0     0     0     0
     0     0     0     2     4     0     0     0     0
     0     0     0     2     2     0     0     0     0
     0     0     6     3     4     0     0     0     0
     0    13     4     1     7     3     1     1     0
     0     9    11     8     6     1     1     4     0
     0     0    14     5     5     5     4    10     0
     0     0     2     4     1     1     0     0     0
     0     0     0     0     0     0     0     0     0
 Class 2
     0     0     0     0     0     0     0     0     0
     0     0     0     0    96     0     0     0     0
     0     0     0     0    98     0     0     0     0
     0     0    94     0    96     0     0     0     0
     0    87    96    99    93    97    99     0     0
     0    91    69    92    94    99    99    96     0
     0     0    86    95    95    95    96    90     0
     0     0    98    96    99    89     1     0     0
     0     0     0     0     0     0     0     0     0
 Class 3
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
     0     0     0     0     0     0     0     0     0
```

Appendix 7: The Example of WATFLOOD SHD File

```
   32    9    9    3    1    1   81  745    0    4    4   31
     5000.  2.0    0    3
   95  135   95  135
    9    9                # rows & columns resp.
   0    0    0    0    0    0    0    0    0    9 135
   0    0    0    1    2    0    0    0    0    8 130
   0    0    0    6    3    0    0    0    0    7 125
   0    0   20   24   31   32    0    0    0    6 120
   0   15   17   27   30   23   12    0    0    5 115
   0    4    5   10   29   26   14   11    0    4 110
   0    0    9   13   25   28   19   16    0    3 105
   0    0    7    8   21   22   18    0    0    2 100
   0    0    0    0    0    0    0    0    0    1  95
     1    8    4     4.750   0.89167   0.00100    266.     1     2     3     6
0 0.19 0.00 1.00 0.00 0.00
     2    8    5     3.250   0.64167   0.00020    266.     1     2     4     3
0 0.13 0.00 0.04 0.96 0.00
     3    7    5       10.      1.85   0.00500    265.     3     2     1    31
0 0.29 0.00 0.02 0.98 0.00
     4    4    2     9.500   1.68333   0.00020    263.     1     1     4     5
0 0.38 0.00 0.09 0.91 0.00
     5    4    3       34.      5.77   0.00300    262.     1     1     4    17
0 0.98 0.00 0.11 0.89 0.00
     6    7    4       18.      3.10   0.00298    261.     3     2     2    31
0 0.53 0.00 1.00 0.00 0.00
     7    2    3     3.250   0.64167   0.00014    252.     1     2     4    13
0 0.13 0.00 0.02 0.98 0.00
     8    2    4       12.      2.10   0.00020    252.     1     2     4    13
0 0.48 0.00 0.04 0.96 0.00
     9    3    3     2.750   0.55833   0.00020    252.     1     2     4    13
0 0.11 0.00 0.14 0.86 0.00
    10    4    4       25.      4.27   0.00200    252.     2     2     3    29
0 1.00 0.00 0.08 0.92 0.00
    11    4    8    10.000   1.76667   0.00020    252.     1     1     4    14
0 0.40 0.00 0.04 0.96 0.00
    12    5    7     6.500   1.18333   0.00020    252.     1     1     4    14
0 0.26 0.00 0.01 0.99 0.00
    13    3    4       43.      7.22   0.00140    251.     1     2     4    25
0 0.99 0.00 0.05 0.95 0.00
    14    4    7       42.      7.02   0.00113    251.     2     1     3    28
0 1.00 0.00 0.01 0.99 0.00
    15    5    2     3.750   0.72500   0.00020    248.     1     2     4    17
0 0.15 0.00 0.13 0.87 0.00
    16    3    8     8.250   1.47500   0.00020    247.     1     1     4    19
0 0.33 0.00 0.10 0.90 0.00
    17    5    3       56.      9.39   0.00060    247.     2     2     3    27
0 0.72 0.00 0.04 0.96 0.00
    18    2    7     2.000   0.43333   0.00020    246.     1     1     4    22
0 0.08 0.00 0.00 1.00 0.00
    19    3    7       24.      4.18   0.00060    246.     1     1     4    28
0 0.65 0.00 0.04 0.96 0.00
    20    6    3     9.250   1.64167   0.00020    246.     1     1     4    24
0 0.37 0.00 0.06 0.94 0.00
    21    2    5       16.      2.72   0.00020    245.     1     1     4    25
0 0.63 0.00 0.01 0.99 0.00
    22    2    6       24.      4.14   0.00040    245.     1     1     4    28
0 0.89 0.00 0.01 0.99 0.00
```

```
      23     5     6          11.       1.98     0.00020    245.     1     2     4    26
   0 0.45 0.00 0.03 0.97 0.00
      24     6     4          32.       5.52     0.00100    245.     1     1     4    31
   0 0.93 0.00 1.00 0.00 0.00
      25     3     5          84.      14.02     0.00020    244.     1     1     4    28
   0 1.00 0.00 0.05 0.95 0.00
      26     4     6          36.       6.14     0.00040    244.     2     1     3    29
   0 1.00 0.00 0.01 0.99 0.00
      27     5     4          81.      13.56     0.00028    244.     2     1     3    29
   0 1.00 0.00 0.01 0.99 0.00
      28     3     6         199.      33.22     0.00014    243.     2     1     3    29
   0 1.00 0.00 0.05 0.95 0.00
      29     4     5         366.      61.06     0.00020    242.     4     1     1    30
   0 1.00 0.00 0.06 0.94 0.00
      30     5     5         390.      65.14     0.00020    241.     4     1     1    31
   0 0.98 0.00 0.07 0.93 0.00
      31     6     5         465.      77.64     0.00020    240.     5     1     1    32
   0 0.56 0.00 0.04 0.96 0.00
      32     6     6        0.000    0.10000     0.00001    239.     5     1     1     0
   0 0.00 0.00 0.00 0.00 0.00
```

Appendix 8: The Example of WATFLOOD Climate Data File

```
  5   95  135   95  135
  1  744 1.00          94 04 01 00
117  120 OBS
  0.15
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  2.60
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
  1.20
  0.00
  0.00
  0.00
  0.00
  0.00
  0.00
```