APPLICATIONS OF GIS IN HYDROLOGIC MODELING

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Abstract

Literature on applications of geographic information systems (GIS) to hydrologic modeling, stormflow generation in steep watersheds of humid regions, and automated configurations of watersheds was reviewed. A hydrologic model in conjunction with GIS technology was constructed to simulate stormflow hydrographs from a watershed. The model consists of three components: stormflow generation, translation and detention. Two major aspects were emphasised in the model: one is taking advantage of standard GIS to extract, overlay and delineate land and water-related characteristics required for stormflow modeling; another is integrating GIS with hydrologic modeling to simulate both spatial and temporal transformation of rainfall into stormflow. A good agreement between simulated and observed stormflow hydrographs was achieved when the model was tested using real data from Jamieson Creek, a well gaged and forested watershed in North Vancouver. Applications of this model in an ungaged and forested watershed, Nitinat watershed on Vancouver Island, show that the model is capable of handling the effects of complexities of soil, land use, topography and rainfall intensity on stormflow simulation. It was revealed that for a given return period the maximum peak flow for a design storm would increase with the duration of the storm and the Rational Method would not be suitable in estimating the maximum peak flow from a watershed with large storage capacity. The GIS technology was highly recommended for water resources management because of its ability of managing and modeling spatial information. Further improvement and testing of the model would result in a comprehensive GIS based model, simulating stormflow, soil erosion and non-point source water pollution.

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Chapter I

INTRODUCTION

1.1 Water Resource Management and Hydrologic Modelling

Water resource is one of the most critical and dynamic natural resources in the world. It is essential to plants, animals and human beings. Moreover, water is a renewable resource that is continuously in transit through various stages of the hydrologic cycle.

The hydrologic cycle implies that water is in constant movement from place to place and from one state to another. Although the overall amount of water is nearly constant for a certain place in a long period, the distributions of various components, such as evapotranspiration, interception, infiltration, overland flow, interflow and channel flow are rarely uniform in space and steady in time, which frequently causes flood or drought.

The need of watershed management thus arises from the mismatch between the spatial and seasonal distribution of water as determined by the hydrologic cycle and the spatial and seasonal dimensions of the human need structure.

In British Columbia, flooding resulting from long duration rains or a combination of rain and snowmelt has caused extreme damage locally and in some cases over large area. In British Columbia, there has been widespread concern about changes to stormflow characteristics of streams following logging, particularly clearcutting on forested watersheds. Fishery managers are also concerned about the impacts of peak flow and the change caused by logging on the environment of the streams where a large proportion of coho, pink and chum salmon, and steelhead and cutthroat trout are produced.

Commercial clearcutting, grazing, transportation and the increasing demands for agricultural land, industrial area and urban settlement have caused large scale change to vegetative cover and soil characteristics. The public has become increasingly concerned with the subsequent impact on the hydrological regime in a watershed.

Aside from land uses, the climate, soil, and topographic characteristics of a watershed also affect the hydrologic regime in general, and stormflow in particular.

A reliable base of knowledge of the interactions between the aforementioned factors and the hydrologic regime is therefore crucial for watershed management. However, a central problem for water resources managers and engineers to conduct proper management is the insufficient measurement and study of hydrologic regime in most of watersheds, especially in remote area.

For this reason, a large number of models estimating peak flow and runoff volume, such as Stanford Watershed Model (Crawford and Linsley, 1966), HEC-1 (HEC, 1981), WATERSHED (Band, 1986a) and so forth, have been developed. Most of these models are deterministic models, which can be divided into two categories: lumped models and distributed models. In a lumped model, the hydrological processes are spatially averaged, or regarded as a single point in space without dimensions. For example, many models of the rainfall-runoff process treat the precipitation as uniform over a watershed and ignore the internal spatial variation of the entire watershed. In contrast, a distributed model considers the hydrologic processes taking place at various points in space and defines the model variable as functions of the space dimensions.

Since the hydrologic regime in a watershed varies in all three dimensions of space, the estimation of average stormflow may not be sufficient to reflect the mechanism of stormflow movement and satisfactory for the uses in large watershed management. On the other hand, however, explicitly accounting for all of this variation may make the model too cumbersome for practical application, or even impractical for ungaged watersheds where hydrologic information is limited.

Apparently, the applications of many deterministic hydrologic models have been limited by the lack of ability to adequately represent spatial phenomena, a serious problem considering the basic spatial character of hydrologic processes. A solution or improvement on it may be found through the geographic information system (GIS) technology.

1.2 GIS

The term GIS has been defined in several ways. To some GIS means only the software used to analyze geographically referenced data; to others, the term includes the hardware utilized by the system; yet others would include all processes from data acquisition to data presentation, even the organizations operating the system. There are many definitions of GIS (Tomlinson, 1984; Goodchild, 1985; Burrough, 1986; Aronoff, 1989 and Taylor, 1991). The most obvious feature of GIS is the capability of spatial analysis. This capability distinguishes GIS itself from other systems, such as computer-assisted mapping (CAM), computer-aided design (CAD), land information system (LIS), data base management system (DBMS). One common definition is: GIS is a computerized system for capturing, storing, retrieving, analyzing and displaying data that are spatially referenced to the Earth. It can be said that GIS is an information system primarily concerned with spatial and temporal phenomena ranging in scale from the entire Earth down to a land parcel (Chieng, 1990).

A GIS combines two computer software technologies: data base management and digital mapping. Data base management is a systematic way of organizing and accessing attribute data. Digital mapping represents map elements as points, lines, polygons, or grid cells. The key feature of a GIS is that the digital map elements are linked with the attribute information in such a way that, when either the map or the attribute data are manipulated, both sets of data are updated and adjusted to maintain the relationship between them (Lanfear, 1990). From this linkage perspective, the differences between GIS and LIS are not great. However, LIS are used primarily for the storage and retrieval of spatial data while GIS are used essentially for more complex spatial analysis.

1.3 GIS and Hydrologic Modelling

1.3.1 GIS and parameterization

Since many hydrologic models have parameters defined in terms of land use, soil, precipitation and topography which vary greatly on a watershed, the potential for applying GIS to hydrologic modeling is considerable. Several GIS applications in hydrologic modeling have achieved significant improvements in the quality and efficiency of analysis in water resources management (Muzik, 1990; Vieux, et al., 1988 and Jett, et al., 1979).

GIS is in essence a spatial data base management system. Therefore, it has been used to concentrate on providing computerized abilities to input, store, edit, query and output land and water-related information important in stormflow modeling, which makes spatial data collection become less model-oriented like data base management system (DBMS). With the flexible means of storing data representing the physical system, it becomes possible to use a variety of alternative stormflow models with a single data base selecting the most appropriate model for different phases of hydrologic modeling. Muzik and Pomeroy (1990) described a hydrologically oriented geographic information system. This system is a raster (i.e. grid cells) based GIS which stored hydrological parameters such as land use, soil type, rainfall intensity-frequency-duration statistics, runoff curve numbers (CN), regional dimensionless unit hydrograph, and regional lag-time relationship, required for stormflow prediction. It was concluded that the relatively laborious task of data input for permanent storage in GIS is more than compensated for by the speed and efficiency achieved in subsequent hydrologic simulation. Sasowsky and Gardner (1991) developed a set of GIS techniques that provides many of the relevant topographic and soil parameters in hydrology modeling. It was pointed out that GIS allows for (1) rapid parameterization of relevant topographic parameters from grid cell digital elevation models, and (2) computation of weighted averages for appropriate topographic and soil parameters in each watershed configuration.

1.3.2 Watershed configuration and digital elevation model of GIS

Digital elevation model (DEM) now has become a major feature of GIS, which gives GIS the capability of converting elevation contours or points into 3 dimensional graphs. More importantly, the elevation data output from DEM is frequently used for watershed configuration. Since the hydrologic response of watershed is governed, in part, by the characteristics of watershed such as the shape, size, slope, the length of main stream and so forth, the degree of complexity presenting these hydrologic characteristics may significantly affect the simulation results of hydrologic models. The usefulness of DEM in stormflow modelling has been recognized in several recent studies. Jett, Weeks and Grayman (1979) applied the Triangulated Irregular Network (TIN), a terrain network in which terrain is represented as a faceted surface with each facet being a triangular plane, to derive the stream network of 24 county area of the Ketucky river basin in the United States. Sasowsky and Gardner (1991) obtained the contributing areas and stream segments in a watershed by using the DEM derived aspect data layer and x, y coordinate pair defining the location of the basin outlet cell. The same technique was used by Stuebe and Johnston (1990) to delineate the watershed boundary.

1.3.3 The interface between GIS and hydrologic models

GIS technology has evolved for 20 years since the first design concept was proposed by Tomlinson in 1972. GIS application in hydrologic modeling has only about 10-year history. Many GISs only have some ad-hoc functions of spatial analysis, which make them inconvenient to be used for stormflow modeling. Most of GISs still lack of the powerful spatial analysis capabilities specially for stormflow modeling. Alternatively, some GIS applications in stormflow modelling have to develop an interface between GIS and available hydrologic models. Hodge et al (1988) described the linkage of a hydrographic program and watershed process model with the raster GIS (GRASS). The hydrographic program, "Watershed" (Version 3.0), was designed to find watershed boundaries, storm drainage channels and sub-basins for the watershed in GRASS. Wolfe and Neale (1988) used GRASS to provide limited data input to a finite element model. Fisher (1989) developed an interface to automate many spatial display and analysis tasks with an easily understandable screen selection.

It has been felt that most existing GISs have many capabilities that may only be of marginal use in hydrologic modeling while there are many parameters and procedures unique to stormflow modeling that are not included in standard GISs. Considerable research in the GIS applications to stormflow modeling has been conducted in the spatial variability of rainfall and watershed characteristics such as terrain, land use, soil, etc. There has not been, however, commensurate level of effort spent on other spatial considerations in the actual transformations of rainfall into stormflow.

The GIS applications to stormflow modeling in present study will be emphasised in two major aspects: one is taking advantage of standard GIS to extract, overlay and delineate land and water-related characteristics required for stormflow modelling; another is integrating GIS with hydrologic modeling to simulate both spatial and temporal transformation of rainfall into stormflow.

1.4 Objectives

The main objectives of this study are:

a. to use GIS technology to establish a hydrologic model for simulating stormflow hydrograph,

b. to estimate the peak flow of a watershed for a given rainfall return period,

c. to simulate hydrographs of stormflow caused by spatially non-uniform and temporally unsteady storms passing over a watershed,

d. to evaluate the impacts of land use changes on the discharge of a watershed under a design storm, and,

e. to explore the use of digital elevation model (DEM) in GIS for watershed configuration.

1.5 Organization of the Thesis

This chapter (Chapter One) is an introduction of the study. The applications of GIS to hydrologic modeling have been reviewed and the objectives were specified.

In Chapter Two, the background information of study watersheds is provided, including topography, climate, soil, forest, as well as instrumentation and data collection. Both study watersheds are steep watersheds with shallow soil and presently covered with dense coniferous forest. The physiographic similarities existing between the two study watersheds have been analyzed in this chapter, which gives the confidence for the model established in one watershed to be applied in another.

The theories of stormflow mechanism and automated techniques in watershed configuration are reviewed in Chapter Three. A downhill searching program is described. This program is designed to simulate the direction and path of stormflow movement in a watershed. As the program searches through the grid formatted elevation matrix of a watershed, the flow length, flow time and contributing area of each grid are calculated, and the flow path is recorded as well. Consequently, many watershed characteristics such as stormflow time-area, watershed boundary and drainage network can be figured out when this program is interfaced with GIS.

Subsequently, the establishment and verification of a stormflow model is discussed in Chapter Four. The synthetic Clark's Instantaneous Unit Hydrograph Time-Area Method is modified and integrated with GIS in this model. Stormflow is considered to be generated from hydrologic response units determined by soil, land use and topography of a watershed. The stormflow translation is simulated with the distributed method while the stormflow attenuation is presented using the lumped method. The two most important factors for the translation (time of concentration, T_c) and attenuation (storage factor, R) are verified with the real data from a small, steep and forested watershed, Jamieson Creek, located at the North Vancouver of British Columbia.

Chapter Five gives several applications of the verified stormflow model. The effects of land use and storm movement on stormflow are evaluated by changing the spatial distribution of rainfall and land use within GIS. These evaluations are conducted for an ungaged watershed, Nitinat watershed in Vancouver Island, where DFO (Department of Fisheries and Oceans) Nitinat River Hatchery is located. In addition, the Rational Method is reexamined for design rainfalls with different durations in a large watershed by using the established model.

It is concluded in Chapter Six that GIS is very useful in stormflow modeling. This study has demonstrated several uses of GIS in this area. The results obtained from this study can be further improved when the antecedent soil moisture spatial distribution is combined with GIS. Based on the watershed configuration derived from elevation data, the model will be able to be expanded to include the simulation of soil erosion and non-point source water pollution on a watershed.

Chapter II

STUDY WATERSHEDS

Two watersheds in southwest British Columbia were selected for this study. One is a small but well gaged watershed, Jamieson Creek watershed, used for the model testing; another is a large but ungaged watershed, Nitinat watershed, used for the model application.

Jamieson Creek watershed has an area of 2.99 km^2 and is situated at the North Vancouver of British Columbia (see Figure 2.1). Since 1969, it has been involved in a series of extensive research programs conducted by the Faculty of Forest, University of British Columbia. In addition to a long period of systematic rainfall and streamflow records, many results obtained from previous research in this watershed are available for further hydrologic study in this region.

Nitinat watershed is a large watershed with an area of 426.90 km^2, located on the southwest side of Vancouver Island (see Figure 2.1). There is no gage station installed to measure discharge for this watershed. Instead, some justifications of discharge peak flow can be roughly made based on the data of flood stage provided by a pumphouse at the outlet of the watershed. It is such a large watershed that the effects of the complexities of storm, soil, land use and topography on discharge prediction cannot be ignored for a hydrologic model.

This chapter will describe the physiographic characteristics and data collections for both watersheds in order to provide the background information for the interpretation of

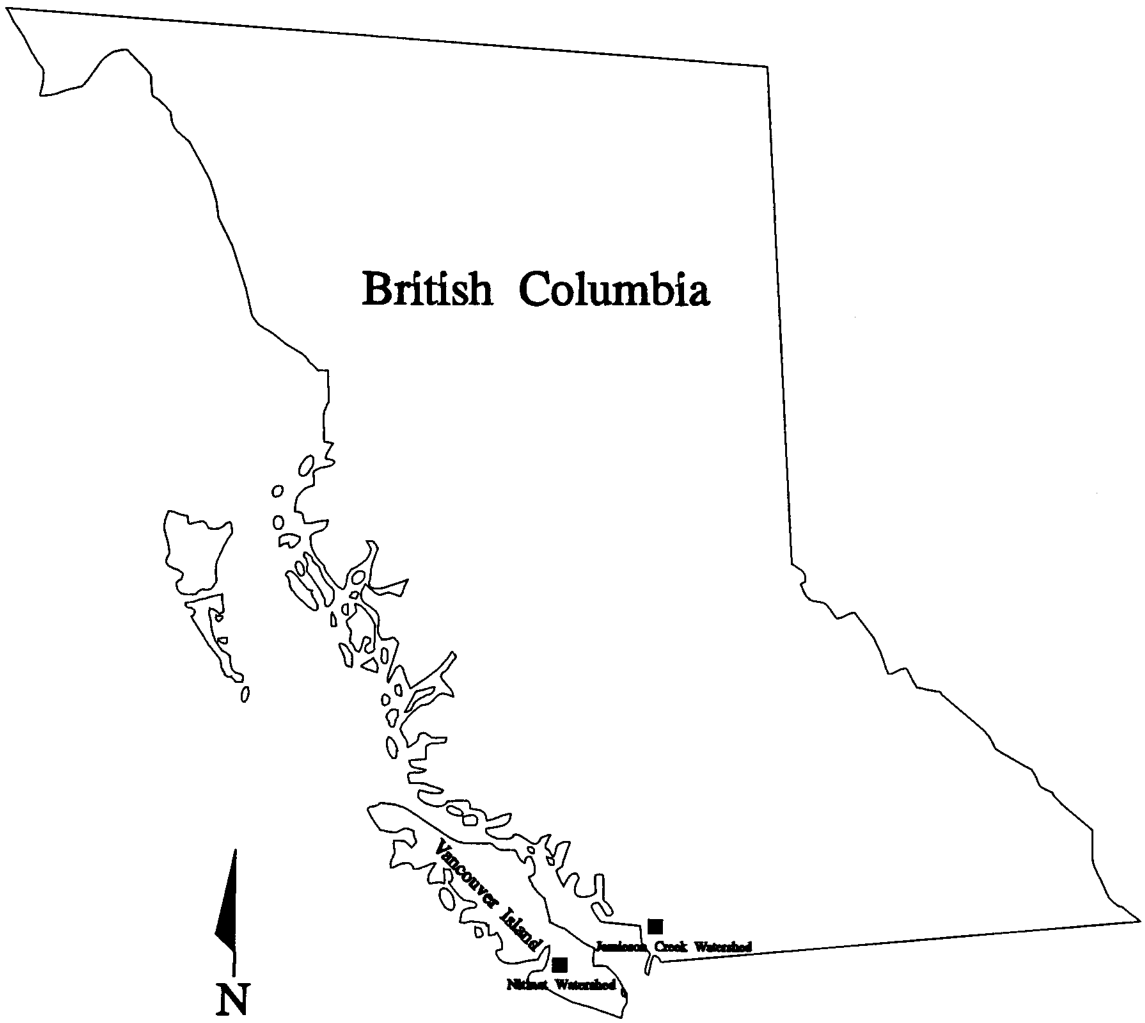

Figure 2.1 *The locations (■) of Jamieson Creek and Nitinat watersheds.*

the assumptions, parameterizations, simulations and applications of the model in the subsequent chapters.

2.1 Topography

As shown in the topographic map given in Figure 2.2, Jamieson Creek watershed has elevations ranging from 1,000 feet (305 m) at the mouth of the watershed to 4,000 feet (1,310 m) at the highest point on the divide. It can be seen from the 3-dimensional

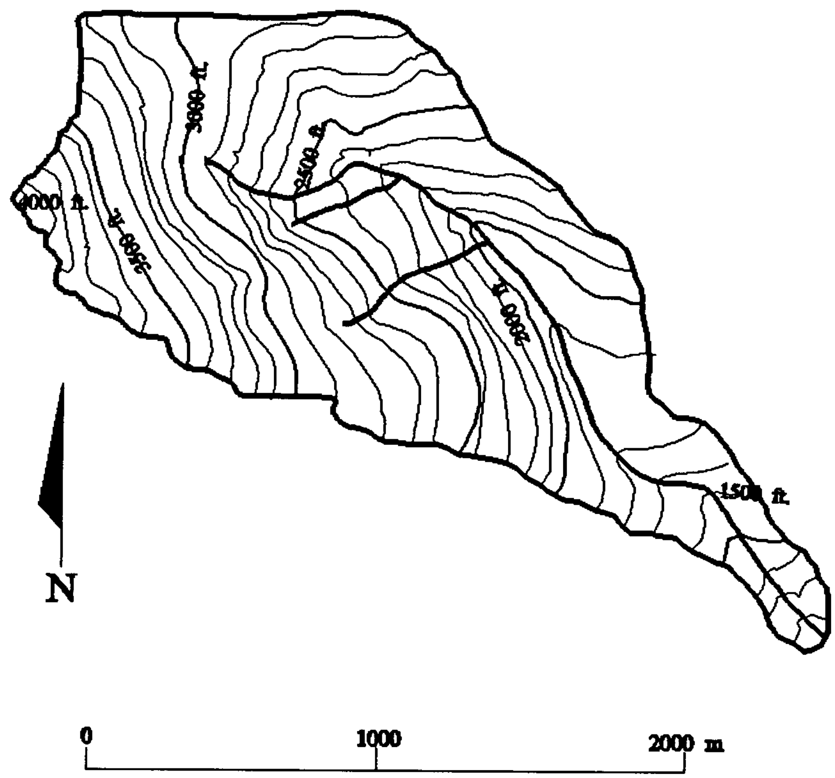

Figure 2.2 *A contour map of Jamieson Creek watershed. The contours were drawn at intervals of 500 feet.*

perspective of the watershed (see Figure 2.3), this is a small and simple watershed in terms of the relief of the watershed. Northeastly, eastly, southwestly and southly facing land slopes are dominant on this watershed, while the main channel is oriented to the southeast.

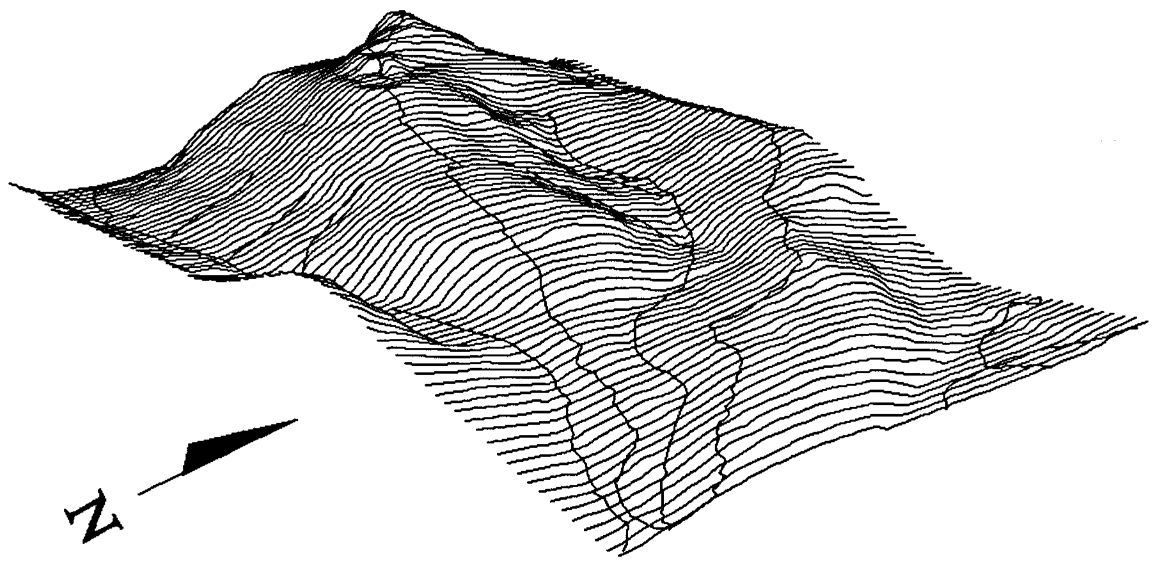

Figure 2.3 *A 3-dimensional perspective of Jamieson Creek watershed.*

The elevation of Nitinat watershed ranges from 100 m to 1400 m (see Figure 2.4). As indicated in Figure 2.5, the watershed main channel has a general orientation to the south. Compared with Jamieson Creek watershed, Nitinat watershed is more complex in the relief of elevation. The topographic complexity comparative to Jamieson Creek watershed is also reflected on a variety of aspects for land slopes (see Figure 2.6).

Both of the study watersheds are steep watersheds. Figure 2.7 and 2.8 show the land slope distribution curves for Jamieson Creek and Nitinat watersheds respectively. Jamieson Creek watershed has an average slope of 48% with 87% of the area having

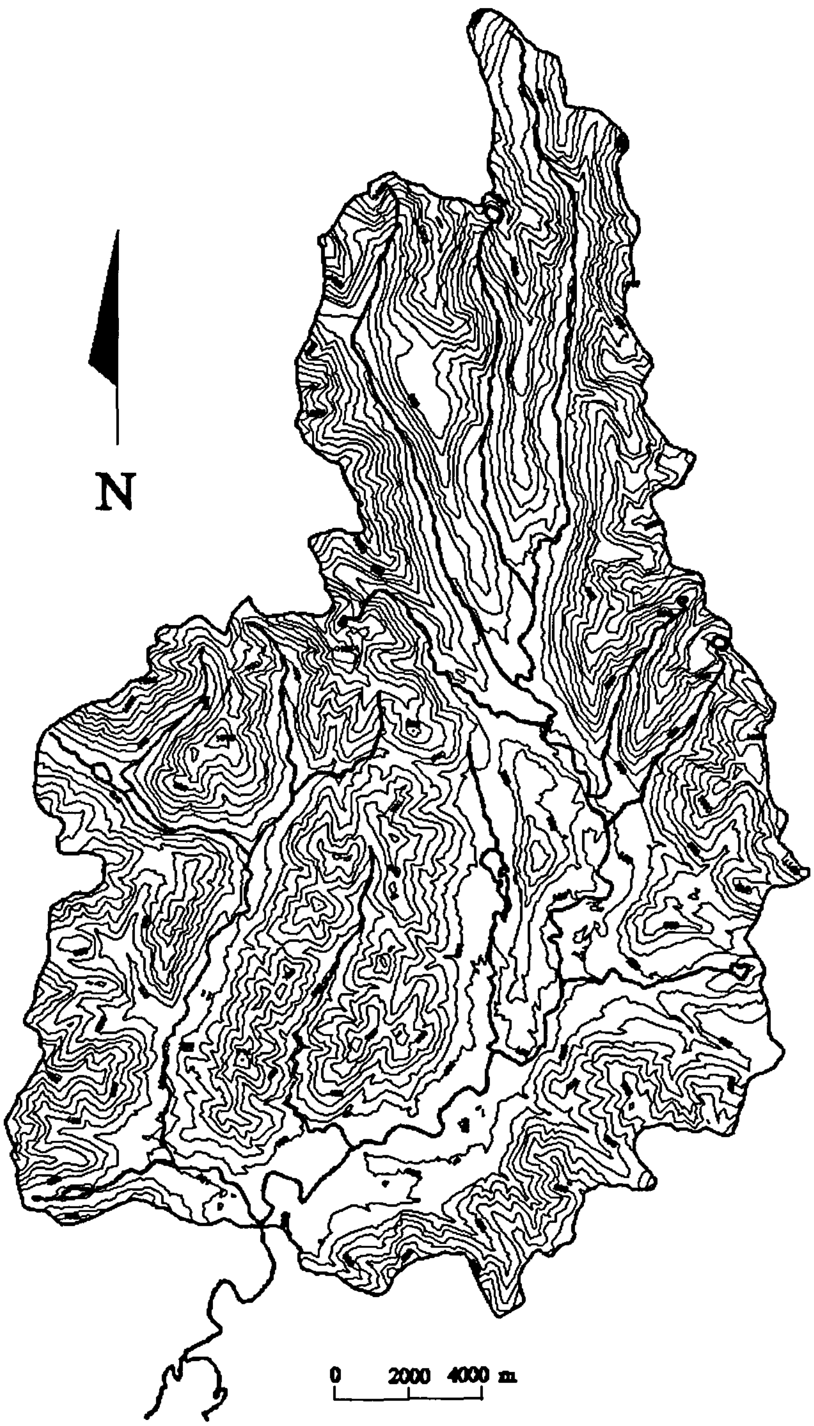

Figure 2.4 *A contour map of Nitinat watershed. The contours were drawn at intervals of 100 meters.*

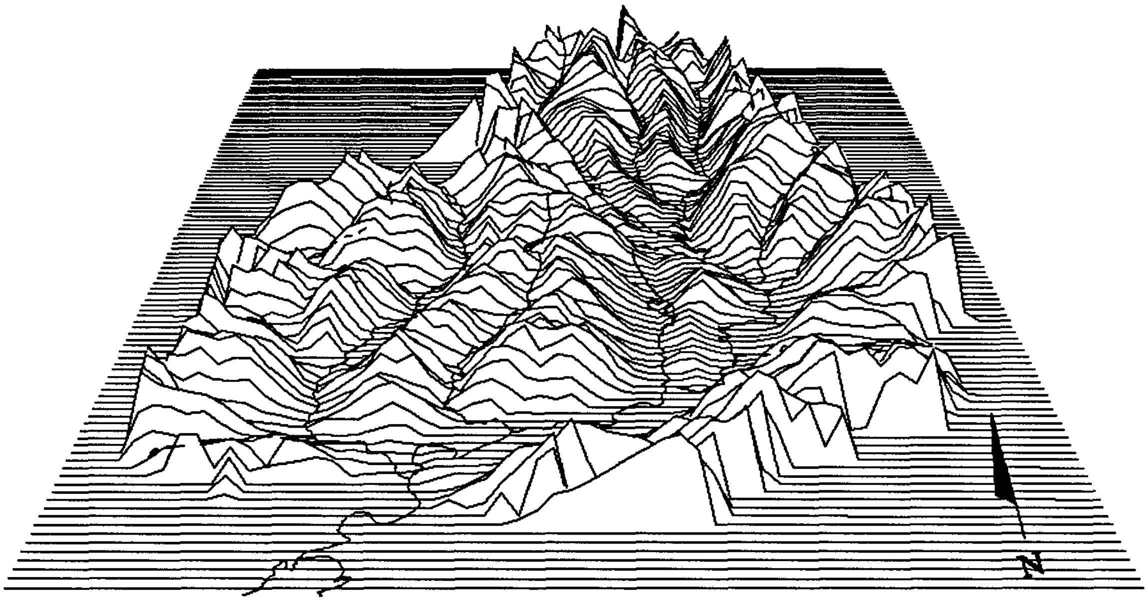

Figure 2.5 *A 3-dimensional perspective of Nitinat watershed.*

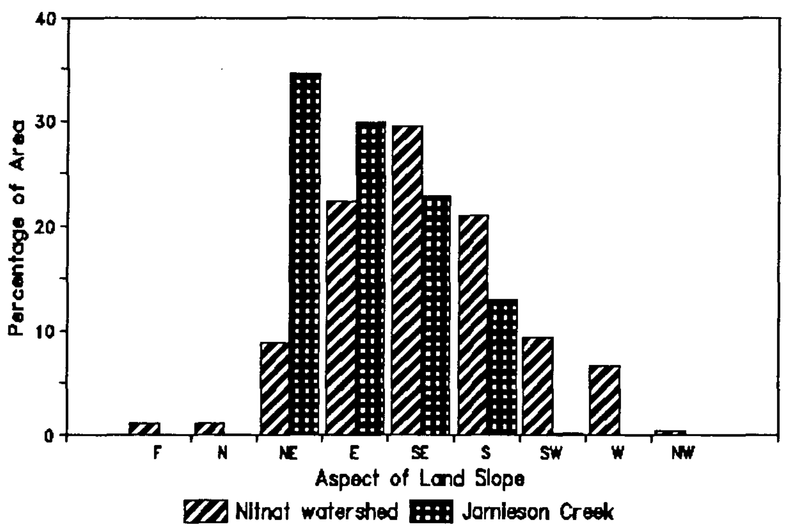

Figure 2.6 *Distributions of aspects of land slope in Jamieson Creek and Nitinat watersheds.*

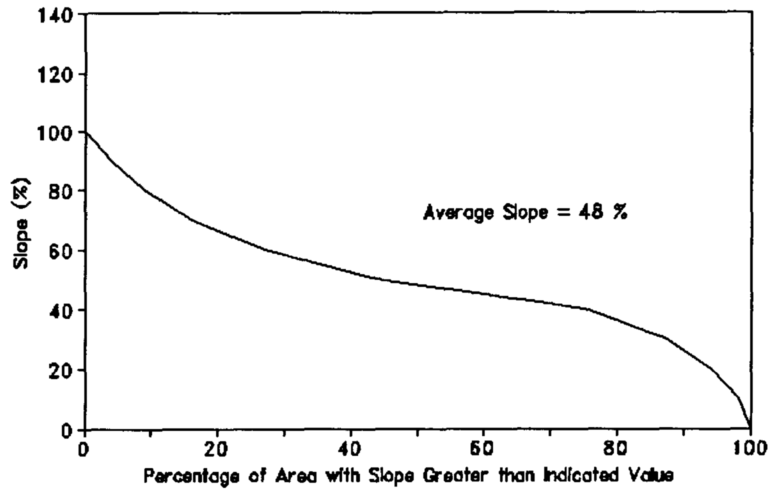

Figure 2.7 *Distribution of land slope in Jamieson Creek watershed (after Cheng, 1975).*

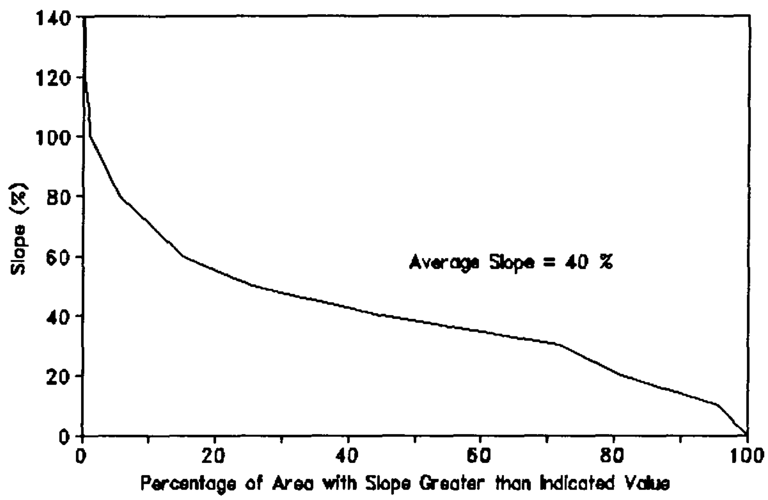

Figure 2.8 *Distribution of land slope in Nitinat watershed.*

slope more than 30%. Similarly, the average slope of Nitinat watershed is 40% and there is 79% of the area with slopes more than 30%.

The longitudinal main channel profiles for Jamieson Creek and Nitinat watersheds are given in Figure 2.9 and 2.10 respectively. The gradient of the main channel at the lower portion in Jamieson Creek is 10%, but the upper portion of the watershed reaches a slope of 100%. The gradient of the main channel in Nitinat watershed is 5% at the lower portion and 105% at the upper portion of the main stream.

2.2 Climate and Streamflow

The weather of southwestern British Columbia is dominated by low pressure systems in the winter and high pressure systems in the summer. Prevailing winds are predominantly from the southeast in the winter, while northwest winds predominate in the summer. Extremes of temperature are rare. Both summer and winter temperature are mild in this region (Jungen, 1985).

The easterly moving moisture-laden masses bring a large amount of precipitation to the watersheds. The annual average precipitation in Jamieson Creek from 1982 to 1988 is 3245.2 mm with a range from 3023.0 to 4025.0 mm. In Nitinat watershed for the same period, the annual average precipitation is 3649.1 mm ranging from 2165.6 to 4371.3 mm.

For both watersheds, as shown in Figure 2.11 and 2.12, most of precipitation are concentrated in the period of November to February. The period between June and September is the driest period of the year, which is also the snow free period.

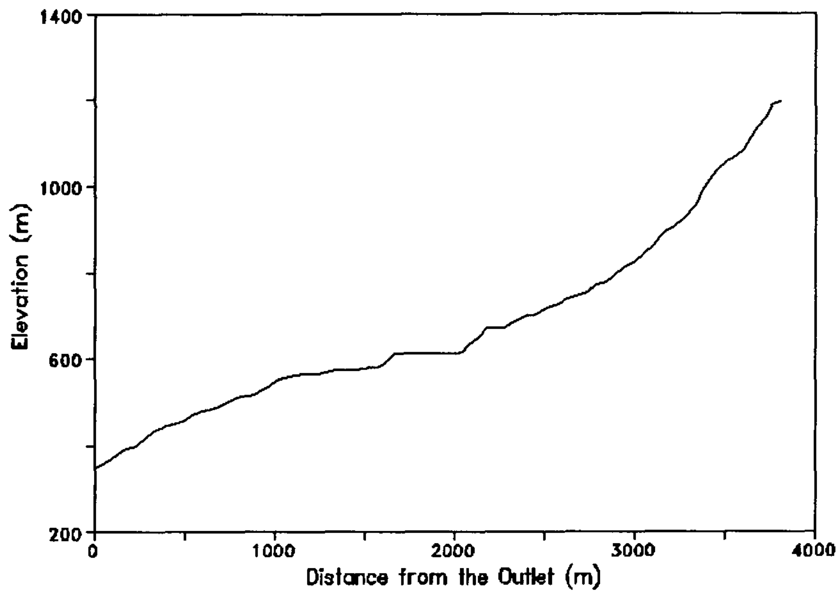

Figure 2.9 *Longitudinal stream channel profile of Jamieson Creek watershed.*

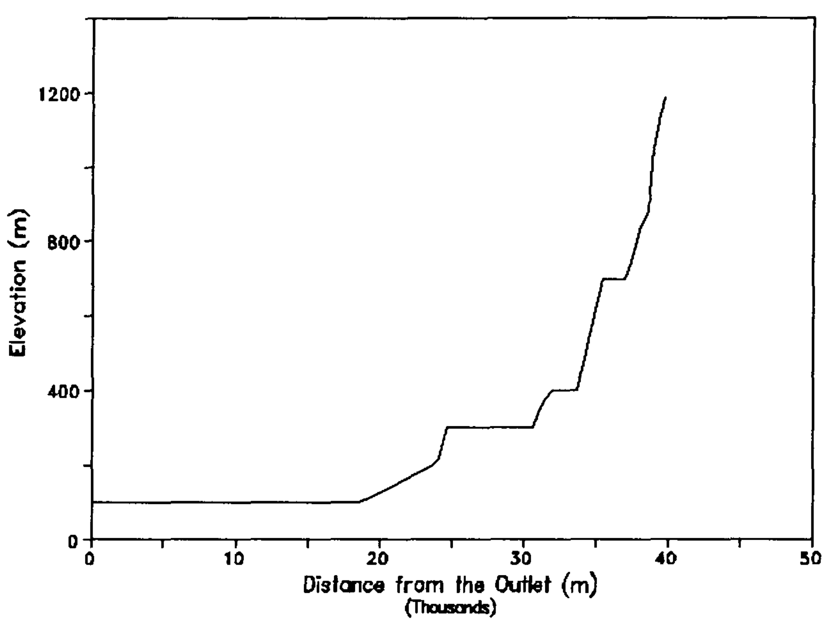

Figure 2.10 *Longitudinal stream channel profile of Nitinat watershed.*

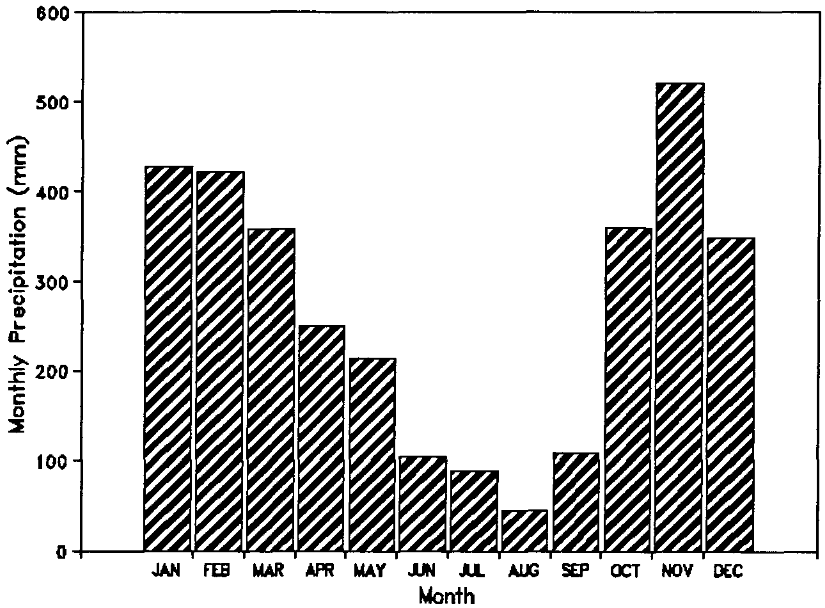

Figure 2.11 *Distribution of monthly precipitation in Jamieson creek watershed.*

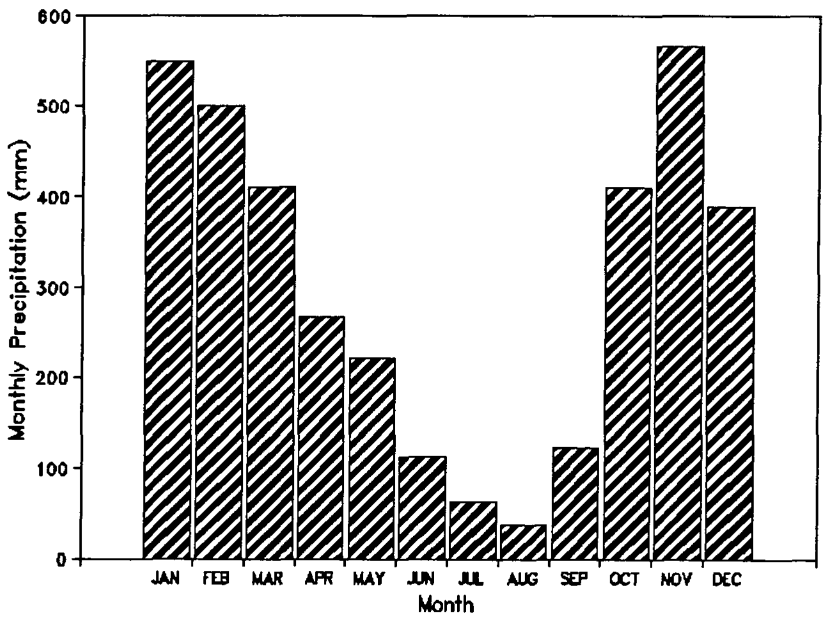

Figure 2.12 *Distribution of monthly precipitation in Nitinat watershed.*

In Jamieson Creek watershed, the average annual streamflow ranges from 0.27 to 0.31 m^3/s. Streamflows in Jamieson Creek watershed are usually quick responses to precipitation. Unlike the monthly distribution of precipitation, however, hydrographs for monthly streamflow have two peaks in Jamieson Creek watershed (Figure 2.13). One peak occurs in November mostly due to high rainfall intensity, while another peak occurs as a result of snowmelt in May. As the annually maximum flood stages at the outlet of Nitinat watershed were observed between November and February (Figure 2.14), the rainfall intensity can be reasonably considered as a major factor of the maximum design flood in Nitinat watershed.

2.3 Soil

Cheng (1975) classified the soils in Jamieson Creek watershed as two types: steep mountain soils and valley bottom soils. The steep mountain soils, mainly ablation and colluvium, are shallow and very permeable. The Valley bottom soils, consisting of glacio-alluvial and lacustrine soils, are thicker and have varying permeabilities. In general, the soils of Jamieson Creek are mostly coarse-textured sands and gravelly sand loams, underlain by mostly granitic impermeable bedrock.

Field observations have indicated that soil channels in the form of old root holes, structural channels or cracks widely exist in the profiles of the watersheds (Cheng, 1975). Because of the porous soils distributed over the entire watershed, overland flow is rarely observed except near stream channels or on bedrock.

Most of soils in Nitinat watershed are gravelly sandy loam or loamy sand (Jungen,

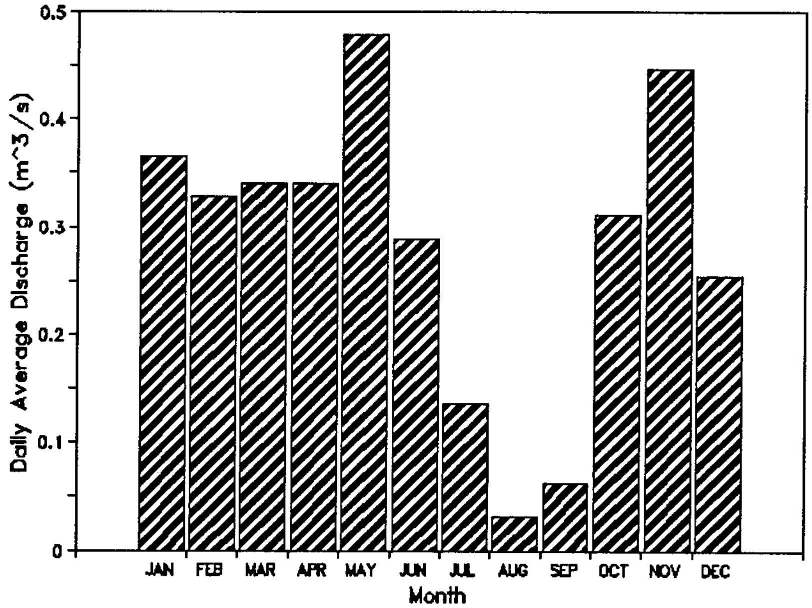

Figure 2.13 *Distribution of daily average streamflow for each month from Jamieson creek.*

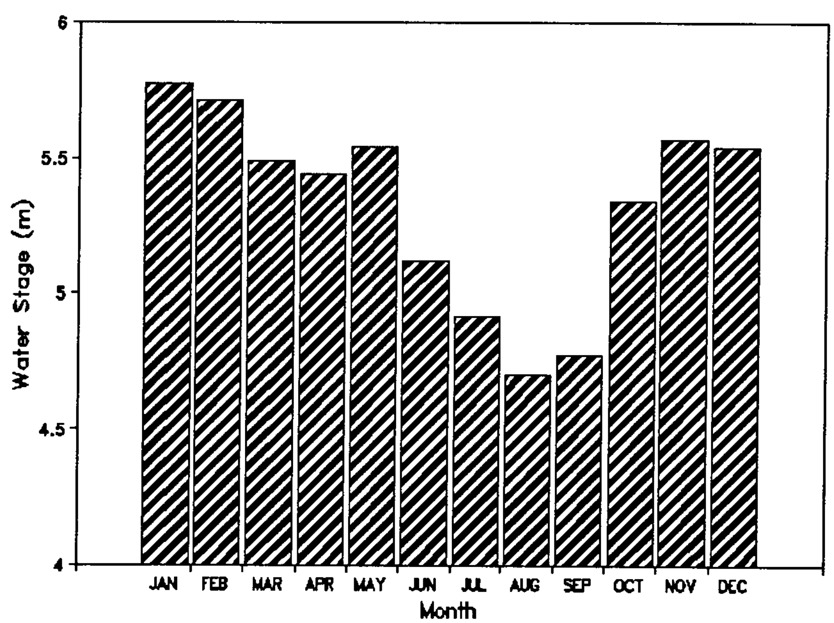

Figure 2.14 *Distribution of daily average water stage measured at the outlet of Nitinat watershed for each month.*

1985). The soils become more coarse in the area approaching to stream channels. There are stony soils sparsely distributed on steep slopes and bedrock exposures are occasionally found on the upper part of the watershed.

2.4 Forest

Both study watersheds are covered with mature and over-mature coniferous forest. On one hand, the combined interception loss and evapotranspiration from the forest make the watersheds consume more water than the watersheds with other types of vegetation; on the other hand, the decaying roots of forest create soil channels through which stormflow is quickly conducted. In addition, litters, mainly tree leaves, on the soil surface increase the storage capacity of watersheds, which will greatly attenuate the watershed peak flow.

In Jamieson Creek watershed, western red cedar, western hemlock and douglas fir occupy most of area below the elevation of 900 m. Above the 900 m level, the dominant species are mountain hemlock, yellow cedar and amabilis fir.

In Nitinat watershed, the forest species have the similar changes with elevation as in Jamieson Creek watershed. At the lower portion of the watershed, red cedar and western hemlock are dominant, while yellow cedar and mountain hemlock again become common at the upper portion of the watershed.

2.5 Instrumentation and Data Collection

2.5.1 Precipitation

a. Jamieson Creek watershed

Five recording rain gages (Belford weighing-type precipitation gage) were installed along the contours trails of Jamieson Creek in 1970. The gage nearest to the place where stormflow is measured was selected for this study. The gage is serviced weekly. For the model uses, the recorded rainfall data were sampled at a time interval of 15 minutes.

b. Nitinat watershed

There are daily rainfall data available for nine years collected by the Department of Fisheries and Oceans (DFO) Nitinat River Hatchery at the outlet of Nitinat watershed. Since the length of these data is not long enough to give the confidence to determine the rainfall intensity for design storms, rainfall data from nearby weather stations, Carnation Creek (1977-1988), Port Alberni Airport (1969-1988) and Cowichan (1960-1988) were obtained in order to estimate intensity-duration-frequency (IDF) curves for Nitinat watershed.

2.5.2 Stormflow

a. Jamieson Creek watershed

A 120° V-notch weir and water stage recorder was installed at the mouth of Jamieson Creek watershed in 1970. The water stage is monitored by a Leupold and Stevens water level recorder. A calibrated water stage-discharge relationship is used to calculate discharge based on the measured water stage. For this model, the discharge data were also sampled with a time interval of 15 minutes.

b. Nitinat watershed

There is no gage installed for measuring discharges of Nitinat watershed. Some estimations of discharges for the watershed can be roughly made using the flood stage data provided by the pumphouse at the outlet of Nitinat watershed. The stage data recorded from 1982 to 1988 was used for this study. Since the water stage readings were taken twice a day in the morning and afternoon, they did not necessarily reflect the stages for instantaneous peak flood discharges. The discharge of the watershed was measured once on November 9, 1989 when a peak flow occurred (McFarlane, 1990).

2.5.3 Other data collection

Topographic maps for both Jamieson Creek and Nitinat watershed, 1:50,000, were obtained from the Survey and Mapping Branch: Energy, Mines and Resources, Canada.

Land use and soil maps of Nitinat watershed, 1:100,000, were obtained from the Surveys and Resources Mapping Branch, B.C. Ministry of Environment.

Land use and soil maps of Jamieson Creek watershed, 1:15,840, were obtained from the Faculty of Forest, University of British Columbia.

These maps were digitized into GIS. The information related to these maps were linked with the digitized maps and processed for the model in GIS.

Chapter III

WATERSHED CONFIGURATION

A physically distributed hydrological model is established on the understanding of hydrological process. Overland, partial area and variable source area flow are considered as three typical models of flow generation of watershed, describing the sources where stormflow is generated in the process. The generated stormflow is subsequently translated to the outlet of watershed in the forms of overland flow, interflow or channel flow. The pathway through which the stormflow is translated to the outlet from each point on the watershed and the travelling time that stormflow takes to a point of interest are simulated using the digital elevation model of GIS. This chapter will discuss the mechanism of stormflow generation and translation, and describe a computer program developed by the author to automatically delineate some hydrologically important geomorphic characteristics of watershed.

3.1 Stormflow Generation

The time distribution of stormflow at a point of interest is usually expressed as a hydrograph, which essentially reflects the hydrologic nature of stormflow. A typical hydrograph for a single storm is conventionally divided into two components: quick flow and slow flow (see Figure 3.1). The quick flow, or direct runoff, is produced by a volume of water derived from the storm event, which usually occurs soon after the beginning of the storm. The slow flow, or base flow, is contributed from groundwater, the rate of which changes relatively slowly.

The portion of rainfall contributing to the quick flow is called excess rainfall. Theoretically, the amount of excess rainfall is equal to that of quick flow. However, the way that quick flow is generated from excess rainfall may change the time distribution of quick flow at the outlet of watershed, which is more important for land managers and engineers. Overland flow, partial area and variable source area are three major models describing how the quick flow is generated from a watershed.

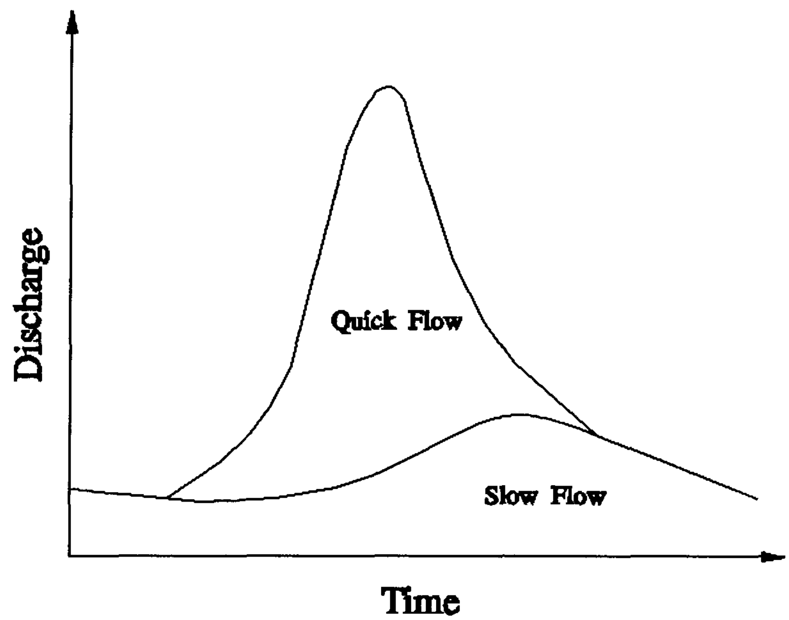

Figure 3.1 *Typical single-storm hydrograph.*

3.1.1 Overland flow

Horton (1933) considered that stormflow is generated in the form of overland flow. In

Horton's theory, the overland flow is produced only after the rainfall rate exceeds the infiltration rate of the surface soil. The infiltration rate decreases with time during a storm until a capacity value of soil, the saturated conductivity of surface soil, is reached. When the rainfall rate is greater than the rate of soil infiltration, the rainwater collects on the soil surface. As the surface storage is filled up, overland flow occurs. Since this model considers overland flow occurs uniformly over the watershed, the source area is considered equal to that of the entire watershed. Horton proposed that overland flow is common and areally widespread.

The Hortonian concept of stormflow generation prevailed for many years, and is still valid when applied to land surfaces with low soil infiltration capacity. Much of range land and urban area fall in this category. However, overland flow is rarely observed in forested watersheds of humid regions, where infiltration capacities are usually greater than expected rainfall intensities (Cheng, 1975; Hibbert and Troendle, 1988).

3.1.2 Partial area

In fact, not all parts of a forested watershed contribute equally to the runoff process in humid regions. Overland flow is rare except as "overland flow" in small ephemeral waterways. Under these conditions, interflow becomes a primary mechanism for generating stormflow.

Freeze (1974) illustrated the process of interflow by using the results of his mathematical simulation. This model emphasizes that stormflow results from overland flow generated only from small but relatively limited areas near the stream (riparian or partial areas) during a storm event. According to this model, the rainfall falling on channels is the first contributor to the stormflow. The second to contribute are areas of shallow water table close to the channels where saturation occurs from below because of rising shallow water table fed by vertical infiltration of rainwater from above.

For the partial area model, the conditions necessary for interflow to be a significant contributor to stormflow are quite stringent. The interflow is assumed to move laterally due to the difference of hydraulic head before it seeps from the hillside above the water table. The saturated conductivity values used as the highest limits of the velocity of interflow are usually inadequate to explain the flashy response of storm in a forested watershed of humid regions (Loukas, 1991).

3.1.3 Variable source area

The explanation for the quick response of interflow to a storm in a forested watershed can be given partly by the fact that soil channels (macropores, or soil pipes) exist in most forest soils and provide pathways of low resistance to interflow (Whipkey, 1965; Aubertin, 1971). Some soil channels may exist between surface soil and a relatively impermeable soil layer beneath the surface soil because of the frequent passing of lateral subsurface flow. Activities of small animals, insects and decaying roots partly account for the existence of the soil channels.

Soil channels begin to fill when rainwater ponds on the soil surface in local depressions or when the surrounding soil matrix becomes saturated. Water conducted into these channels moves downward in response to the force of gravity. The water even can be delivered in the soil channels through the unsaturated soil zones during its movement downslope, without significant losses (Mosley, 1982). In other words, stormflow may be generated before soil is completely saturated in a forested watershed of humid regions. Since the surrounding soil is saturated when the channel flow starts to deliver water quickly downslope, the velocities of channel flow are comparable to those of overland flow (Mosley, 1979).

Hursh (1936) presented the concept of interflow as the primary source of stormflow from forest lands of humid regions. As pointed out by Hewlett (1974), the origin of the "variable source area concept" of stormflow generation has been the subject of reports by Hursh (1936). Based on the observations in the field that steep watersheds with shallow soils produce more stormflow than the low slope watersheds with deep soils, Hewlett and his co-workers further developed this concept to give more precise answer for the quick response caused by the interflow. In essence, the concept assumes that certain regions within a watershed contribute runoff to the streamflow while other areas act as recharge or storage zones. It suggests that the stream channel system expands into and shrinks from intermittent and ephemeral source areas during and following rainfall.

3.1.4 Comparison of the models of stormflow generation

The stormflow generation models discussed above described three possible sources producing stormflow, the forces conducting stormflow to the outlet, the ways through which rainwater is conducted, as well as the physiographic conditions under which these models can be applied (see Table 3.1). They may serve either as separated or integrated pathways for stormflow concentration. Hewlett and Troendle (1975) concluded that these models are different ways of looking at the same complex process in the first-order basin, and it will come as no surprise that the others are merely special cases of the variable source area concept, which attempt to explain the entire range of hillslope processes of stormflow generation. Like overland flow, there seems little question that overland source will also vary with increasing precipitation. Oka (1990) also noted that additional water is drained into the lateral channels from soil matrix and increases the contribution of channel flow in the total runoff.

Table 3.1 *Comparison of the models of stormflow generation*

Models	Sources	Forces	Pathways	Soils	Land Use	Climate
Overland flow	The whole watershed	Gravitational potential	Soil surface	Fine soil, deep or shallow	Range, cropped, urban area	Arid and humid
Partial area	Riparian areas and channels	Hydraulic head	Soil matrix	Coarse, deep soil	Forested land	Humid
Variable source area	From riparian to the whole watershed	Gravitational potential	Soil channels	Very coarse, shallow soil	Forested land	Humid

As described in Chapter II, both Jamieson Creek and Nitinat watershed are steep, presently forested watersheds with shallow, thin and well drained soils in humid area. The wide existence of interconnected soil channels has played a very important role in producing stormflow in these areas (Cheng, 1975; Loukas, 1991). The expanding and shrinking nature of the stream network observed by Cheng (1975) indicates that stormflow generation mechanisms in forested watersheds of these areas are similar to the model of interflow from a variable source area of the watersheds.

3.2 Stormflow Translation

In theory, all "effective" raindrops striking on a watershed will eventually find their ways to the outlet of the watershed. The sources in which the stormflow is generated from these raindrops have been discussed in the previous section. The question is: how is the stormflow translated from where it is generated to the outlet of a watershed? This section describes a computer program designed for simulating the pathway and time of stormflow, two important aspects of stormflow translation.

Manual interpretation of the pathway and time of stormflow from topographic maps or aerial photographs and the subsequent measurement or digitization of geometric or topologic properties may be quite tedious, time-consuming and error-prone for any but the smallest data sets. The development of automated techniques to extract, store and provide measurements of the hydrological parameters related to geomorphology of watershed has recently received increased attention (Puecker and Douglas, 1975; Mark, 1984; O'Callaghan and Mark, 1984; Marks et al., 1984; Band, 1986; Hodge et al., 1988). The growing availability of digital elevation model (DEM) facilitates the applicability of these techniques to a variety of hydrologic research.

The most common form of DEM used for deriving the hydrological characteristics of watershed is the elevation matrix usually obtained from quantitative measurements from stereoscopic aerial photographs. The elevation matrix can also be converted from elevation contours digitized or scanned from quadrangle topographic maps using GIS techniques.

Because of the ease with which matrices are processed in the computer, particularly in raster-based geographical information systems, two 1:50,000 topographic maps were digitized and then converted into the elevation matrices using DEM of GIS in this study. The computer program designed for searching the stormflow pathway and calculating the stormflow time is called downhill searching program (DSP), implying that the program traces the pathways of stormflow in the downslope direction throughout the elevation matrix of watershed.

3.2.1 Assumptions of the simulation of stormflow translation

Based on the models of stormflow generation as discussed in Section 3.1 and the physiographical characteristics of both Jamieson Creek and Nitinat watersheds, the following assumptions are made:

> *Assumption 1*. If the two watersheds are kept forested, soil channels are main pathways for both of them to conduct rainwater to stream channels; and, if the land use is changed to grass land, urban area or a combination of them, overland flow will be dominant where such changes occur.

Since both interflow through soil channels and overflow on the soil surface are the response of stormflow to the gradient of gravitational potential, another assumption is:

> *Assumption 2.* The stormflow always goes in the direction of steepest slope.

For forested watersheds in humid regions, rainwater is usually delivered through vertical soil channels to a relative impermeable soil layer beneath the surface soil and becomes lateral flow above the layer. Because the surface soil is shallow and coarse, it can be assumed:

> *Assumption 3.* The impervious soil layer and soil channels conducting the lateral flow are basically parallel to the soil surface.

The above three assumptions constitute the basis on which the pathways of stormflow are simulated over the study watersheds. The last assumption gives the convenience for modeling the pathways of interflow with the available surface elevation data.

3.2.2 Simulation of the pathways of stormflow

Puecker and Douglas (1975) employed a simple local algorithm that uses a kernel of four cells to detect stream lines and ridges. As this kernel is moved over the elevation matrix for each set of four cells at a time, the concave and convex pixels are flagged as potential stream and ridge points, which, however, are not well connected. Band (1986) improved this algorithm with a kernel of nine cells to refine the potential stream and ridge points into geomorphologically reasonable, connected graph structures representing drainage channels and divide networks. Although this algorithm works well, it is not based on any understanding of fluvial process.

Mark (1984) proposed a more realistic algorithm to detect the drainage lines on a watershed. For each point in the elevation matrix of the watershed, its elevation is compared with its eight neighbours within the 3 × 3 kernel. The lowest neighbour is flagged and the kernel is moved to the lowest neighbour. When this process is repeated, this algorithm accumulates upstream drainage area to successively lower pixels, delineating the major drainage lines.

Sasowsky and Gardner (1991) applied a set algorithm to configure a watershed into discrete, connected channel segments and corresponding contributing areas. This algorithm delineates the topographic boundary and drainage area of a basin by using the DEM derived aspect data layer and an x,y coordinate pair defining the location of the basin outlet cell. The aspects of neighbours are recursively evaluated to determine the number of cells accumulated and if a cell can be added to the channel network.

By reference to the previous research, this study attempts to make an improvement for delineating stream channels and divides in steep watersheds. The contour lines were processed using a GIS program (TerraSoft registered by Digital Resource Systems Ltd.) to produce the elevation matrices with a square-grid of 40 m × 40 m for Jamieson Creek and 400 m × 400 m for Nitinat watershed. The downhill searching program (see Figure 3.2), written in FORTRAN language, searches through the matrices to find the flow path from each point to the outlet and accumulates the number of upstream points drained to each point from its upstream drainage area. Finally, the flow pathways and accumulated numbers of points are stored in two separated files, and input back to TerraSoft as a new layer in GIS and a new GIS theme respectively. GIS displays the drainage network on the new layer, and outlines stream channels and divides of the watershed with the new GIS theme.

The program searches for the pathways of points on the watershed through the

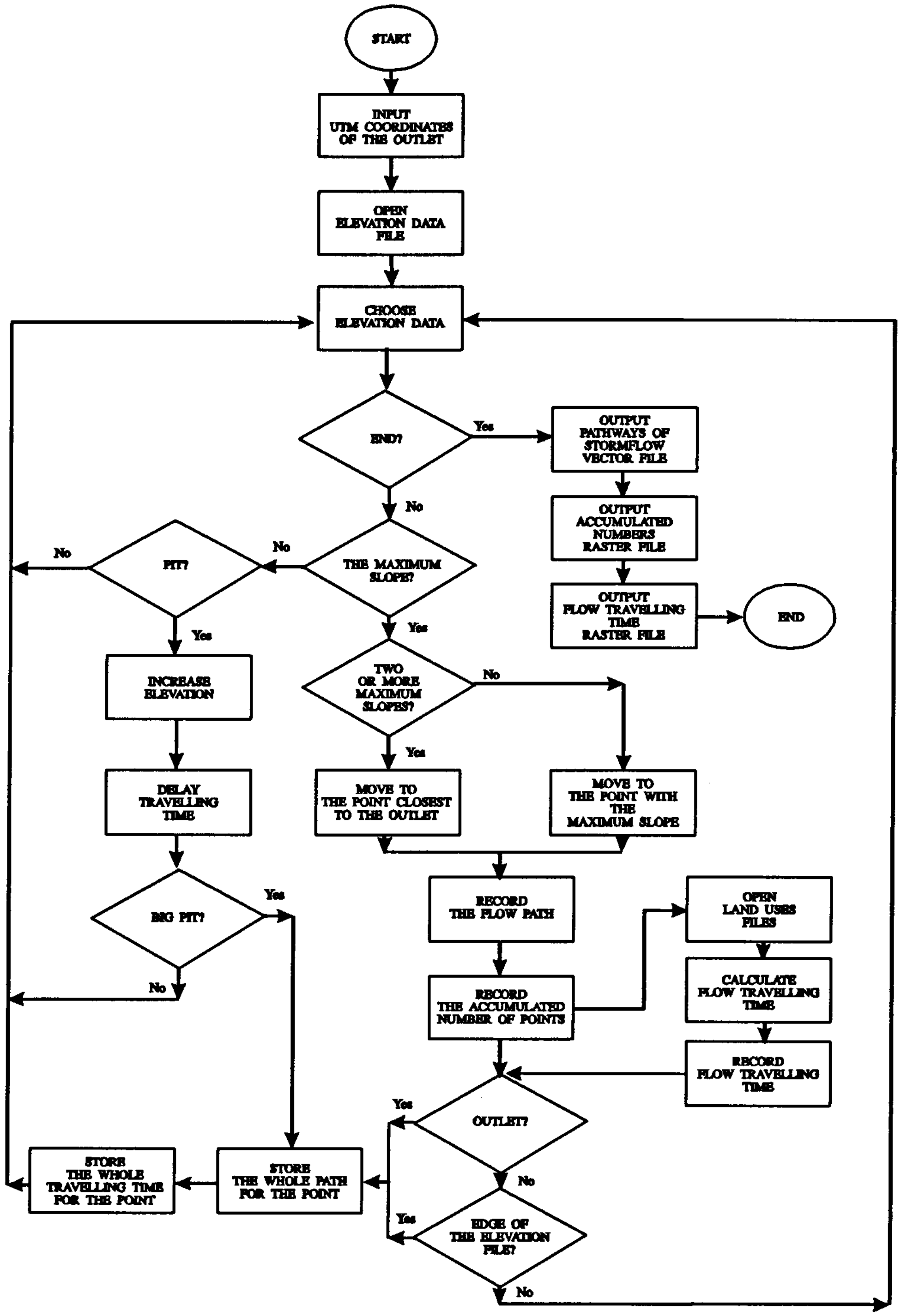

Figure 3.2 *Flow chart of the downhill searching program (DSP)*

elevation matrix with a kernel of 3 × 3 points. The direction in which the program conducts the search is determined by detecting the steepest downwards slope existing between the central point and its eight neighbour points within the kernel of 3 × 3 points (see Figure 3.3).

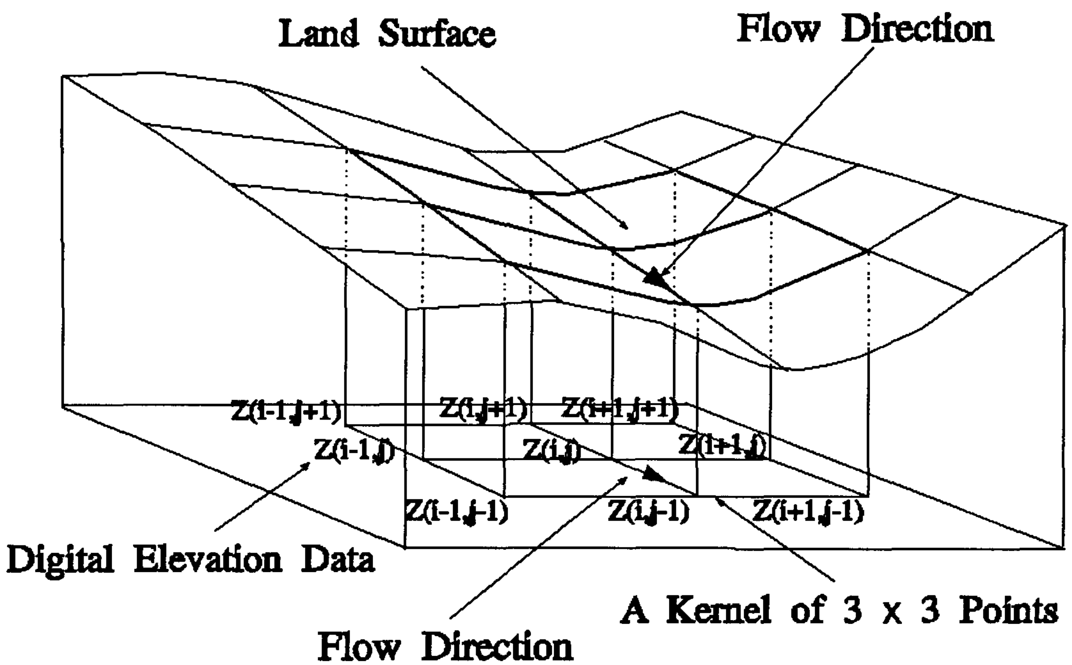

Figure 3.3 *The direction of stormflow. It is simulated by detecting the steepest slope between the central cell and its eight neighbour cells.*

The biggest problem for algorithms in using elevation matrices for continuously detecting the pathways of stormflow is that of "pits" in the digital surface caused either by data error or complex topography with natural or artificial depressions. Although the numerical smoothing method, i.e., moving a kernel of 3 × 3 points over the elevation matrix to recalculate the elevation data, can remove a large number of pits, it has been noted that it may oversmooth the topography, leading to a loss of significant terrain information (O'callaghan and Mark, 1984). To avoid the significant loss of terrain information, the downhill searching program gives a small increase of elevation and a delay of travelling time of stormflow when a pit is met. Such an increase and delay will continue until the program finds its way out of the pit. In other words, the rainwater has to fill up the pit before it flows out of it. If the pit is too big to be filled up within a certain of time, the area drained to the pit will be considered as a local drainage area excluded from the watershed.

For the areas, usually flat areas, within which there exist two or more points with equally steep downward slopes from the central point in the kernel, the program will arbitrarily designate the direction to the point closest to the outlet.

If the program meets a point on the edge of the elevation matrix rather than the outlet while searching for the flow pathways for a point of interest, the point of interest will be flagged, indicating that the point of interest does not belong to the watershed, otherwise segments from the point of interest will be connected to the outlet as its flow pathway (see Figure 3.4).

Figure 3.5 shows the pathways of stormflow from each point on Nitinat watershed. This graph was stored in the vector file with TerraSoft compatible format. Clearly, the flow pathway from any point on the watershed can be traced on the graph.

As the flow pathway of each point is traced to the outlet, the points traversed by the flow pathway automatically accumulate the numbers of upstream points from which they receive rainwater until all points have been evaluated. Figure 3.6 shows the accumulated numbers derived from the elevation matrix presented in Figure 3.4.

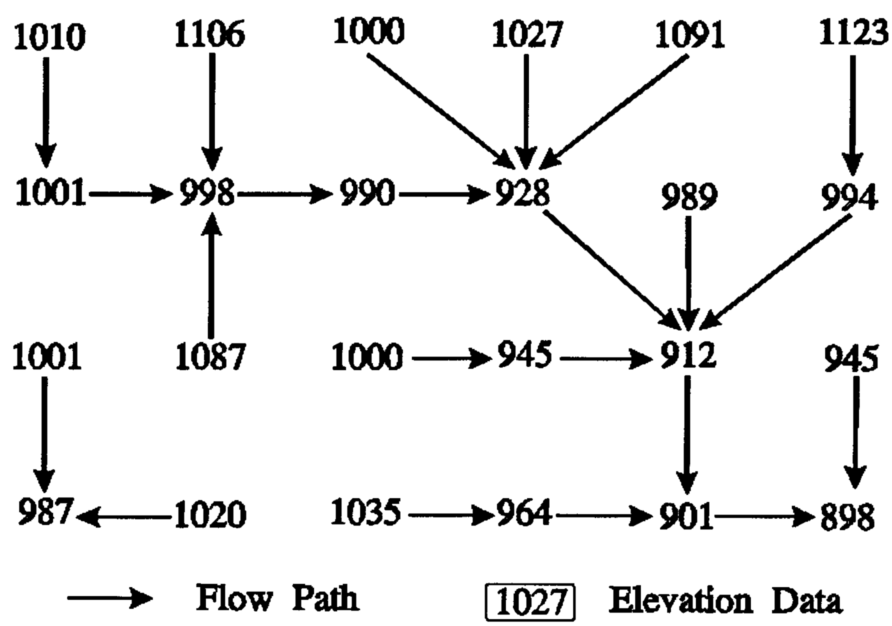

Figure 3.4 *The pathways of stormflow. The pathways are connected in the direction of the deepest slope calculated using the elevations between the concerned point and its eight neighbour points. They are stored in a vector file compatible with GIS.*

The results are recorded in two files with the GIS compatible formats. One is a vector file, containing the pathways of stormflow for each point; another is a raster file, containing the numbers of accumulated points. Each file is then transferred to GIS with corresponding UTM (Universal Transverse Mercator) coordinates. The vector data becomes a new layer of watershed map in GIS, while the raster data is treated as a GIS theme for further analysis.

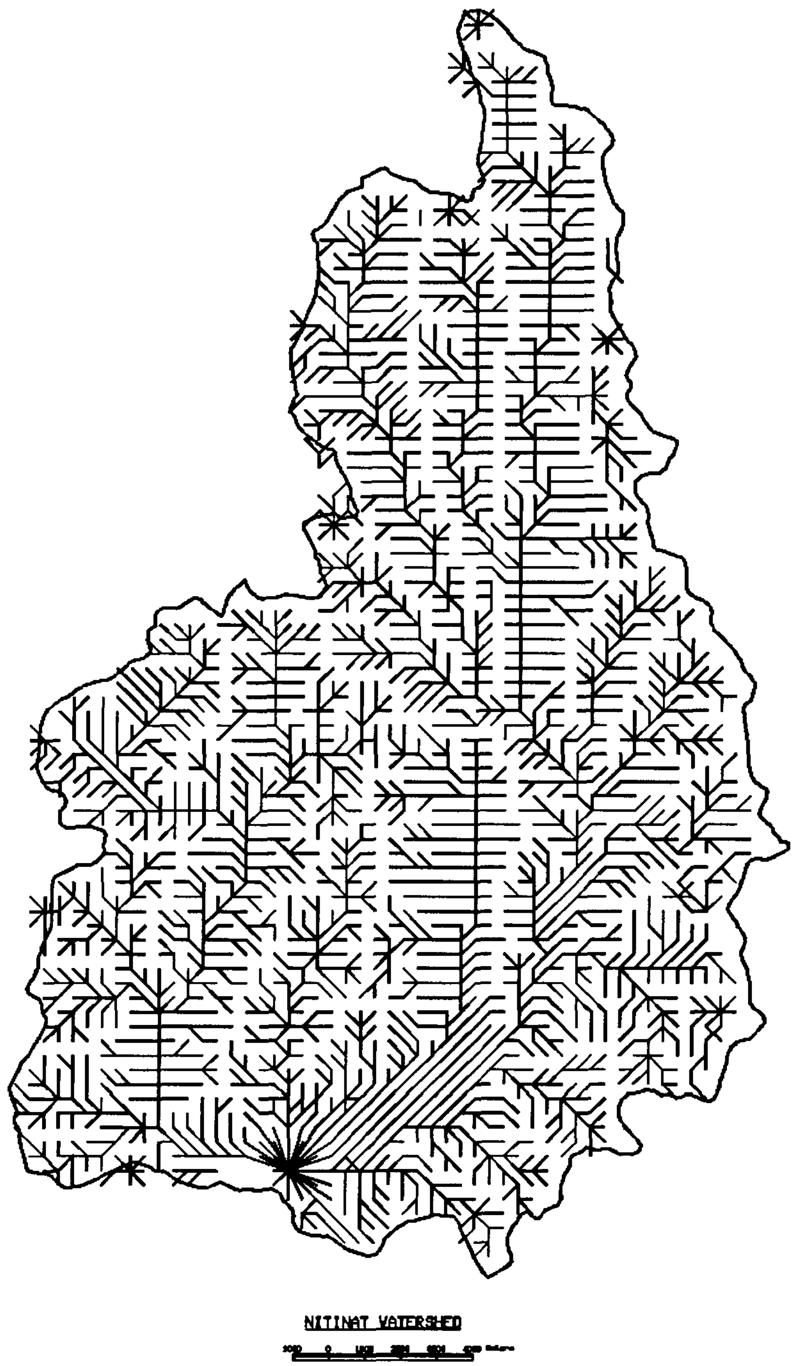

Figure 3.5 *Simulated pathways of stormflow from each point on Nitinat watershed.*

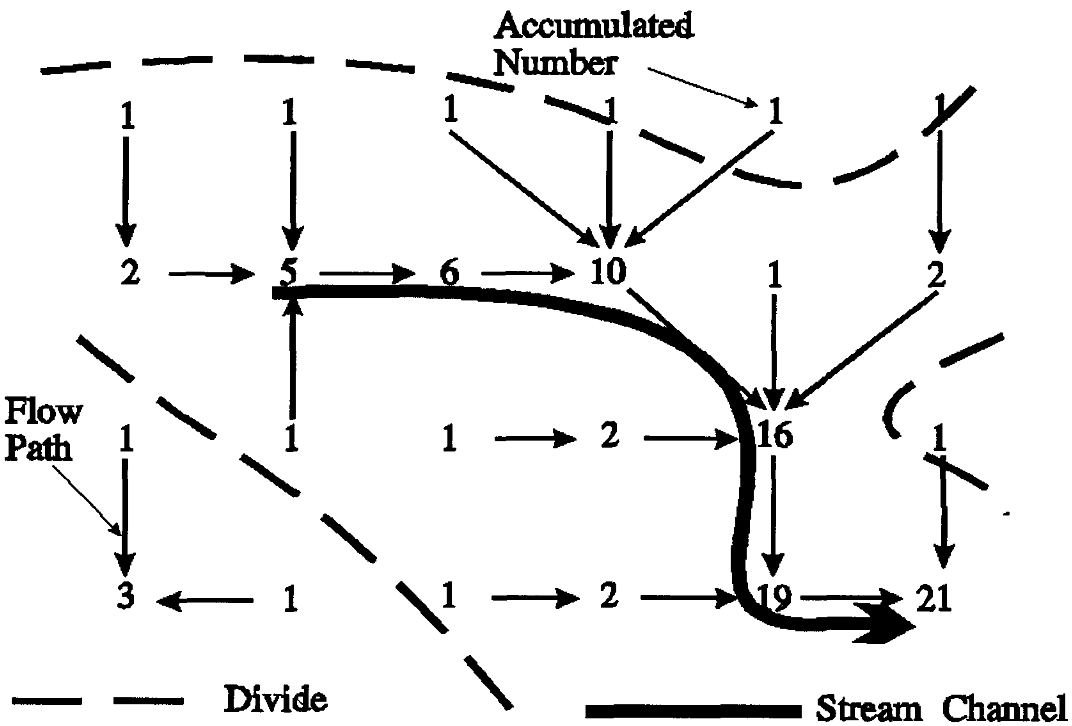

Figure 3.6 *The accumulated numbers of upstream points. It shows the number of upstream points from which rainwater contributes to each point. Divides can be located where the number is equal to one, while the stream channels can be identified for the points with the larger accumulated numbers.*

Since each point has the same area of grid cell in the elevation matrix, the accumulated number of upstream points, in essence, represents the area contributing rainwater to the point of interest, namely, the drainage area.

Unlike the pathways of stormflow from each point, stream channels can only be found in the places where stormflow frequently reaches a certain amount. Because the derived contributing area indicates a relative amount of stormflow that a point receives from its drainage area, the points with larger contributing areas are more likely to become stream channels than those with smaller contributing areas. Therefore, a threshold of contributing area can be selected to identify the stream channels by using the contributing areas data. Points with their contributing areas larger than the threshold are considered on the stream channels of the watershed, as shown in Figure 3.6.

To match the derived stream channels to mapped ones, the threshold may vary with watersheds because of the problem of different map scales. For Jamieson Creek watershed, the threshold is selected as a contributing area of 30 points (48,000 m^2) to define the stream channels (see Figure 3.7), whereas a threshold contributing area of 5 points (800,000 m^2) is used to identify the stream channels in Nitinat watershed (Figure 3.8). The good consistency between the derived and natural channels shown in Figure 3.8 for Nitinat watershed demonstrates that the downhill searching program can perform well in automatically deriving the stream channels in forested watersheds with steep slope in humid areas. For Jamieson Creek watershed as shown in Figure 3.7, the result could be better if more accurate elevation data could be provided, because the program becomes more sensitive to the accuracy of elevation data as the grid resolution increases.

3.2.3 Configuration of stormflow time-area

Although the quantitative analyses of drainage network have gone through dramatic advance, there has not been a commensurate level of effort spent on the coupling of these analyses with the most important hydrologic variable, namely, the streamflow response to rainfall in a watershed. Some researchers (Rodrigues-Iturbe, Valdes and Devoto, 1979)

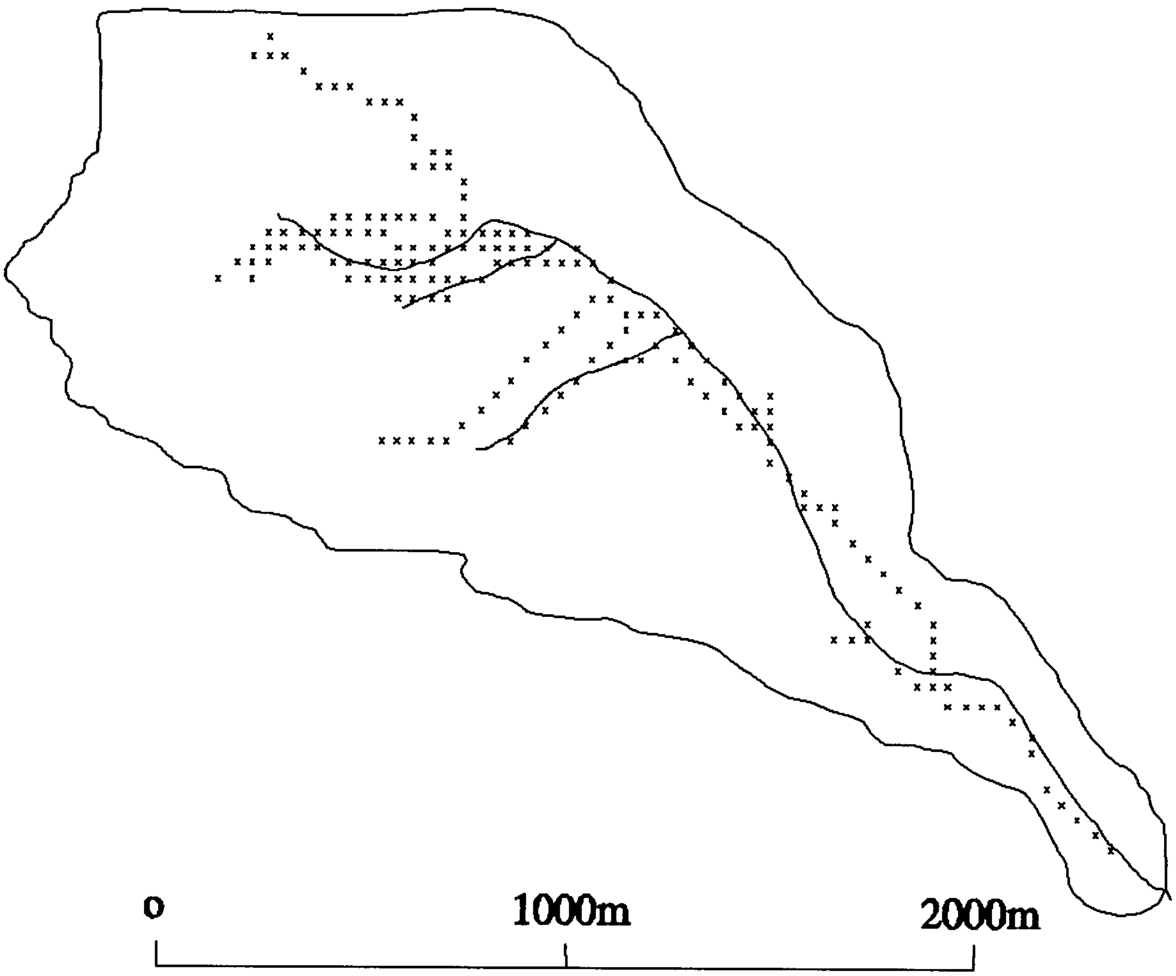

Figure 3.7. *Derived (×) and mapped (—) stream channels in Jamieson Creek watershed.*

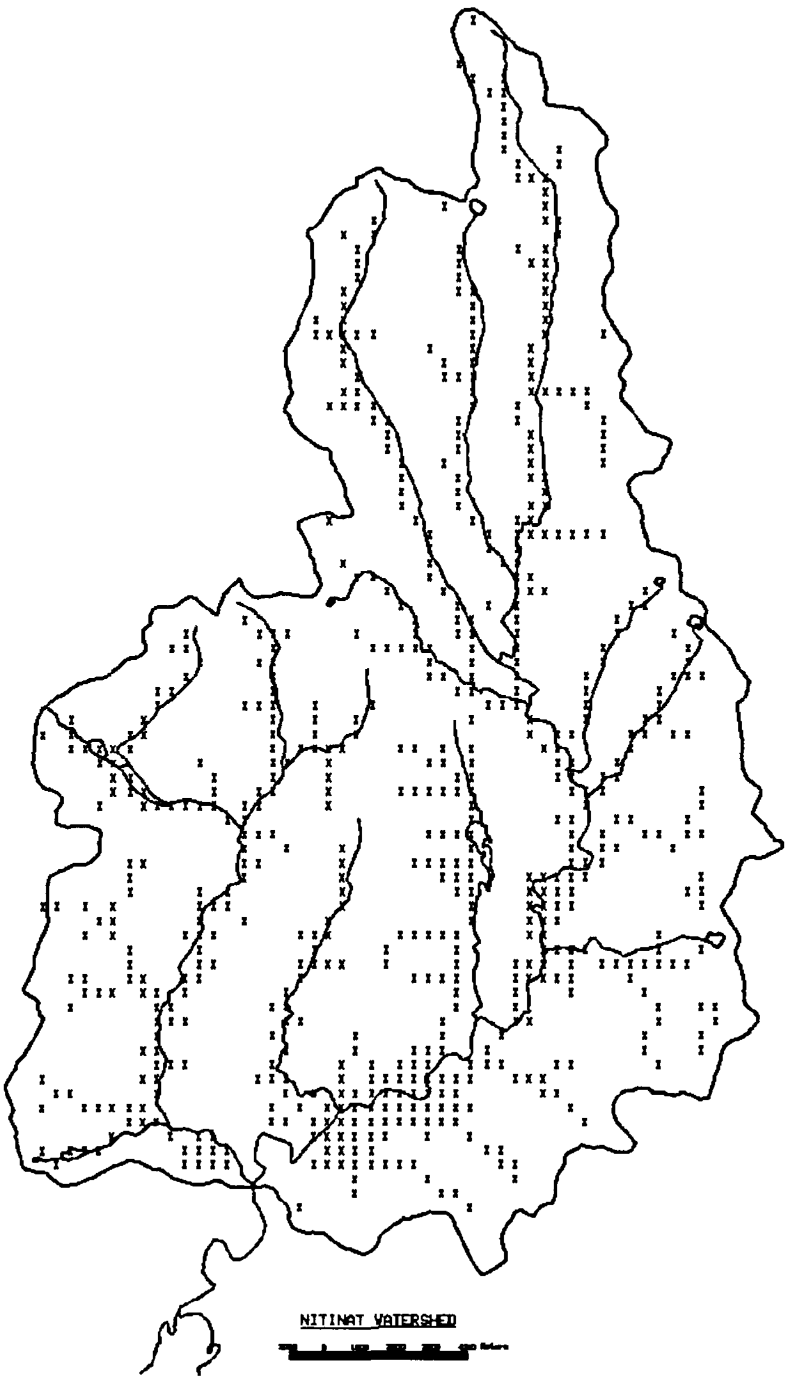

Figure 3.8. *Derived (×) and mapped (—) stream channels in Nitinat watershed.*

attempted to link the instantaneous unit hydrograph (IUH) with some geomorphologic parameters described by Horton's well-known empirical laws (Horton, 1945). The derived equations express the IUH as a function of Horton's numbers, a mean velocity of streamflow, but they do not give a good representation of the physical mechanism of the stormflow process.

An interesting way to understand how excess rainfall is converted into stormflow is to use the concept of flow time-area. It assumes that the outflow hydrograph results from the pure translation of direct runoff to the outlet, ignoring any storage effects in the watershed. If one unit of excess rainfall were spread uniformly over the watershed instantaneously, rainwater first flows from areas immediately adjacent to the outlet, and other upstream areas will subsequently contribute to the outlet until rainwater from the remotest area reaches the outlet with the travelling time equal to the time of concentration (T_c). The flow time-areas are defined by dividing the area of a watershed into subareas with distinct runoff travelling times to the outlet. These areas are delineated with isochrones of equal travelling time, spaced in equal travelling time increments numbered sequentially upstream from the outlet (Hoggan, 1989).

The flow time-area concept provides useful insight into the runoff phenomena. However, its application for estimating stormflow is limited because of the difficulty of constructing isochronal lines and because the hydrograph must be further adjusted or routed to represent storage effects in the watershed. An algorithm to construct isochronal lines for a watershed using digital elevation data is described below. Discussion of the storage effects on the time-area method is given in next chapter.

The travelling time of stormflow from one point on a watershed to another can be deduced from the flow distance and velocity.

$$t_{i,j}=\sum_{m=1}^{M}\frac{\Delta l_m}{V_m} \qquad \text{3-2-1}$$

where $t_{i,j}$ is the flow travelling time from a point with the UTM coordinates of *i,j* to the outlet;

$m=1,2,\ldots,M$, the steps from the point (i,j) to the outlet;

Δl_m is the length of segment m on the pathway; and,

V_m is the flow velocity with which rainwater goes through the segment m.

In Manning's equation, the flow velocity of segment m is expressed as:

$$V_m=\frac{R_m^{2/3}\times S_{f,m}^{1/2}}{n_m} \qquad \text{3-2-2}$$

where R_m is the hydraulic radius;

n_m is the Manning roughness coefficient; and,

$S_{f,m}$ is the friction slope, equal to the slope of land surface or channel's bottom for a steady uniform flow.

To simplify the estimation of the hydraulic radius R_m, $R_m^{2/3}/n_m$ in Manning's equation is considered as a constant variable, P, for each pattern of land use. So the Manning's equation can be rewritten as:

$$V_m=P\times S_m^{1/2} \qquad \text{3-2-3}$$

where P is regressively derived by reference to data in Table 3.2.

As shown in Figure 3.9, the velocities, in meters per minute, for different land use patterns described by the regression equations are:

Table 3.2 *Approximate average velocity in metres per minute of runoff*

	Slope in Percent			
Land use	0-3	4-7	8-11	12-
Forest	0-28	28-46	46-59	59-
Grass land	0-46	46-64	64-78	78-
Urban area	0-155	155-247	247-311	311-
Natural channel	0-37	37-73	73-128	128-

(Source: Applied Hydrology, Chow et al., 1988, p.165)

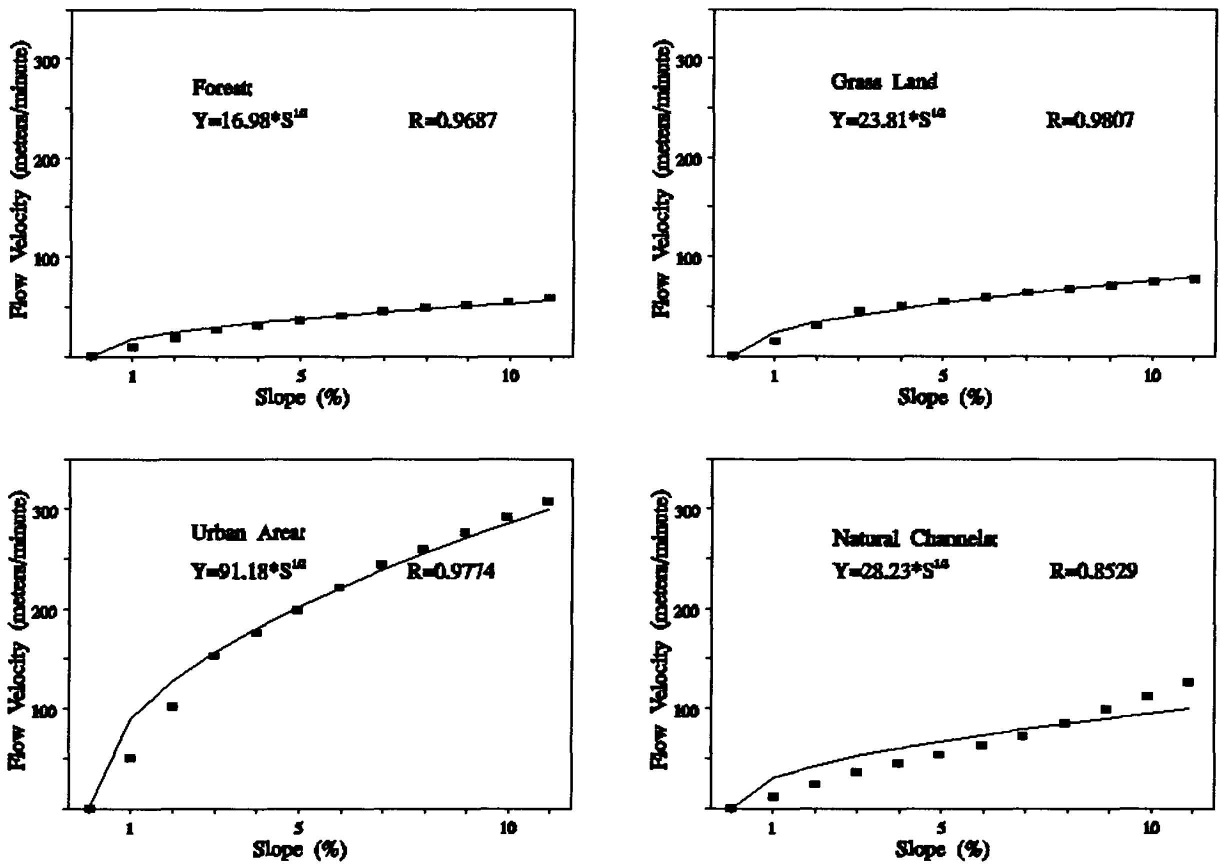

Figure 3.9 *Linear regression lines for flow velocity as related to land slope with different land uses. The experimental data are referred to Table 3.2.*

Forest,	$V_m = 16.98 x S_m^{1/2}$
Range Land,	$V_m = 23.81 x S_m^{1/2}$
Urban Area,	$V_m = 91.18 x S_m^{1/2}$
Natural Channels,	$V_m = 28.23 x S_m^{1/2}$

The flow travelling time is given by:

$$t_{i,j}=\sum_{m=1}^{M}\frac{\Delta l_m}{V_m}=\sum_{m=1}^{M}\frac{\Delta l_m}{PS_m^{1/2}}=\frac{1}{P}\sum_{m=1}^{M}\Delta l_m S_m^{-1/2} \qquad 3\text{-}2\text{-}4$$

where $t_{i,j}$ is calculated by an application program written in FORTRAN language.

This application program is quite similar to the downhill searching program (see Figure 3.2). The difference is that it sums the travelling time to the outlet for each point while tracing its flow pathway. In addition to the elevation matrix data, the derived contributing area data are processed to locate the natural channels where the flow velocity is different than other land uses. The travelling time of stormflow for other land use patterns will be discussed in Chapter V.

The travelling time data are then input back to TerraSoft as another GIS theme for the configuration of time-area maps. Figure 3.10 and Figure 3.11 show the derived 15-minute and 2-hour time-area maps for Jamieson Creek and Nitinat watersheds respectively when both watersheds are covered by forest and drained by natural channels.

Because the flow travelling time data are stored in GIS with grid-based format for each point, the flow time-areas can be spaced at any selected time intervals by simply changing the color scheme for the representation on computer. As a result, GIS can easily produce a flow time-area map with selected flow time interval suitable for hydrological modeling. Figure 3.12 and Figure 3.13 give another example of time-area maps at intervals

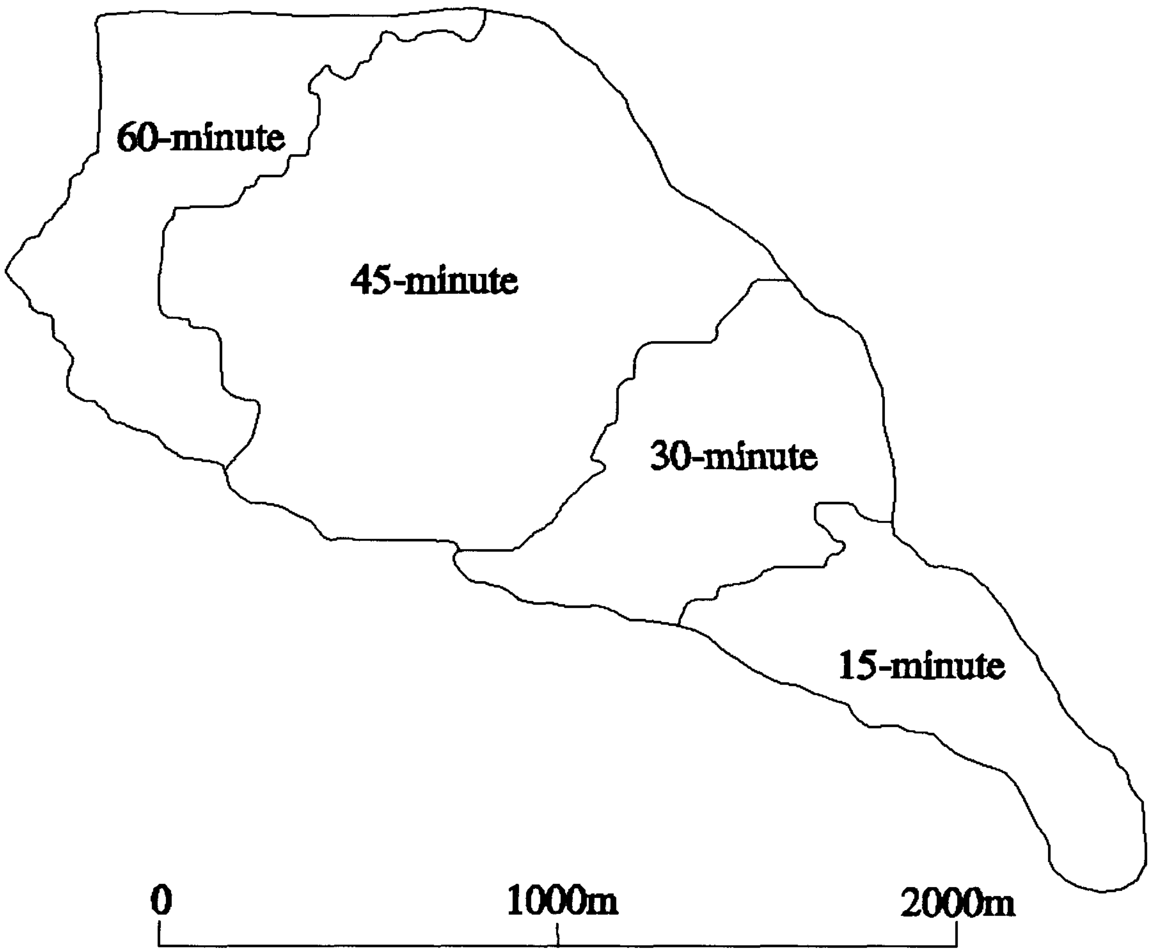

Figure 3.10 *15-minute flow time-area map for Jamieson Creek*

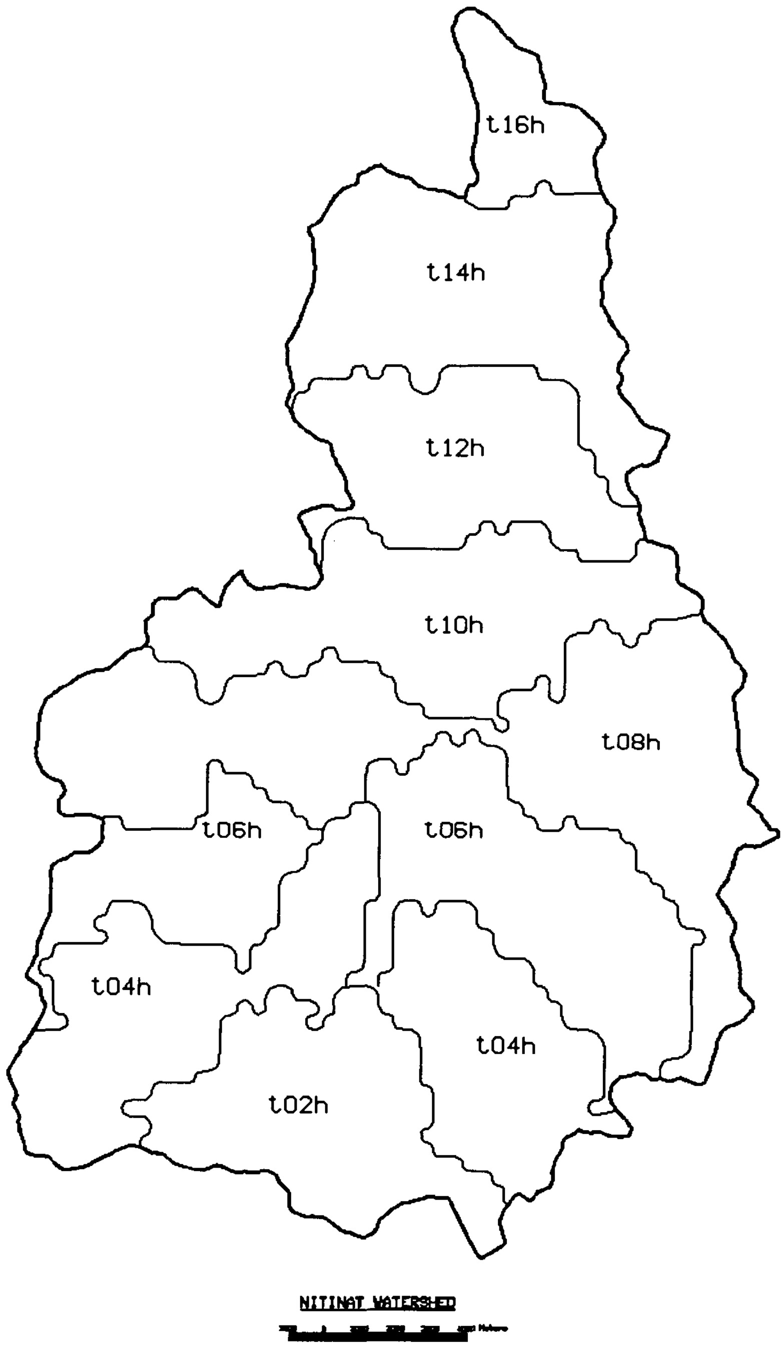

Figure 3.11 *2-hour flow time-area map for Nitinat watershed*

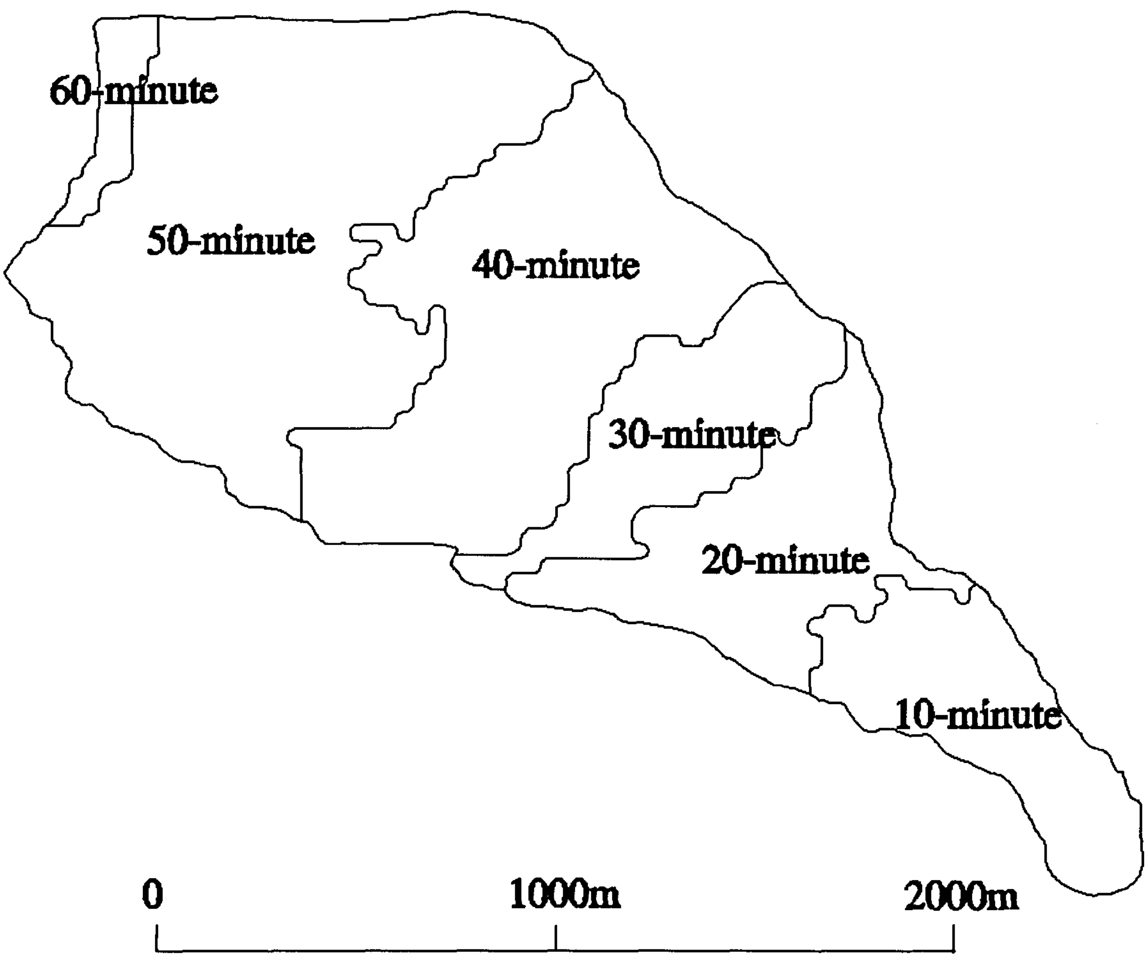

Figure 3.12 *10-minute flow time-area map for Jamieson Creek watershed.*

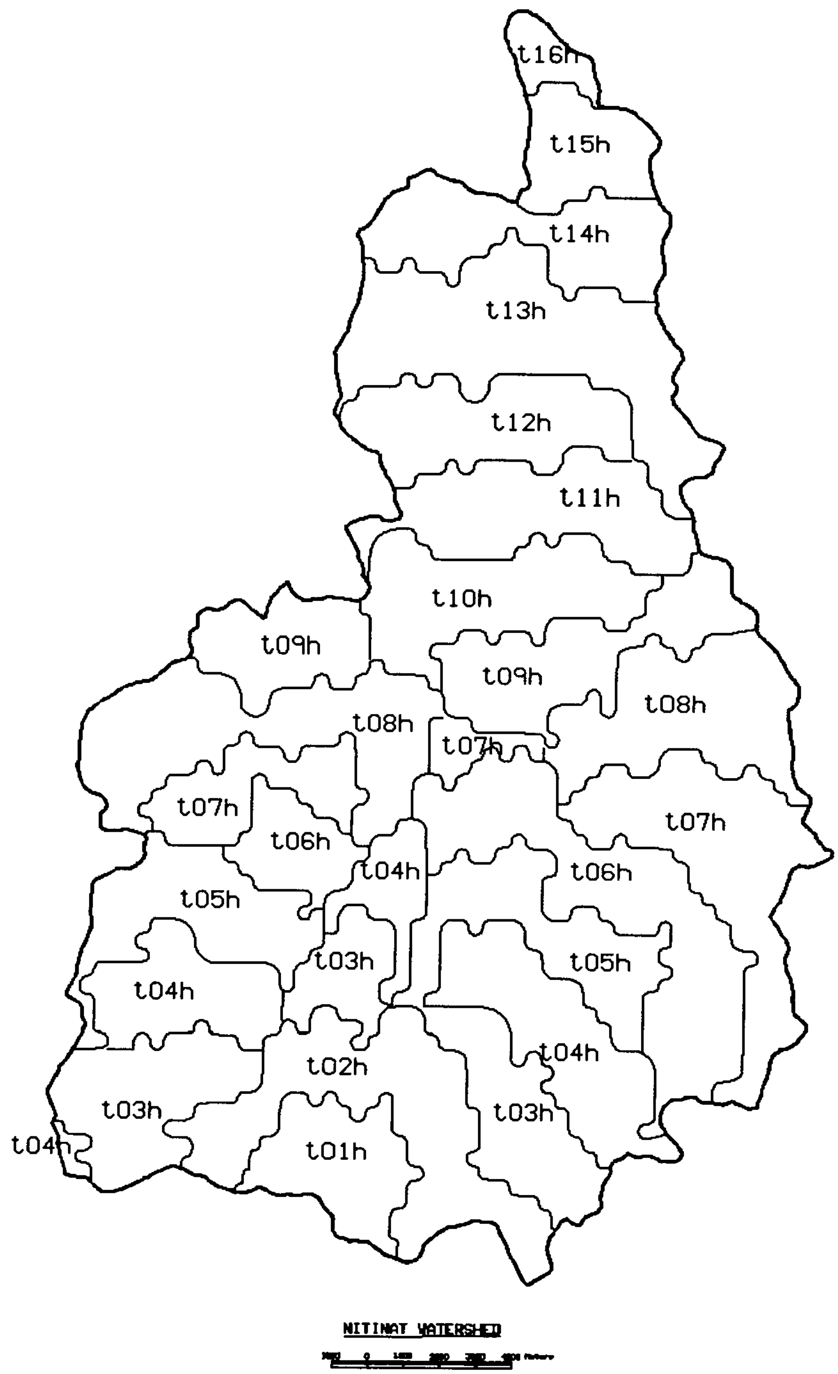

Figure 3.13 *1-hour flow time-area map for Nitinat watershed*

of 10 minutes and 1 hour time for Jamieson Creek and Nitinat forested watersheds respectively.

3.3 Digital Derivations of Other Watershed Characteristics

The derived contributing area data have considerable potential for automatically constructing the hydrological characteristics of watershed. The capabilities of GIS in displaying and analyzing these spatially distributed data have made such constructions much easier. The followings are some examples.

3.3.1 Drainage density

The drainage density is the length of streams per unit area within a watershed. In the same climate region, a watershed with a higher value for drainage density will usually have a fine-textured topography and short, generally steep, slopes. Conversely, a watershed with a lower drainage density will have longer, gentle slopes and larger distance between stream channels. To some extent, the similarity of drainage density between watersheds indicates the similarity of their geomorphological characteristics and hydrological responses.

The drainage density (Dd) may be expressed as:

$$Dd=\frac{\sum L}{A} \qquad \text{3-3-1}$$

where ΣL is the total length of streams; and,

A is the drainage area.

Since each point in the contributing area matrix represents a square cell with same area, the drainage density can be rewritten as:

$$Dd=\frac{l\times\sum n}{l^2\times\sum N}=\frac{\sum n}{l\times\sum N} \qquad \text{3-3-2}$$

where Σn is the total number of the points whose contributing areas are greater than the selected threshold of stream channels;

ΣN is the total number of the points within the watershed boundary; and,

l is the length of one side of the square cell for which a point represents.

For Jamieson Creek, the selected threshold of accumulated numbers is 500 with an area of 800,000 m^2, equivalent to the contributing area designated as the threshold of 5 accumulated numbers for stream channels in Nitinat watershed. Σn, ΣN and l are 44, 1711 and 40 m respectively. The drainage density is calculated as:

$$Dd=\frac{\sum n}{l\times\sum N}=\frac{44}{40\times1711}=0.0257(m/m^2) \qquad \text{3-3-3}$$

For Nitinat watershed, the threshold of 5 accumulated points is selected. Σn, ΣN and l are 652, 2668 and 400 m respectively. The calculated density is:

$$Dd=\frac{\sum n}{l\times\sum N}=\frac{652}{400\times2668}=0.0244(m/m^2) \qquad \text{3-3-4}$$

The similar values of drainage density in Jamieson Creek and Nitinat watersheds give another evidence that the hydrological similarity does exist between the two watersheds, which supports the application of the hydrological model derived from Jamieson Creek to Nitinat watershed.

3.3.2 Divides of watershed and its subwatersheds

The contributing area data indicate the total number of points from which a point of interest will receive rainwater if the rainfall continues indefinitely. Theoretically, a point right on a hydrological divide will only receive rainwater from itself no matter how long the rainfall lasts. The points with their accumulated numbers equal to one, therefore, can be automatically distinguished as the divides of the watershed and its subwatersheds, as shown in Figure 3.14. The vector connections of these points can be used to delineate the subwatersheds (see Figure 3.15).

Having draped these derived vector-based divide lines on the 3-dimensional plot of the watershed, the GIS shows the good agreement existing between the derived divides and the ones in the real world (see Figure 3.16).

3.3.3 Generalized stream channels

The channel network is a concept of both theoretical and practical importance in drainage watershed analysis. As defined by Shreve (1966), a channel network consists of all channels upstream from a given (arbitrarily chosen) point in the drainage system.Most of excess rainfall on the watershed is conducted to tributary channels through land surface or soil channels and then converged to the main stream which carries the water to the outlet where the stormflow hydrograph is measured.

In contrast to the tree-shaped drainage network that gives a perspective of the pathways of stormflow translation, the generalization of the drainage network has at least two implications: one is that it represents the relative importance of stream channels in conducting stormflow; another is that it gives a rough idea of variable source area of the

Figure 3.14 *Raster derived divides on Nitinat watershed.*

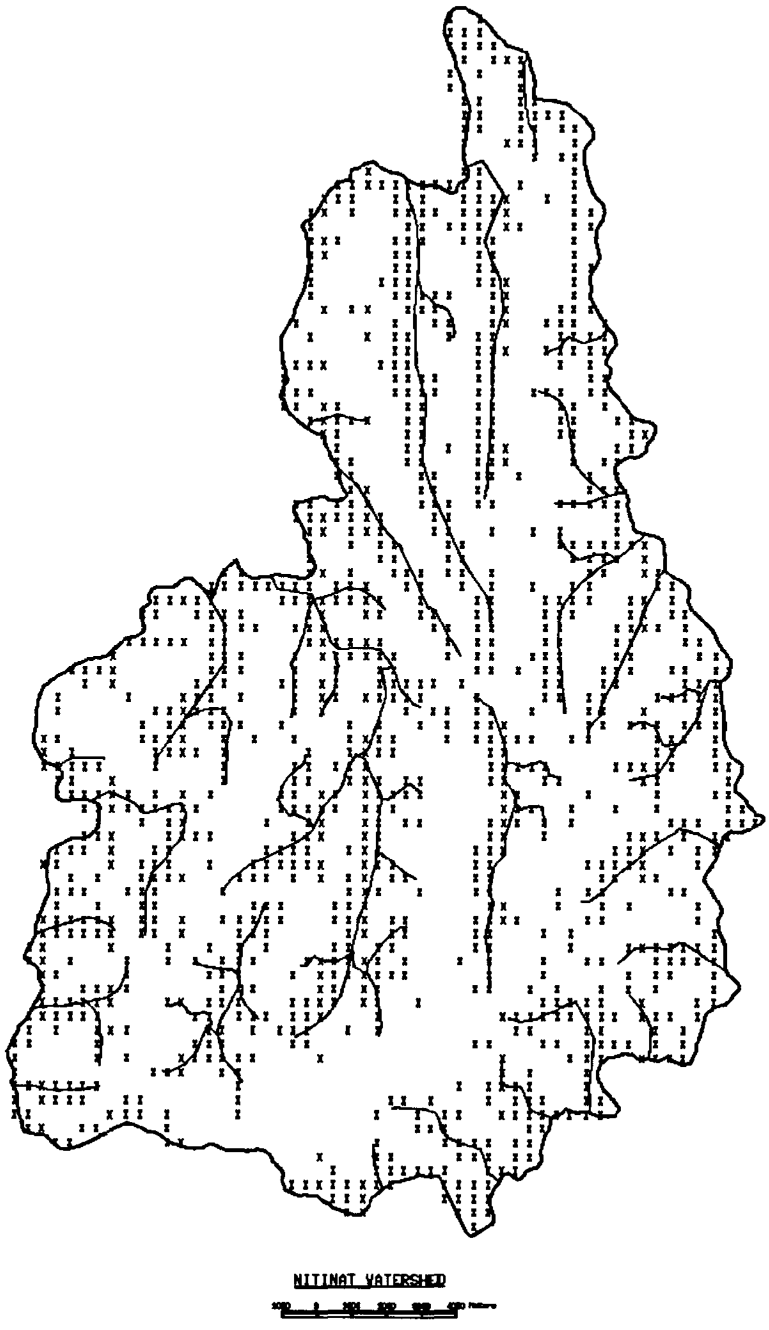

Figure 3.15 *Vector derived divides on Nitinat watershed.*

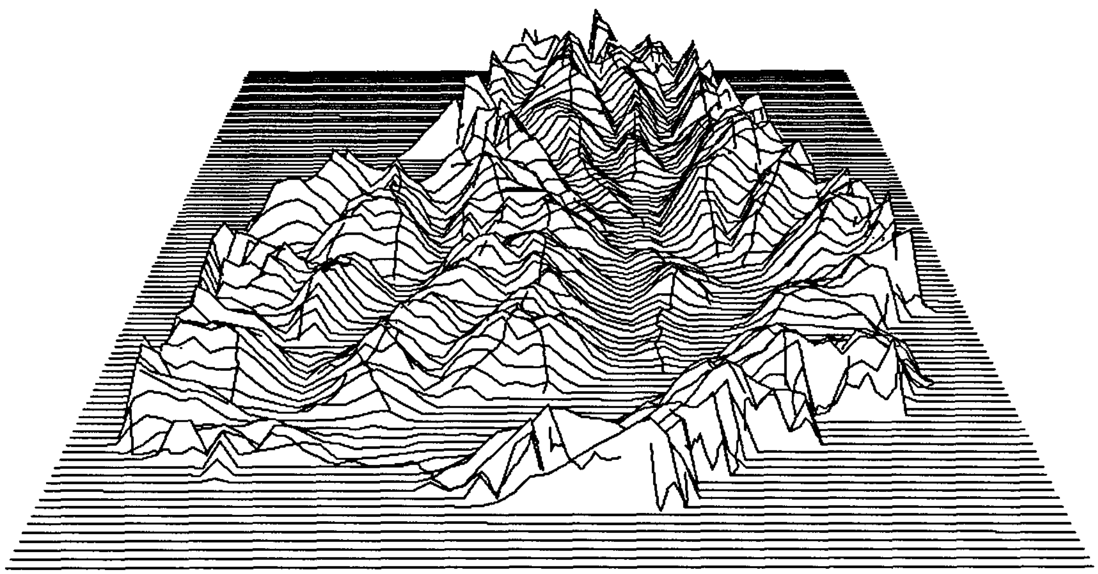

Figure 3.16 *3-dimensional plot of Nitinat watershed, draped with derived divide lines.*

watershed.

Because the contributing area represents the area contributing to a concerned point, the points with larger values of contributing areas will be more important than the points with small values in the terms of producing and conducting stormflow. Therefore, the stream channels can be generalized to distinguish the tributary channels and main stream by flagging the points whose contributing areas are greater than the given thresholds. Figure 3.17 gives the results of the generalization of stream channels on Nitinat watershed.

Also, by adjusting the thresholds of contributing areas, the variable source area can be roughly mapped out. Figure 3.18 shows that the sources of stormflow in Jamieson Creek expands from the places with larger contributing areas to the places with smaller contributing areas during rainfall and contracts thereafter. The principle applied here is that the more water a point receives the more easily it produces streamflow. The numerical simulation of variable source area of Jamieson Creek is based on this principle and suggests that the downhill searching program is very useful in enhancing the automated configurations of hydrological characteristics of watershed.

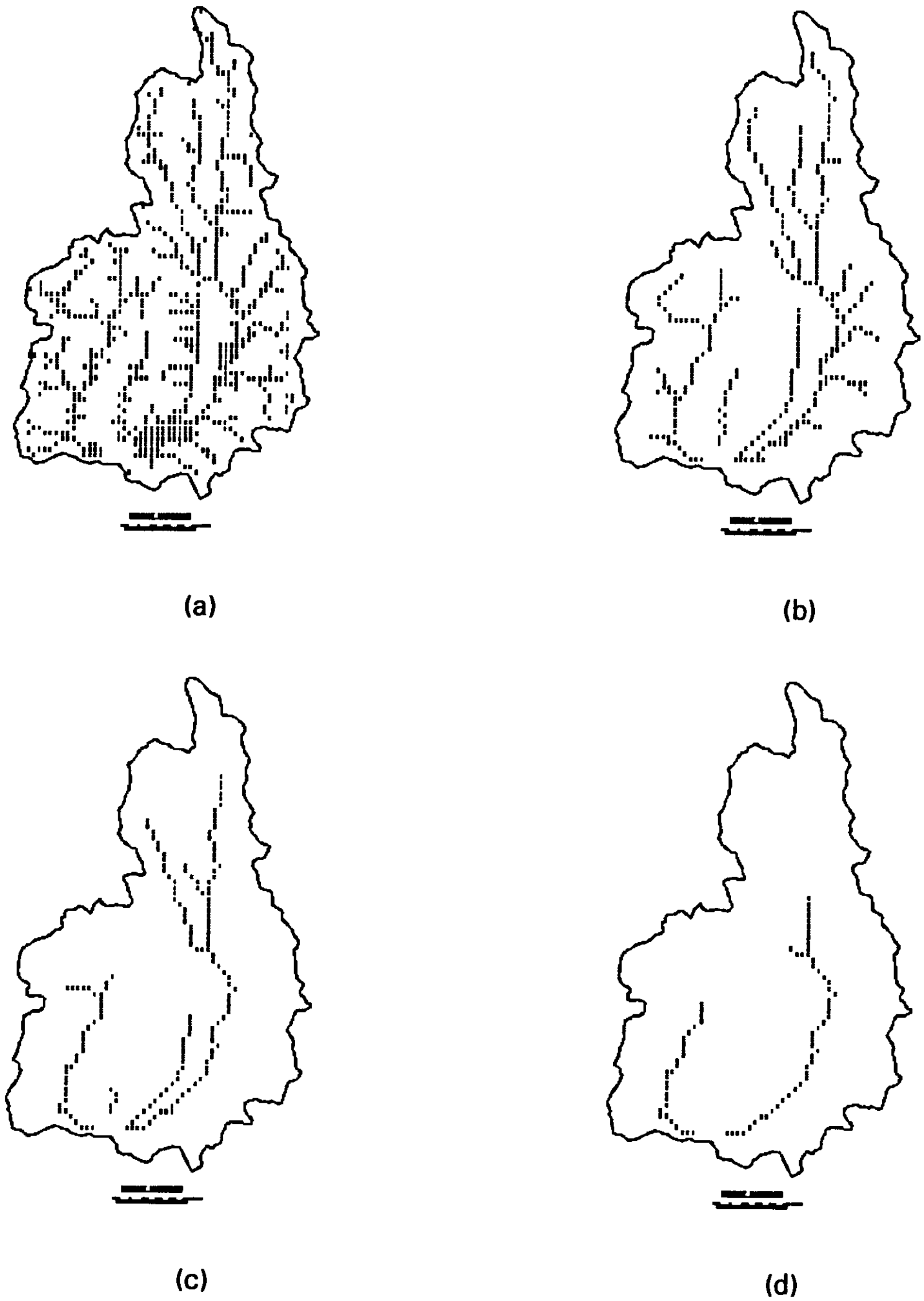

Figure 3.17 *Generalization of stream channels on Nitinat watershed. The thresholds of accumulated numbers are 5 for (a), 30 for (b), 100 for (c) and 300 for (d).*

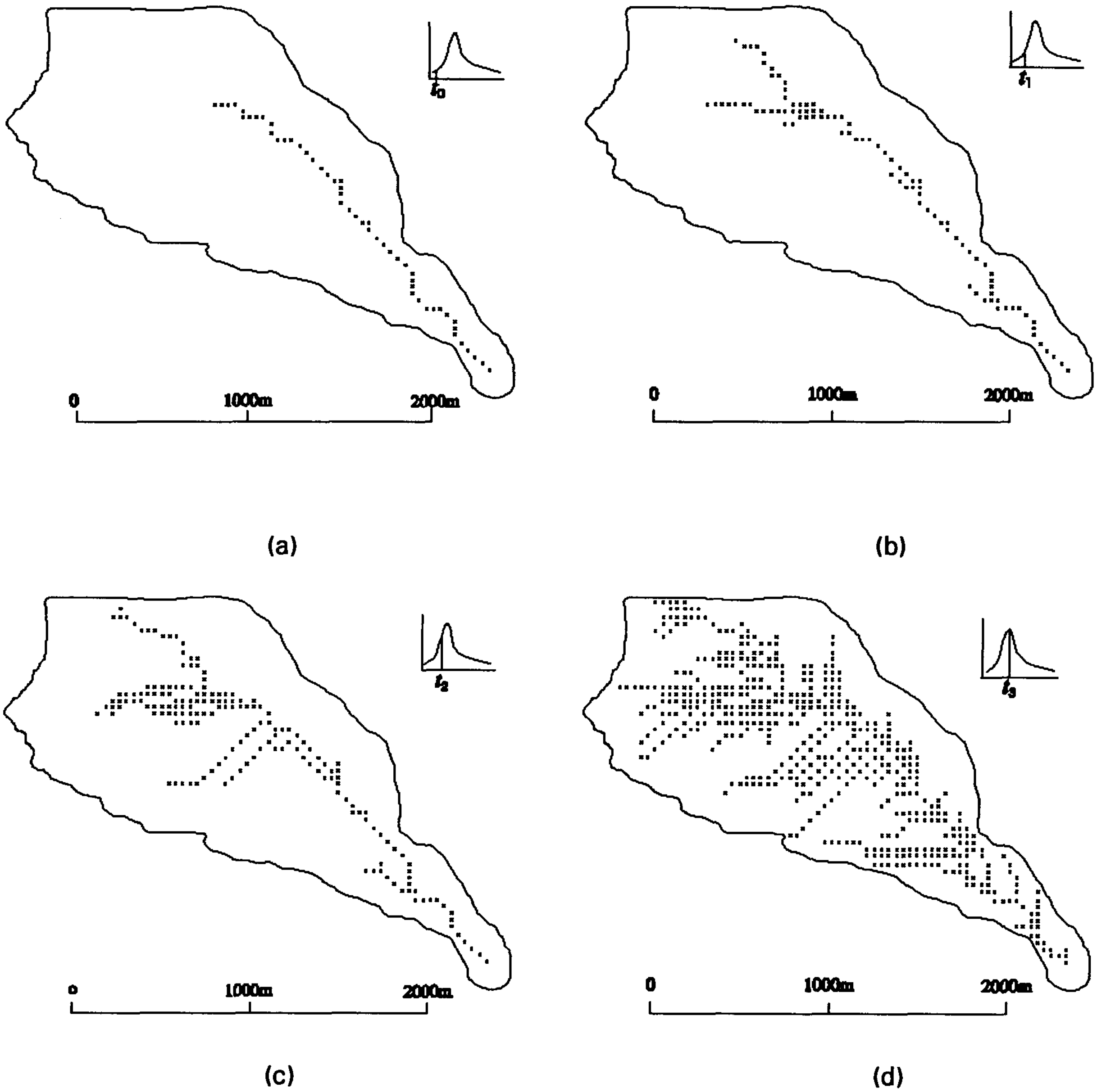

Figure 3.18 *The derived variable area source of Jamieson Creek. The variable source areas are indicated by changing the thresholds of accumulated numbers. The flow source expands from the areas with larger accumulated numbers to the areas with smaller accumulated areas during rainfall, and shrinks in the reverse direction after rainfall. The thresholds selected in this graph are, 300 for (a), 100 for (b), 30 for (c) and 10 for (d).*

Chapter IV

MODEL ESTABLISHMENT AND TESTING

The synthetic Clark's Instantaneous Unit Hydrograph Time-Area Method (Clark 1943), considering the discharge at any point in time as a function of the translation and storage characteristics of the watershed, was modified for this study. A model has been established based on the integration of the modified Clark's method and GIS technology. By taking advantage of GIS technology in spatial information analysis, an attempt in this model has been made to simulate the effects of the complexities of rainfall, soil, land use and topography of watersheds on the prediction of stormflow. This is a storm event basis model, consisting of three main components as depicted in Figure 4.1. The first component calculates runoff coefficients and generates excess rainfall for each discrete area of watershed. The second component simulates the translation of the generated excess rainfall from the discrete areas to the outlet and produces a pure translation hydrograph. The third component then routs the translation hydrograph to a hypothetic linear reservoir and outputs the final simulated hydrograph. These three components of this model are run in sequence. The results of simulation were compared with the measurements conducted in Jamieson Creek watershed.

4.1 Delineation of Hydrologic Response Units

To describe the spatial variances of parameters affecting the runoff generation, the

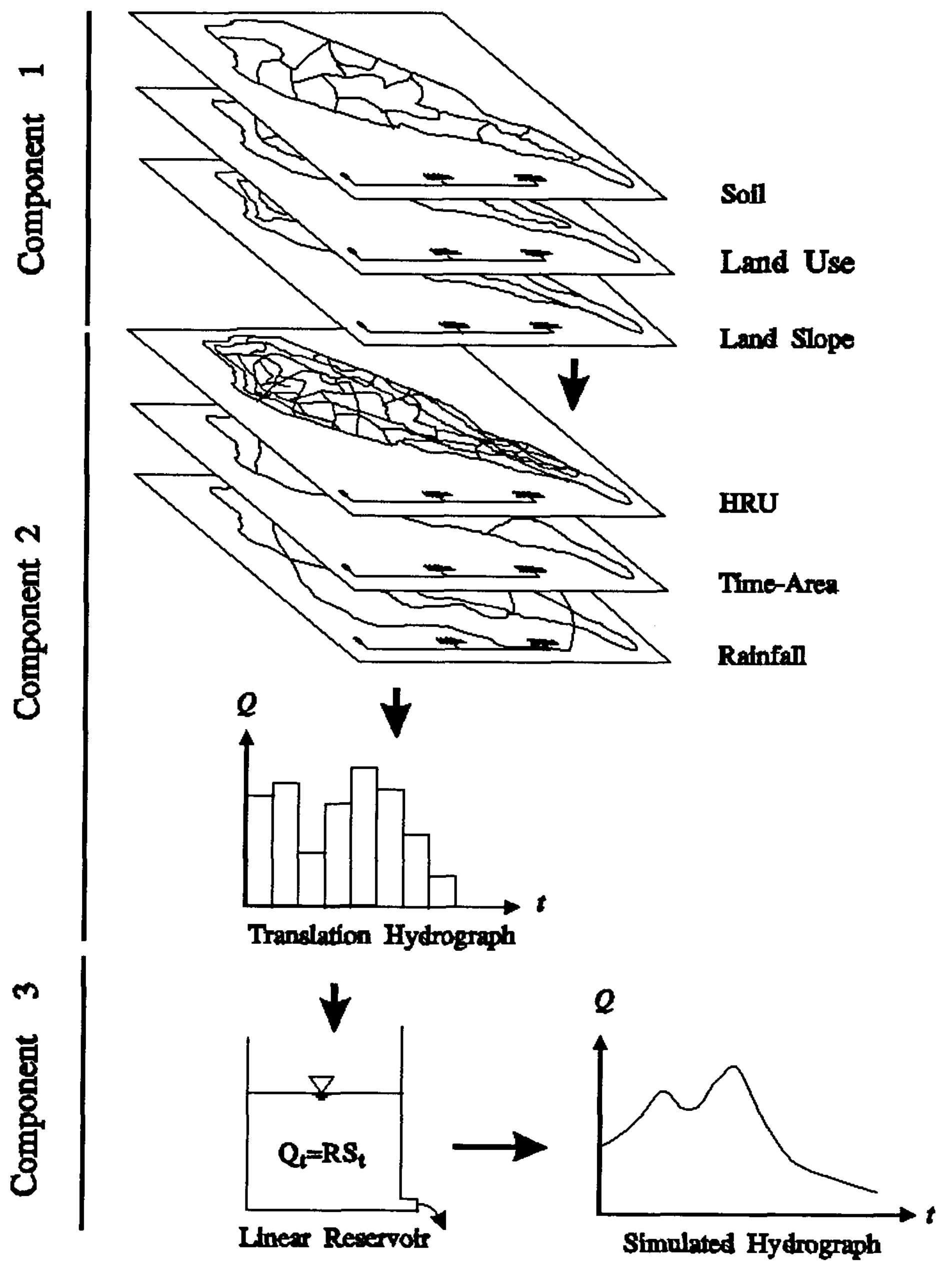

Figure 4.1 *Schematic of the model. It consists of three components, describing stormflow generation, translation and detention.*

entire watershed is partitioned into small subareas, each of which is small enough to be hydrologically considered as homogeneous area. These small subareas are called hydrologic response units (HRU), which are the unique combination of land use, soil and topography. The physiographic features of each identified unit in the watershed are represented by one set of parameters for each hydrologic process. These parameters are considered to be uniformly distributed with their average values within each unit.

The delineation of the boundaries of HRU can be effectively conducted using GIS technology. The land use, soil and topographic data are widely available in the forms of maps, satellite imageries or even digital files, which can be digitized, scanned or transferred directly to GIS. In GIS, these digital information are topologically organized as individual themes. The topologic structure for each theme not only puts the intelligence to the graphic features of the maps to find their relationships, but also establishes the linkage between the graphic features and their textural attributes. When these themes are overlaid together, the topographic structure is reorganized to construct a new theme with its attributes extracted from the original themes.

In this study, the land use, soil, and topographic maps of studied watersheds were digitized and organized as themes using the GIS software, TerraSoft. The hydrologic response units (HRU) were identified as a GIS theme by overlaying these themes with time-area theme in GIS. Each unit in the HRU theme was automatically related to a record in the accompanying attribute data base. The attribute data base, therefore, contains land use patterns, soil texture, flow travelling time and land slope originally existing in the separated data base related to each individual theme. By referring to Table 4.1a, 4.1b, 4.1c and 4.1d, each HRU were assigned a runoff coefficient based on the combination of its land use pattern, soil texture and land slope. The runoff coefficient for each HRU was then multiplied by rainfall data extracted from the layer containing the information of a passing storm to yield excess rainfall.

Table 4.1a *Runoff Coefficient (Rc) in Forest*

Slope in Percent	Open Sandy Loam	Clay & Silt Loam	Tight Clay
0-5	0.10	0.30	0.40
5-10	0.25	0.35	0.50
10-30	0.30	0.50	0.60
30-50	0.40	0.60	0.70
50-80	0.50	0.70	0.80
>80	0.60	0.80	0.90

Table 4.1b *Runoff Coefficient (Rc) in Grass Land*

Slope in Percent	Open Sandy Loam	Clay & Silt Loam	Tight Clay
0-5	0.22	0.42	0.5
5-10	0.29	0.49	0.57
10-30	0.35	0.55	0.63
30-50	0.44	0.64	0.72
50-80	0.53	0.73	0.81
>80	0.62	0.82	0.92

Table 4.1c *Runoff Coefficient (Rc) in Urban Area, 70% of Area Impervious*

Slope (%)	0-5	5-10	10-30	30-50	50-80	>80
Rc	0.65	0.70	0.80	0.86	0.90	0.95

Table 4.1d *Runoff Coefficient (Rc) in Forest under low antecedent soil moisture*

Slope in Percent	Open Sandy Loam	Clay & Silt Loam	Tight Clay
0-5	0.07	0.25	0.34
5-10	0.10	0.30	0.40
10-30	0.16	0.36	0.55
30-50	0.22	0.42	0.60
50-80	0.29	0.48	0.66
>80	0.35	0.54	0.72

(Compiled from Van Der Guilk, et al. (1986), McFarlane (1990), Chow, et al. (1988) and Viessman, et al. (1989). For rainfall intensity with 200 year return period, these runoff coefficients will be increased by 1.5 times. The maximum runoff coefficient is one.)

4.2 Simulation of Translation Hydrograph

The translation of excess rainfall from its drop falling to the watershed outlet is accomplished using the time-area curve for the watershed. The time-area curve is a form of unit hydrograph. If one unit of instantaneous excess rainfall is uniformly placed on the watershed at $t=0$, the runoff from each time-area will pass the outlet in the upstream time-area sequence. Accordingly, the ordinates of the one unit translation hydrograph is quantitatively equal to the dimensions of the time-area curve.

Assuming that discharge is proportional to excess rainfall in a watershed, called a linear watershed, the discharges produced by excess rainfall separated with the same selected time interval as the time-area can be added and convoluted to yield a storm translation hydrograph for a given storm event. The governing convolution equation for the storm translation hydrograph in discrete form is given as:

$$Q_n = \sum_{m=1}^{n \le M} P_m \times A_{n-m+1} \qquad \text{4-2-1}$$

where Q_n is the discharge at the outlet during the nth time interval;

P_m is the depth of instantaneous excess rainfall uniformly falling on the watershed at the beginning of mth time interval;

A_{n-m+1} is the area of $(n-m+1)$th time-area.

M is the number of time intervals of rainfall;

m is $1,2,\ldots,M$.

The summation is conducted to $m=1,2,\ldots,n$ for $n<=M$, but for $n>M$, it is limited to $m=1,2,\ldots,M$.

This equation allows us to determine an instantaneous storm translation hydrograph produced by a temporally varying rainfall, but it does not account for the effects of the spatial distribution of rainfall and land use on the hydrograph, which may prevent the model from being applied to large watersheds.

To describe the spatial distribution of rainfall and land use in the model, each time-area is further divided into small hydrologically homogeneous sub-areas, i.e., HRUs. Any changes of rainfall or land uses are, therefore, immediately reflected in the excess rainfall generated in each HRU. The excess rainfall falling on each HRU is summed for every time-area and then convoluted to yield the instantaneous stormflow translation hydrograph.

The convolution equation is modified as:

$$Q_n=\sum_{m=1}^{n\leq M}\sum_{i=1}^{L_{n-m+1}} P_{m,n-m+1,i}\times A_{n-m+1,i} \qquad \text{4-2-2}$$

where Q_n is the discharge at the outlet during the nth time interval;

$P_{m,n-m+1,i}$ is the depth of instantaneous excess rainfall falling on $A_{n-m+1,i}$, at the beginning of mth time interval;

$A_{n-m+1,i}$ is the area of the ith HRU within time-area A_{n-m+1}.

L_{n-m+1} is the total number of the HRUs in the time-area A_{n-m+1}.

According to the Rational Method (Chow, 1988), the depth of excess rainfall is given as:

$$P_{m,n-m+1,i}=C_{n-m+1,i}\times I_{m,n-m+1,i} \qquad \text{4-2-3}$$

where $I_{m,n-m+1,i}$ is the depth of instantaneous actual rainfall falling on $A_{n-m+1,i}$, at the beginning of mth time interval;

$C_{n-m+1,i}$ is the runoff coefficient of the HRU, $A_{n-m+1,i}$.

The term $I_{m,n-m+1,i}$ represents the variance of rainfall in both space and time, while the term $C_{n-m+1,i}$ reflects the effects of land uses, soils and topography of watershed on stormflow generation.

An example of the application of the modified convolution equation to a passing storm in a linear watershed is shown diagrammatically in Figure 4.2.

4.3 Stormflow Detention

While stormflow is translated downstream over the land surface, through soil channels or

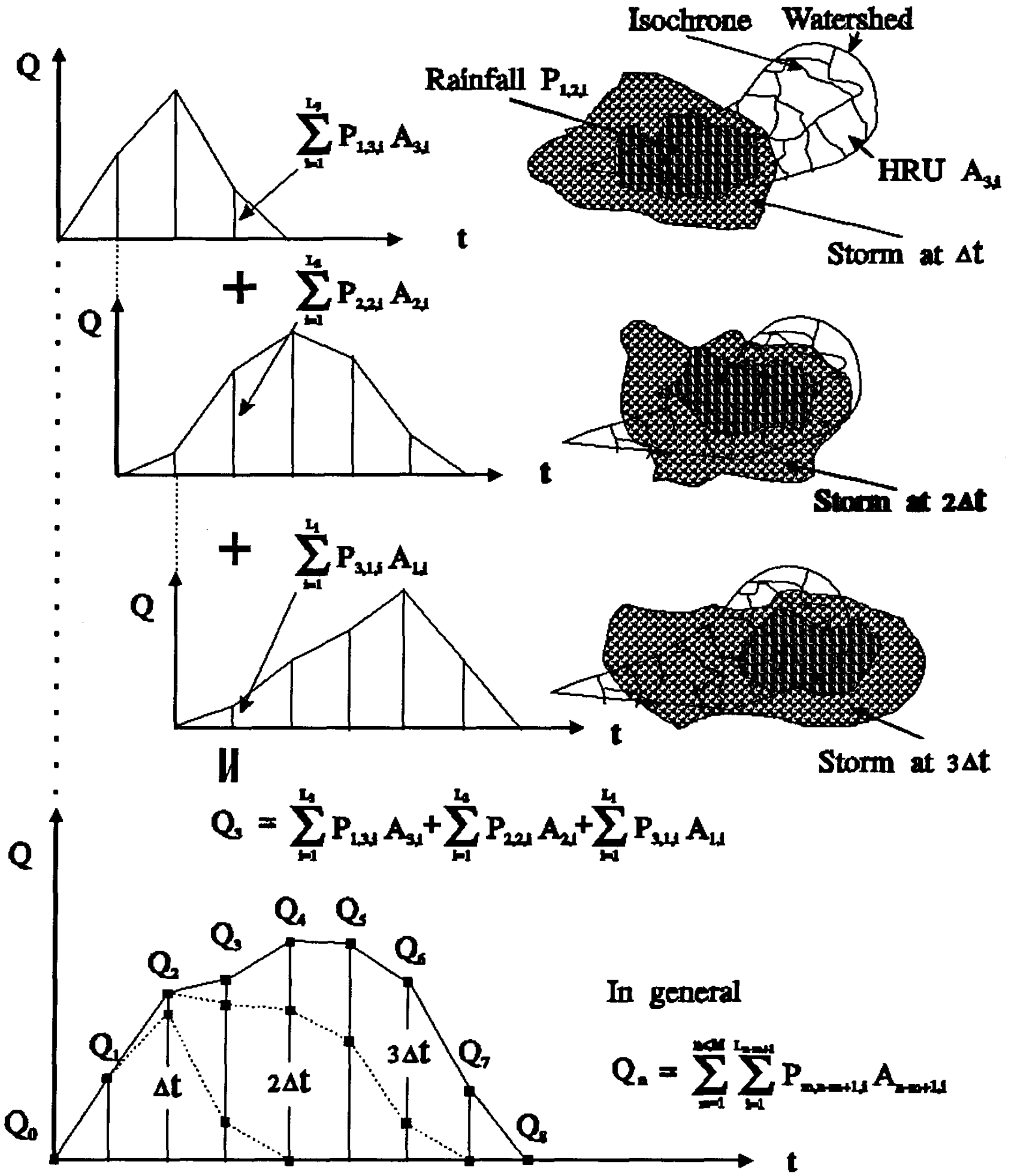

Figure 4.2 *Diagrammatic illustration of the discrete convolution equation for a linear watershed.*

along natural waterways, its peak flow is usually attenuated and delayed because of storage and resistance, i.e., stormflow detention of the watershed. The impact of detention on stormflow translation depends on the coverage, soil, slope of land, channel conditions and size of the watershed.

Unlike stormflow translation, stormflow detention cannot be directly measured from a watershed. In synthetic Clark's Instantaneous Time-Area Method, a hypothetical linear reservoir with a storage coefficient, R, is assumed to describe the impact of stormflow detention of the entire watershed on the translation hydrograph. The reservoir outflow, Q_t, and storage, S_t, are linearly related by:

$$S_t = R \times Q_t \qquad 4\text{-}3\text{-}1$$

When a pure translation hydrograph is routed through the hypothetical linear reservoir, the relationship of inflow, I_t, outflow, Q_t, and storage, S_t, for the reservoir can be given by the flow continuity equation as:

$$I_t - Q_t = \frac{dS_t}{dt} \qquad 4\text{-}3\text{-}2$$

This equation can be approximated with Eq. (4-3-3) in the discrete form, where the subscripts "t" and "t-1" denote the beginning and end, respectively, for Δt.

$$\frac{I_{t-1}+I_t}{2} - \frac{Q_{t-1}+Q_t}{2} = \frac{S_t - S_{t-1}}{\Delta t} \qquad 4\text{-}3\text{-}3$$

Combining Eq. (4-3-1) with Eq. (4-3-3) and reorganizing the terms yield:

$$Q_t = \frac{\Delta t(I_{t-1}+I_t)+(2R-\Delta t)Q_{t-1}}{(2R+\Delta t)} \qquad 4\text{-}3\text{-}4$$

Since I_{t-1} and I_t are known from the translation hydrograph for every time increment, the routed hydrograph is accomplished by solving Eq. (4-3-4) for successive time increments using each Q_t as Q_{t-1} for the next time increment.

R is a constant and has the same time unit as Δt. For ungaged watersheds, it can be determined from the ratio of $R/(T_c+R)$ which may only vary with land use patterns in a physiographically similar region, where T_c is the flow time of concentration. The dimensionless term of $R/(T_c+R)$ represents the storage characteristics for a kind of watershed regardless of the size of the watershed. Generally, the larger the value of $R/(T_c+R)$, the larger the storage capacity of watershed. Not surprisingly, the watershed covered with forest usually has larger value of $R/(T_c+R)$ than that covered with grass or urbanized.

Because of the assumption of instantaneous rainfall in the Clark's method, the final simulated hydrograph produced by real continuous excess rainfall has to be computed by averaging two same routed hydrographs spaced at an interval Δt, equivalent to that selected for rainfall, apart with

$$Q_i=\frac{Q_t+Q_{t-1}}{2} \qquad 4\text{-}3\text{-}5$$

where Q_i is the ordinate of the simulated hydrograph.

4.4 Model Testing

This model includes two important parameters: stormflow travelling time, T, and the storage coefficient, R. The stormflow travelling time can be determined based on the data of land use, land slope and flow travelling distance, which has been discussed in Chapter III. To obtain the parameter, R, for this model, the simulated hydrograph was verified using trial and error technique to best fit the outflow hydrograph observed in Jamieson Creek. The verified model was then applied to another storm event in the same watershed to check for the agreement between the simulated hydrograph and the observed one.

In general, any storm event with apparent discharge rise caused by pure rainfall intensity can be selected for the model testing. To determine the storage coefficient, R, for single land use, the storm events in Jamieson Creek occurring on July 16 and August 22 of 1977 were selected, as the watershed was completely covered by forest at that time. Both rainfall and stormflow data were sampled with the same interval of 15 minutes as that for time-area (see Figure 4.3 and 4.4).

4.4.1 Hydrograph separation

In this study, no attempt has been made to partition the total stormflow hydrograph into overland flow, interflow, channel flow and ground flow. Instead, the total stormflow hydrograph measured during a storm event is considered to be made up of two components: quick flow and slow flow. The quick flow may be overland flow, interflow or channel flow, or a combination of them, which consists of the flashy rise part of outflow hydrograph. The slow flow results from ground flow, which comes gradually up and down during and after a storm event.

There are many empirical techniques available for hydrograph separation. However, these techniques are more or less arbitrary since they do not have a sound physical basis. Fortunately, the slow flow is less important compared to the quick flow, which makes most of the separation techniques acceptable in simulating stormflow hydrographs.

A time-based separation technique proposed by Hewlett and Hibbert (1967) was selected for this study. With this method, the hydrograph separation is made by drawing a line with a given slope from the point of initial hydrograph rise to the falling limb of the hydrograph. This technique has been widely applied to forest hydrology for many years. Cheng (1975) tested this technique with 20 stormflow hydrographs of Jamieson Creek watershed and selected a slope of 0.55 litre s^{-1} $km^{-2}h^{-1}$ for the separation line. After having examined the agreement between hydrographs separated by this technique and a model using 17 stormflow hydrographs observed in Jamieson Creek watershed, Loukas (1991) also suggested this technique can be used for the separation of hydrographs in Jamieson Creek watershed with the same slope of 0.55×10^{-3} m^3s^{-1} $km^{-2}h^{-1}$.

The same slope of the hydrograph separation line is used for this study. Since the area of Jamieson Creek watershed is 2.99 km^2, the slope is transformed to 0.41×10^{-3} m^3 s^{-1}(15 minutes)$^{-1}$ for the convenience of the model testing, as shown in Figure 4.3 and 4.4).

4.4.2 Hydrograph simulation

With the rainfall data of July 16, 1977 as input, the translation equation (4-2-2) and detention equation (4-3-4) are run recursively using macros in a spreadsheet program, Quattro Pro. The simulated hydrograph was finalized with Eq. (4-3-4). After several times of testing for the storage coefficient, *R*, the simulated hydrograph was obtained with the storage coefficient of 180 minutes (see Figure 4.5).

The obtained *R* is then applied to simulate an observed hydrograph for another

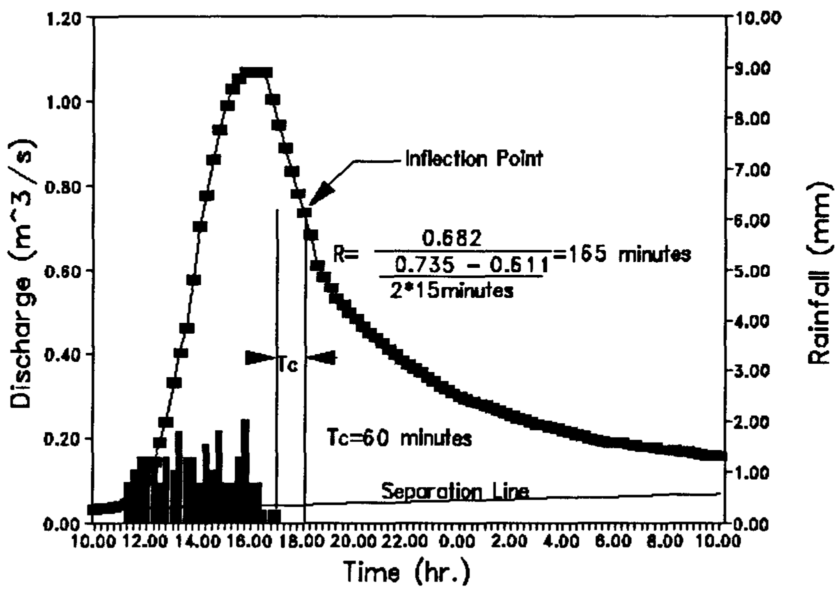

Figure 4.3 *An observed hydrograph for the storm event occurring in Jamieson Creek watershed on July 16, 1977.*

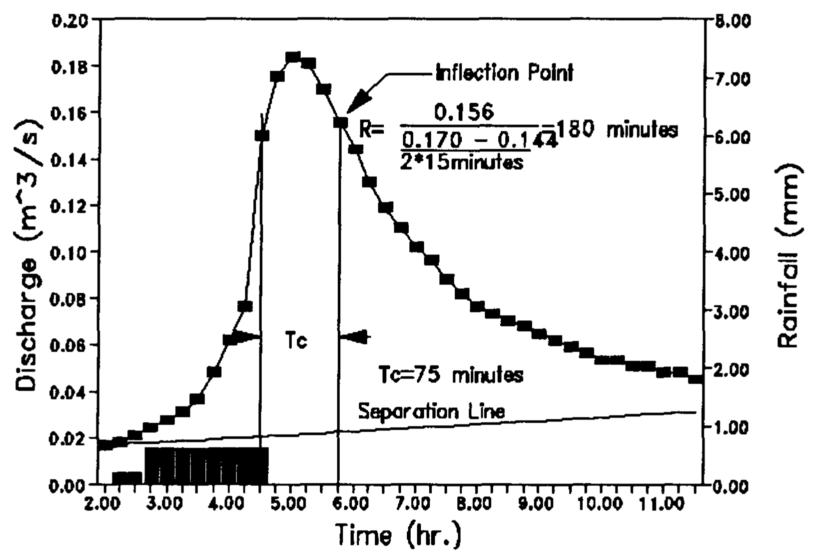

Figure 4.4 *An observed hydrograph for the storm event occurring in Jamieson Creek watershed on August 22, 1977.*

storm event occurring on August 22, 1977. Because the baseflow before the storm occurred was very low, the runoff coefficient for dry condition in forest was used here to reduce the effect of antecedent soil moisture on stormflow simulation (see Table 4.1d). Figure 4.6 shows the result of the hydrograph simulation. Obviously, a good agreement has been achieved between the simulated hydrograph and the observed hydrograph. In addition, both the value of peak flow and the elapse time to peak flow for this storm event are well approximated by the simulation.

4.4.3 Comparison of parameters of the model

As shown in Figure 4.3 and 4.4, there exists an inflection point on the falling limb of hydrograph for every distinct storm. If a watershed is treated as a linear watershed with a linear reservoir at the outlet, the inflection point indicates the moment when the inflow from the linear watershed to the linear reservoir becomes zero. Therefore, dropping the inflow term at this point in Eq. (4-3-3) and combining Eq.(4-3-1) give:

$$R=\frac{(Q_{t-1}+Q_t)/2}{(Q_{t-1}-Q_t)\Delta t} \qquad (4\text{-}4\text{-}1)$$

Since the inflow terminates its influence on the outflow hydrograph at the outlet at the inflection point, the flow time of concentration T_c, can be estimated as the time from the end of excess rainfall to the inflection point (Hoggan, 1989).

Table 4.2 summarises the values of R, T_c and the ratio of $R/(R+T_c)$ calculated for the two selected storm events and used for the simulation model.

The closeness of model parameters R and T_c, as well as the hydrographs, between the observed and simulated results is the basis for confidence in applications of this model

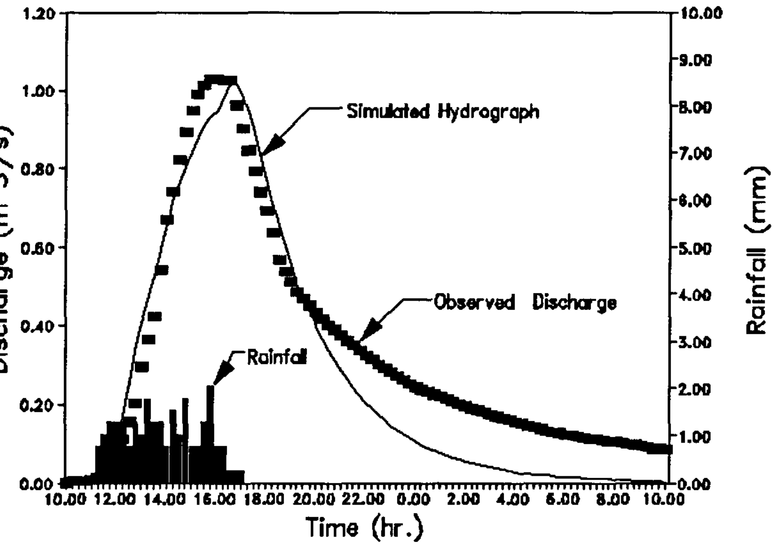

Figure 4.5. *The simulation hydrograph for the storm event occurring in Jamieson Creek watershed on July 16, 1977.*

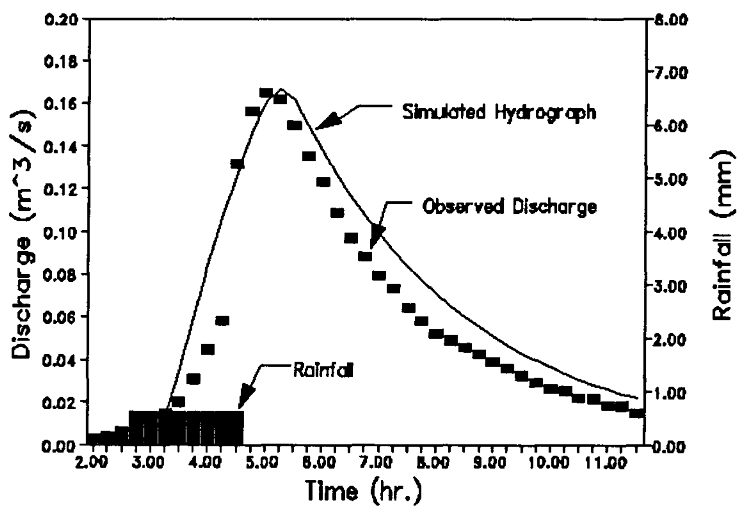

Figure 4.6 *The simulation hydrograph for the storm event occurring in Jamieson Creek watershed on August 22, 1977.*

to ungaged or/and more complex watersheds, which will be discussed in next chapter.

Table 4.2 *Comparison of the parameters for the model.*

Sources	R **(minute)**	T_c **(minute)**	$R/(R+T_c)$
Model	180	60	0.75
Storm on July 16	165	60	0.72
Storm on August 22	180	75	0.74

Chapter V

MODEL APPLICATION

Hundreds of hydrologic models have been developed for engineers and land managers to predict the behavior of hydrologic regime in watersheds since the first comprehensive hydrologic model was developed by a group of scientists at Stanford University (Crawford and Linsley, 1966). A major advantage of simulation models is the insight into mechanisms of hydrologic processes gained by the practices of simulating the responses of the overall model system and the interactions between various components of the system. Another advantage is that models can be nondestructively and repeatedly tested with a little cost.

However, most applications of these hydrologic models have been limited by the facts that there exist the inherent variability in natural processes and the shortage of hydrologic data required as input to the models. Lumped models can only be used in small watersheds due to their inability to deal with the complexities of hydrologic processes in either space or time. Distributed models, on the other hand, are limited to well-gauged watersheds where long term systematic measurements have been conducted.

Apparently, to be applied in a large but ungaged watershed, a hydrologic model may have to have the advantages of both lumped and distributed models. This chapter will demonstrate the usefulness of the model described in last chapter. This model is essentially a combination of lumped and distributed models. With the power of GIS in handling the variability of hydrologic processes, the model can even simulate stormflow hydrographs caused by complex storms in a watershed where soil, land use, rainfall and topographic maps may be considered as only source of input data to the model.

In this study, Nitinat watershed was selected for the applications of this model. As described in Chapter II, it is an ungaged watershed with an area of 426.90 km^2. Only the pump house at the outlet of the watershed and nearby weather stations provide roughly estimated peak flow and long term rainfall data for this watershed. Soil, land use and topographic information are available in the forms of paper maps, which have been digitized into GIS for this study.

The DFO (Department of Fisheries and Oceans) Nitinat River Hatchery is located at the outlet of this watershed. During the hatchery's nine years of operation, river flood levels have come to within a few feet of the site elevation. Since a flood level in excess of 11.5 m site elevation would cause the immediate escape of the annual fish hatch, economic losses would be substantial, as hatchery returns thirty to fifty million dollars to the wild fishery annually. In addition, a more substantial flood level could enable planners to decide the viability of future hatchery expansions and upstream developments.

According to McFarlane's study (1990), the substantial flood level is dependant on the outflow, especially maximum peak flow caused by storm in this area. In this chapter, the effects of variability of storm and land use on the shape and timing of the response hydrograph for Nitinat watershed will be examined.

5.1 Uniform Storm

It is usually the case that design storms are assumed to be distributed uniformly over a watershed. For the sake of safety, a return period of 200 years for these design storms was used for this study. As shown in Figure 5.1, the relationships between rainfall intensity and duration has been found using the Gumbel Method (Gumbel, 1958) with the rainfall data from nearby weather stations (McFarlane, 1990).

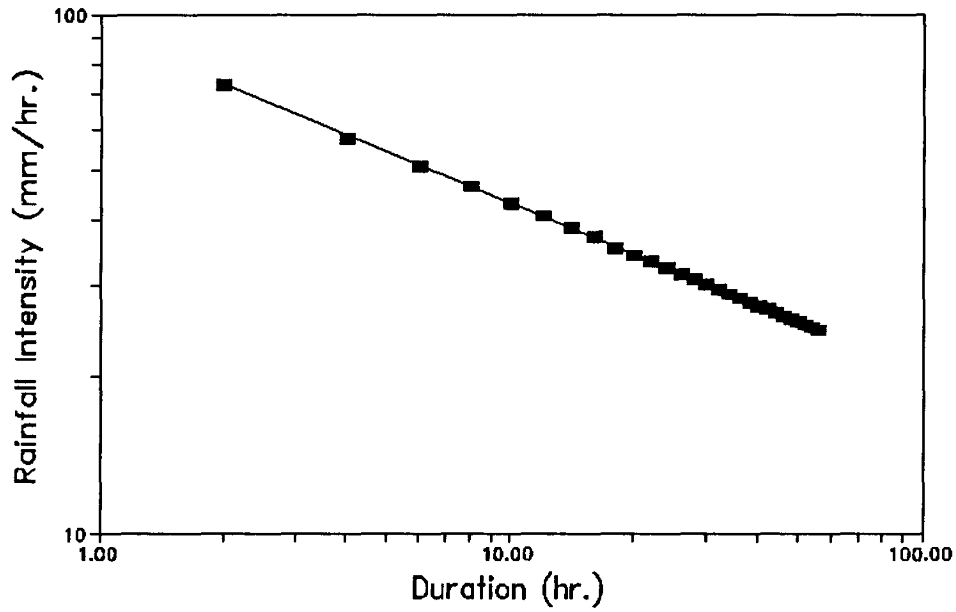

Figure 5.1 *Rainfall intensity curve for 200-year return period in Nitinat watershed.*

Because Nitinat watershed is currently covered with forest, the regional ratio, $R/(R+T_c)$, has the constant:

$$\frac{R}{R+T_c}=0.75 \qquad 5\text{-}1\text{-}1$$

The flow time of concentration, T_c, for Nitinat watershed can be obtained from the time-area map of the watershed, which is 16 hours (see Figure 3.11 and 3.13). Rearranging the above equation with the flow time of concentration, the storage coefficient of Nitinat watershed is given as:

$$R=\frac{0.75T_c}{1-0.75}=3\times 16=48\,hours \qquad 5\text{-}1\text{-}2$$

Figure 5.2 shows the resultant hydrographs simulated by the model for different durations of the design storm with the 200-year return period. It should be noted that within the same return period the maximum peak flow increases with the duration of rainfall. Such increase becomes slow as the duration increases as shown in Figure 5.3, which suggests that the maximum peak flow can only be determined when the rainfall intensity with a comparable long duration is used for the model.

This result seems to conflict with the concept of Rational Method, because, in Rational Method, the maximum peak flow for a given return period is supposed to occur when the duration of rainfall reaches the flow time of concentration of the watershed. According to Rational Method, the maximum peak flow for the 200-year return period in Nitinat watershed is only estimated as 666.8 m^3/s if the duration of rainfall is 16 hours, the flow time of concentration in Nitinat watershed. In contrast, Figure 5.2 indicates that the maximum peak flow can expected to reach 1200 m^3/s as the 200-year return period of rainfall lasts longer than 56 hours. The low estimation of maximum peak flow obtained by using Rational Method is partly because the Rational Method does not account for the effects of storage in a watershed on the maximum peak flow.

The watershed storage delays the occurrence time of peak flow and gradually accumulates the contribution of rainfall to the peak flow. Since the storage factor (R) for

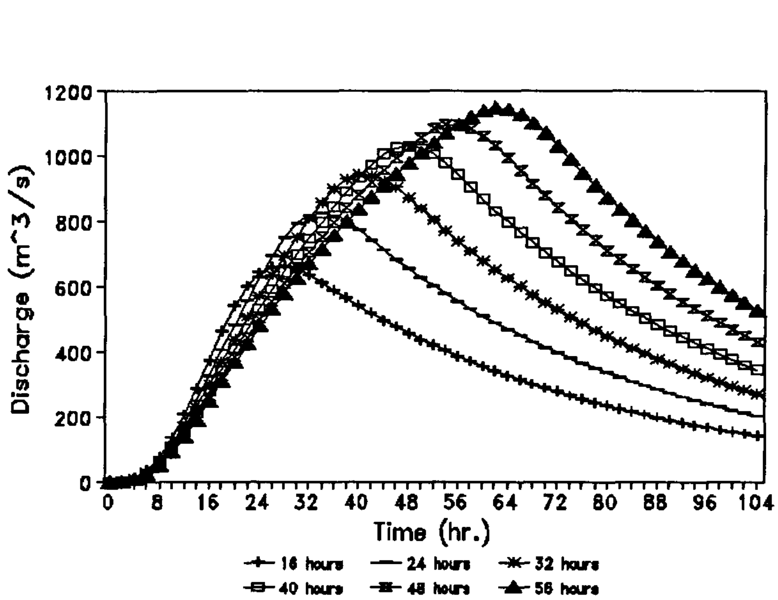

Figure 5.2 *The simulated hydrographs at the outlet of Nitinat watershed for the 200-year return period of rainfall with different durations.*

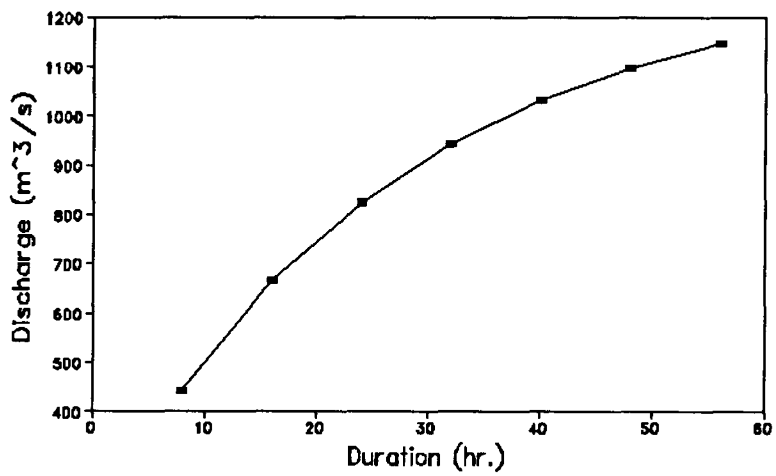

Figure 5.3 *The simulated peak flows at the outlet of Nitinat watershed for the 200-year return period of rainfall with different durations.*

the same land use pattern increases with the size of watershed, the use of Rational Method will underestimate the maximum peak flow in larger watersheds due to the storage effect. Because of this, the Rational Method should not be recommended for these larger watersheds without modification.

The lowest stage of water flow measured at the outlet of Nitinat watershed during 1982-1988 is 4.6 m. It has been observed that a stage of 9.0 m was reached when total discharge was measured at 600 m^3/s at the same place on November 9, 1989 (McFarlance, 1990). For an expected flood discharge of 1200 m^3/s for the 200-year return period, it is reasonable to expect the maximum flood stage at the peak flow to exceed the site elevation of 11 m.

5.2 Non-uniform Storm

Another reason restricting the use of Rational Method is the assumption that rainfall falls uniformly over the entire watershed and steadily continues from the beginning to the end of a storm event. Many other lumped models follow the same assumption because of the shortage of information in ungaged watersheds. Unfortunately, this assumption is rarely true in reality due to the large variability of rainfall intensity in both space and time.

To estimate the effects of non-uniform storms on the time distribution of discharge at the outlet of Nitinat watershed, four patterns of storms were examined with the model. The average rainfall intensity and duration are the same for the four patterns, as described below:

Pattern 1. A storm moves from north to south toward the outlet of the watershed for six hours. Figure 5.4a, 5.5a and 5.6a give three positions where the storm moves by. The storm assumably spends two hours moving from one position to another.

Pattern 2. The storm moves along the same path and with the same time interval as in pattern 1 but in the reverse direction.

Pattern 3. Storms stay on the north, centre and south of the watershed simultaneously for six hours.

Pattern 4. An uniform and steady storm continuously stays over the entire watershed for six hours.

As seen in Figure 5.7, the storm moving toward watershed outlet results in the highest peak flow and shortest lag time of peak flow compared with that in other patterns. The simulated hydrographs for these storm patterns also indicate that hydrograph shape can be modified by spatial and temporal variations in rainfall intensity. Storms moving in opposite direction may produce significantly different hydrographs even though they bring the same amount of rainfall to the watershed.

To simulate the spatial and temporal variations of storm in the model, elevation contours in DEM of GIS are replaced with storm isohyets so that rainfall information can be interpolated to any point on the watershed (see Figure 5.4b, 5.5b and 5.6b). The storm

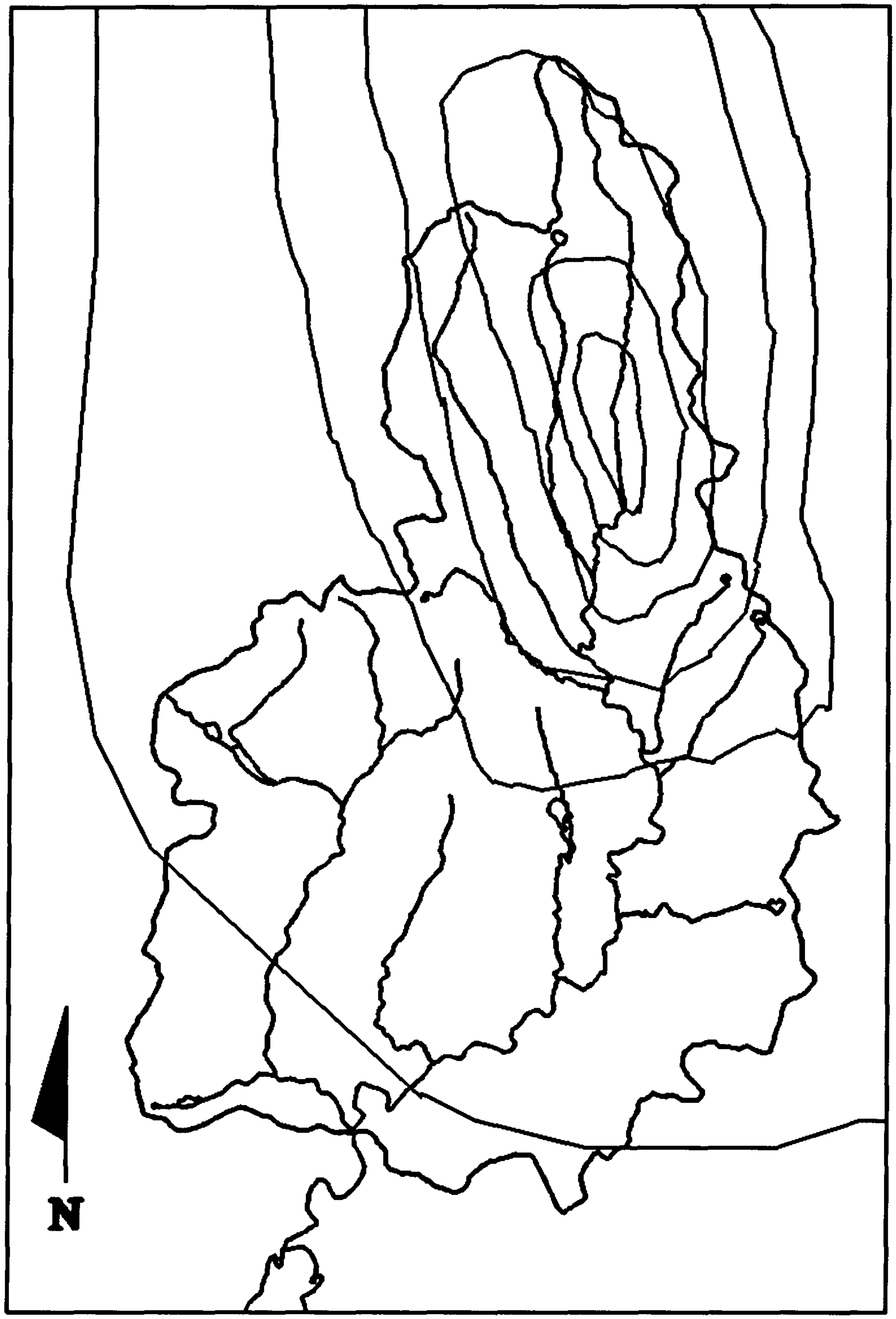

Figure 5.4a *Assumed storm hyetos on the north of Nitinat watershed.*

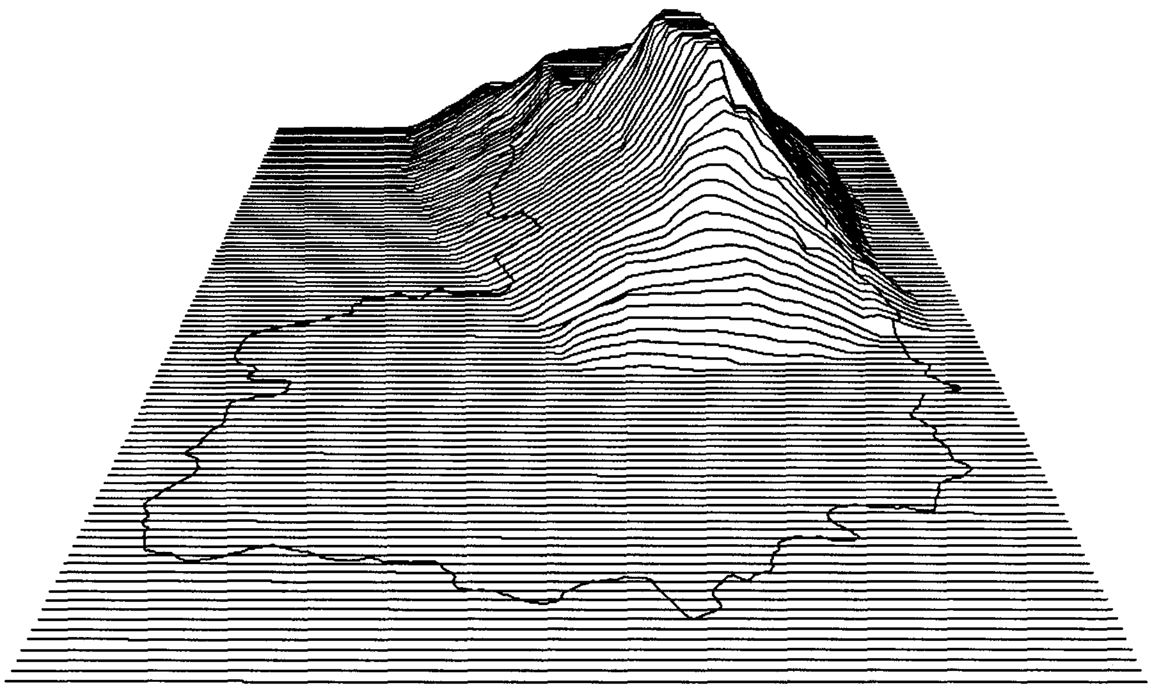

Figure 5.4b *3-dimensional appearance of the assumed storm on the north of Nitinat watershed.*

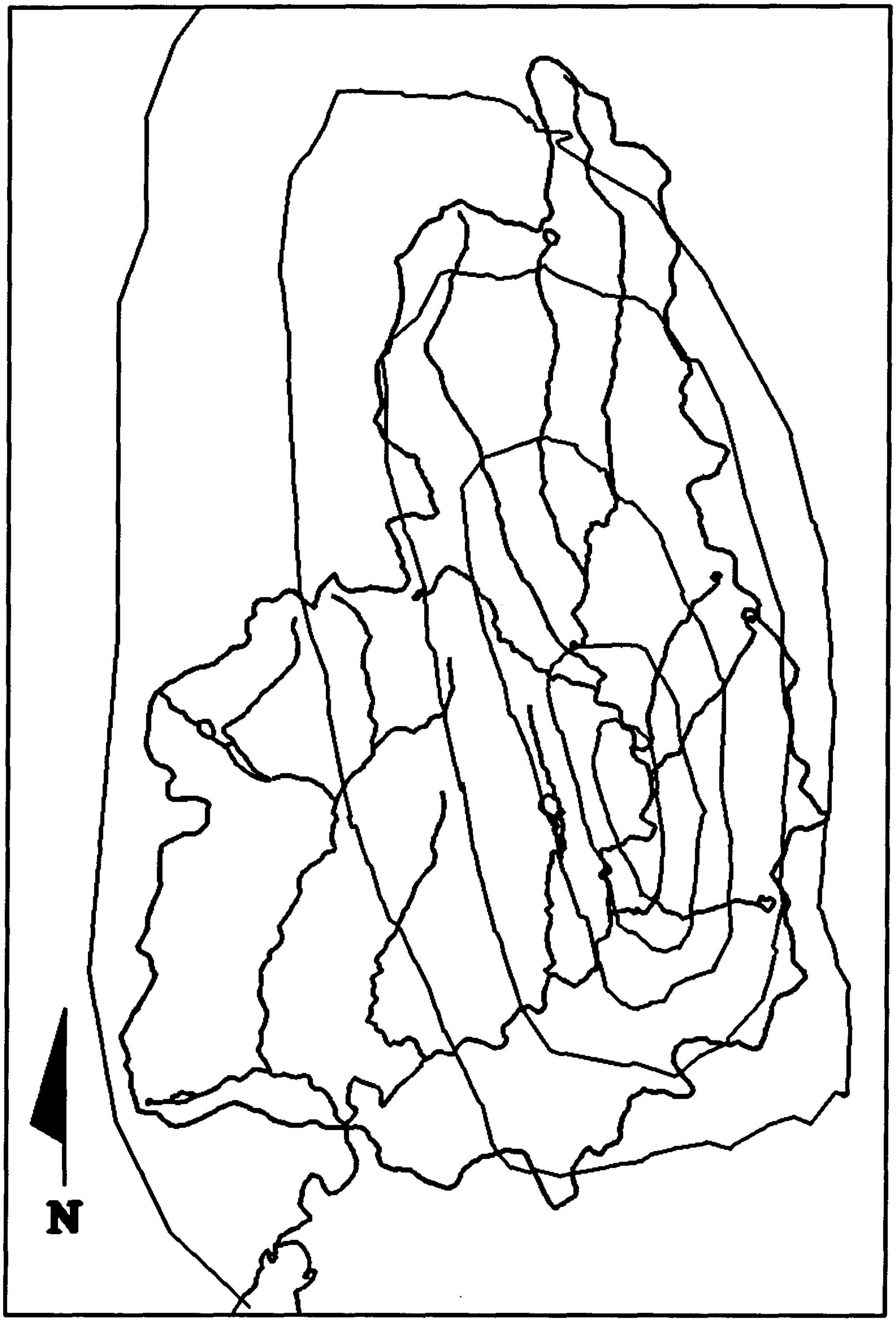

Figure 5.5a *Assumed storm hyetos on the centre of Nitinat watershed.*

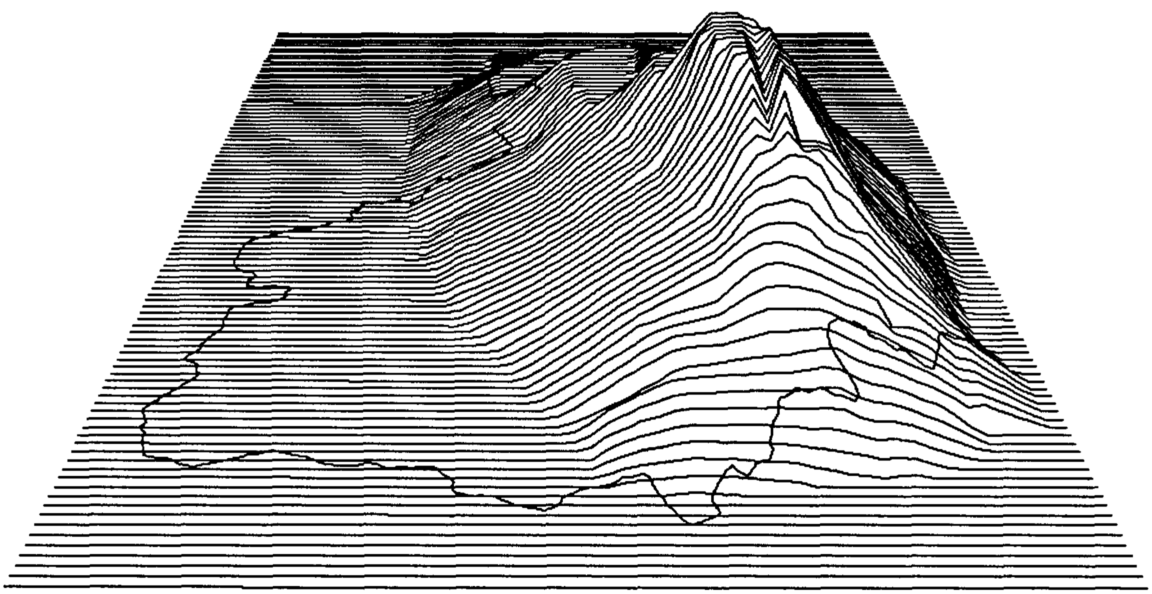

Figure 5.5b *3-dimensional appearance of the assumed storm on the centre of Nitinat watershed.*

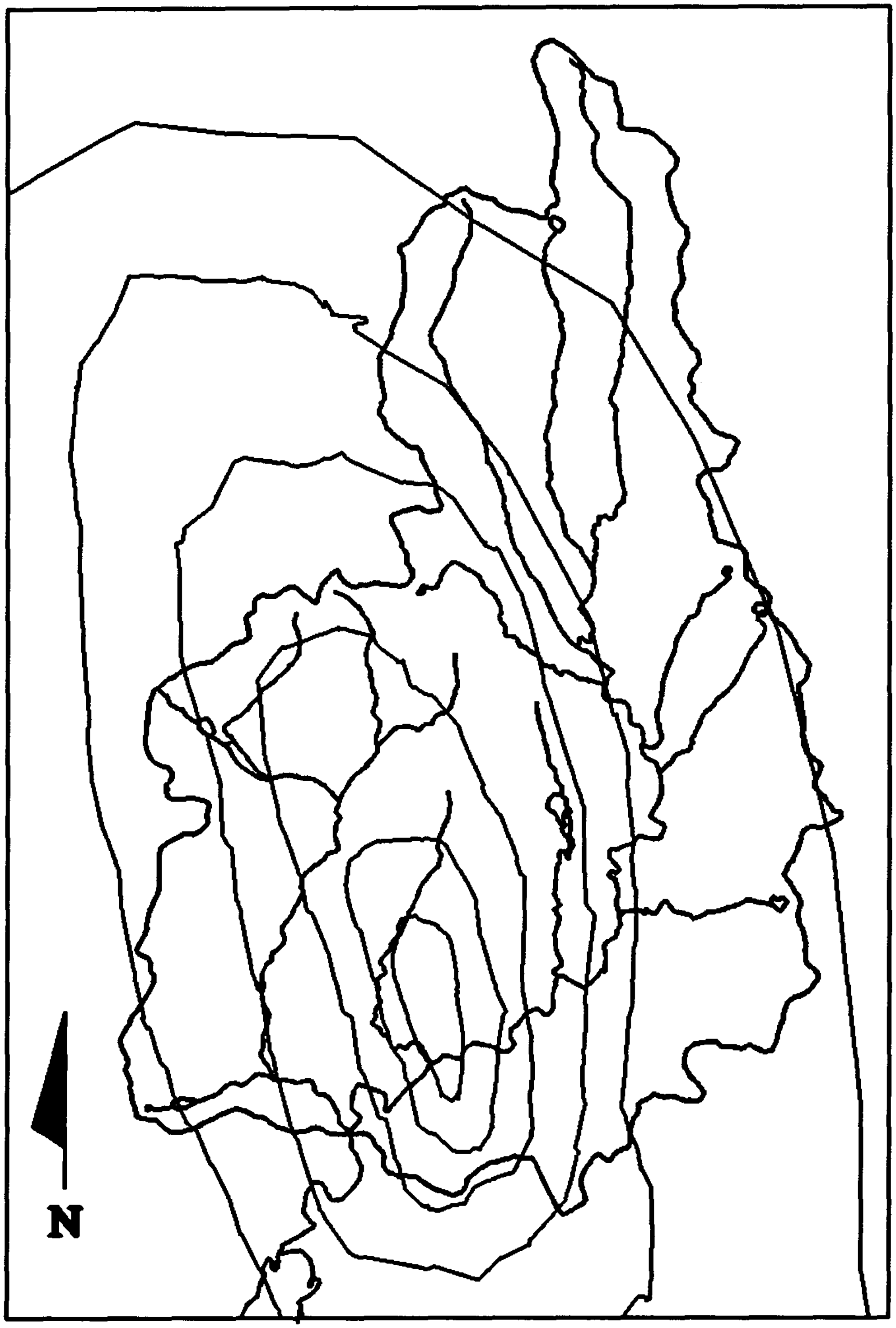

Figure 5.6a *Assumed storm hyetos on the south of Nitinat watershed.*

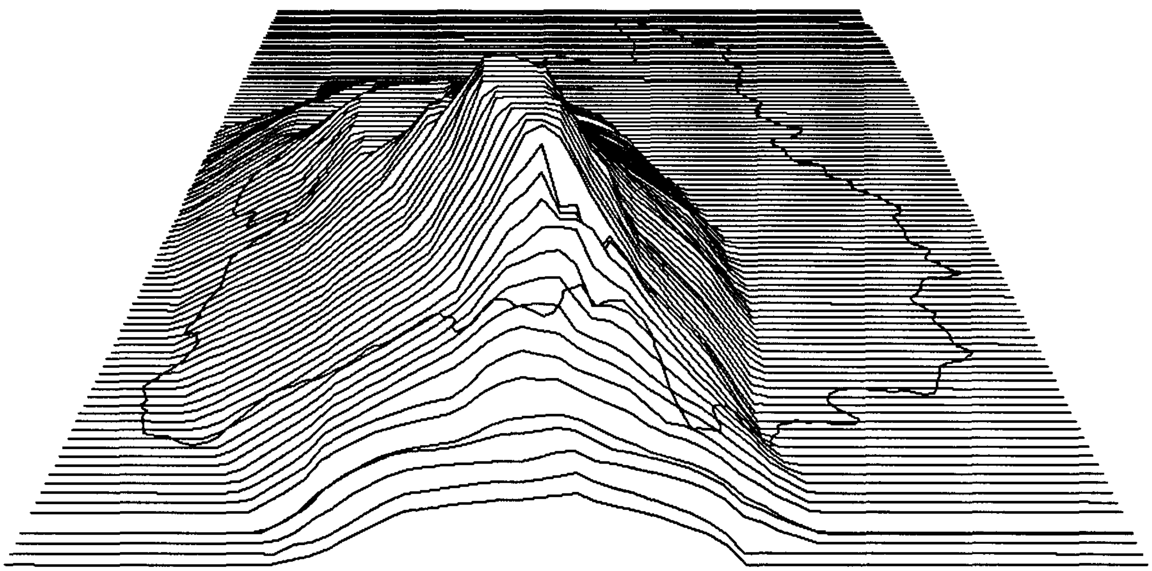

Figure 5.6b *3-dimensional appearance of the assumed storm on the south of Nitinat watershed.*

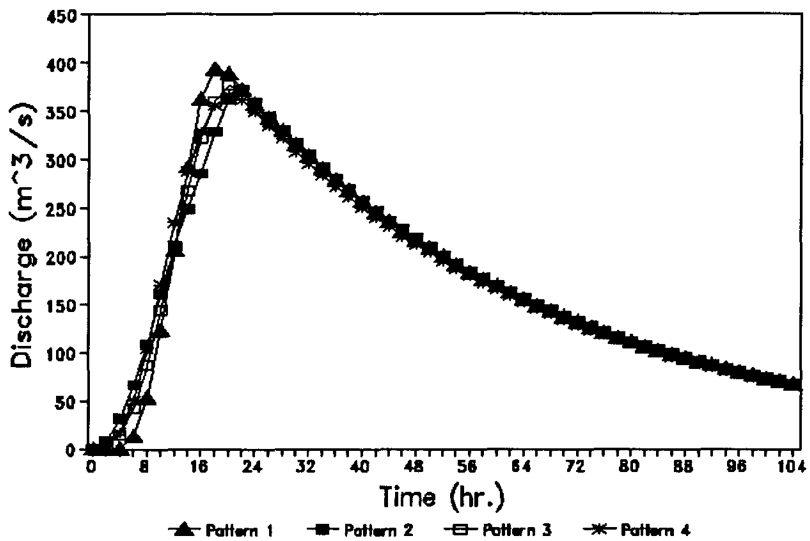

Figure 5.7 *Stormflow hydrographs simulated for four patterns of assumed storms passing over Nitinat watershed.*

isohyets are organized on separate layers in GIS, representing the variations of rainfall intensity for each time interval. GIS sequently extracts these rainfall data on separate layers into each hydrologic response unit (HRU), where excess rainfall is generated and translated to the outlet.

It should be pointed out that it is the digital elevation model (DEM) that makes it possible for the model to simulate discharge hydrographs caused by complex storms for ungaged watersheds in real time if the isohyets maps of the watersheds can be timely received from satellites, airplanes or weather stations.

5.3 Land Use Changes

At present, Nitinat watershed is completely covered with forest. The land use changes including clearcutting and urbanization on any part of this watershed in a large scale will definitely change the discharge pattern at the outlet, which may affect the development of fish hatchery downstream. Since some land use changes are irrevocable, the effects of alternative schemes for such changes on hydrologic regime should be examined using computer models before the mistakes are made to landscape.

Four scenarios of land use changes for Nitinat watershed were evaluated in this study:

Scenario 1. The existing forest is kept untouched. The total area of forest is 426.90 km^2 equivalent to the area of the entire watershed (see Figure 5.8a).

Scenario 2. The existing forest is altered to the combination with the urban area of 76.44 km^2 (17.91%), grass land of 212.61 km^2 (49.80%) and forest of 137.85 km^2 (32.29%) (see Figure 5.9a).

Scenario 3. The urban area as indicated in Figure 5.9a is changed to grass land (see Figure 5.10a), where the grass land is developed to 289.05 km^2 (67.71%) and the area of forest is 137.85 km^2 (32.29%).

Scenario 4. The grass land as indicated in Figure 5.9a is returned to forest (see

Figure 5.11a), where the forest occupies 350.46 km^2 (82.09%) and the urban area is 76.44 km^2 (17.91%).

The changes of land uses also change the travelling time of stormflow to the outlet of the watershed. Consequently, each scenario has its own flow time-areas, which can be calculated by using the flow velocity equations described in Chapter III and spaced with selected time intervals in GIS. Figure 5.8b, 5.9b, 5.10b and 5.11b show 2-hour time-area maps for scenario 1, 2, 3 and 4 respectively . As compared in Figure 5.12, however, the difference between the areas spaced for each time interval on these maps is small because the stormflow on large watersheds is mainly conducted through natural channels. What is significantly changed is the runoff coefficients for the areas of each time interval (see Figure 5.13), which determines the generation of excess rainfall for each time-area in the model.

The ratios of $R/(R+T_c)$ and storage coefficients for these scenarios in Nitinat watershed depends on the regional ratios of $R/(R+T_c)$ and areal proportions for individual land use types involved in each scenario, which are given as:

for scenario 1,

$$R/(R+T_c) = 0.75$$

$$R = 48.0 \text{ hours}$$

for scenario 2,

$$R/(R+T_c) = 0.10 \times 76.44/426.90 + 0.50 \times 212.61/426.90 + \\ + 137.85/426.90 \\ = 0.51$$

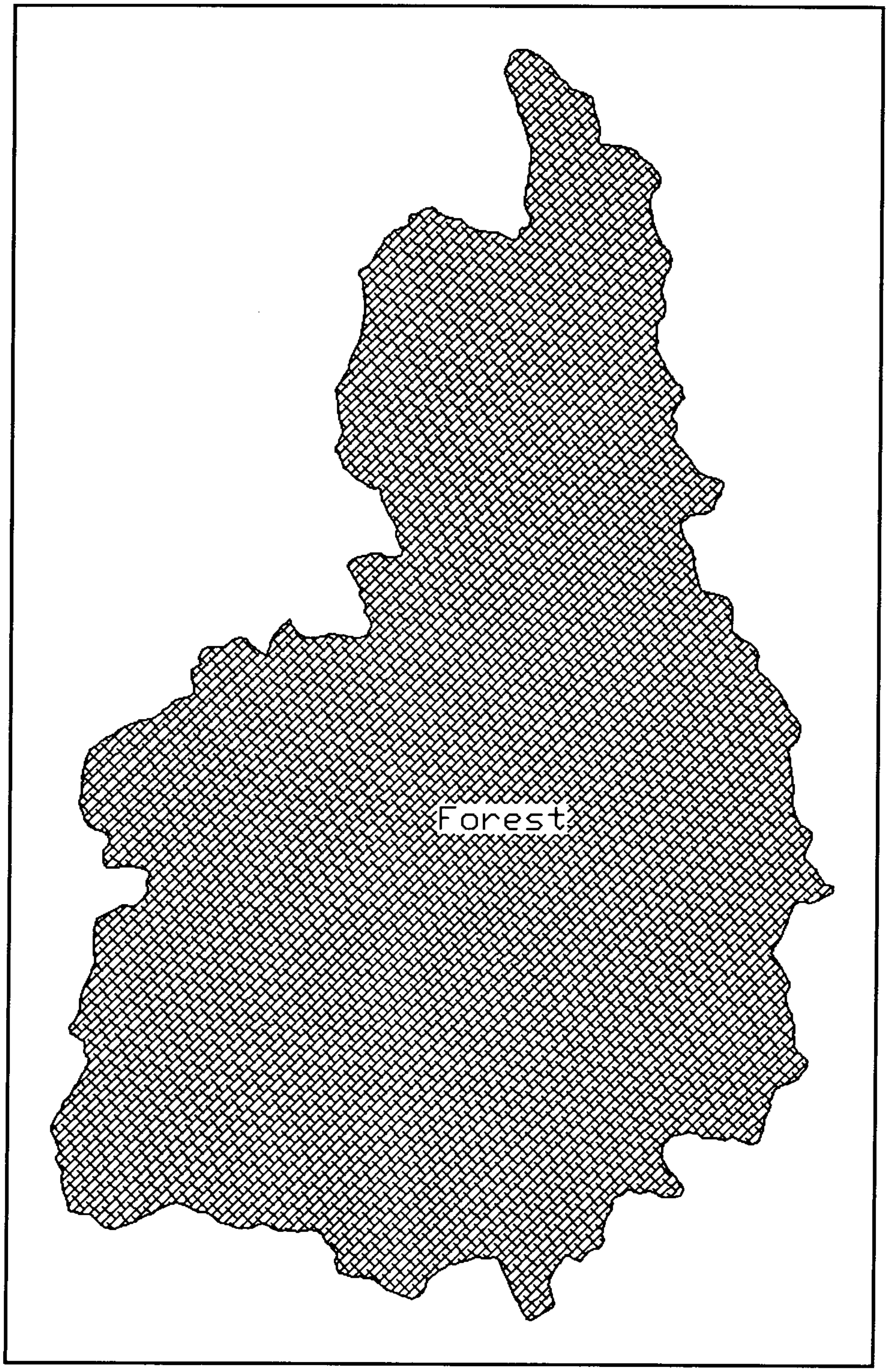

Figure 5.8a *Land use scenario 1. The land is completely covered with forest.*

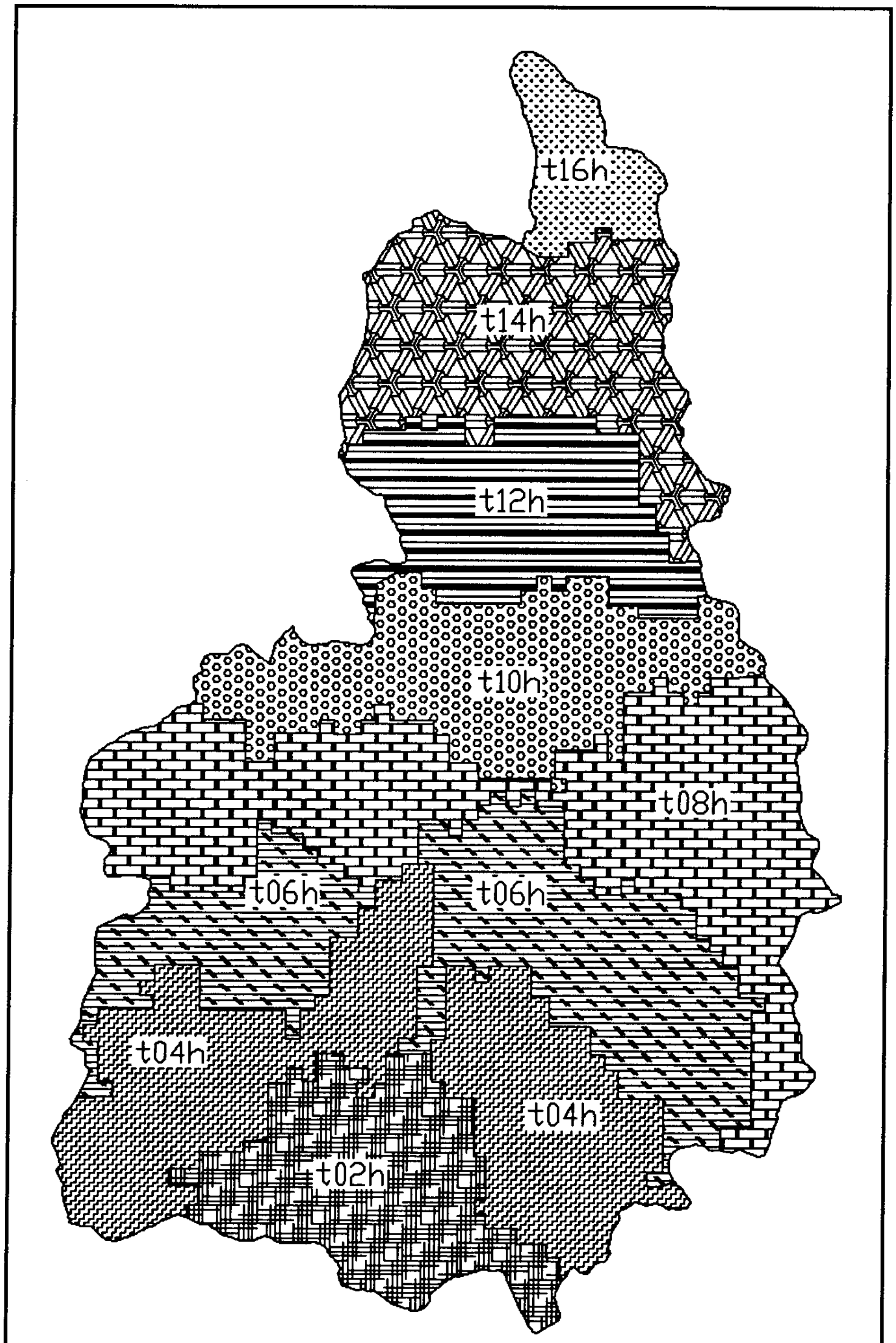

Figure 5.8b *Two-hour time-area map for the land use scenario 1.*

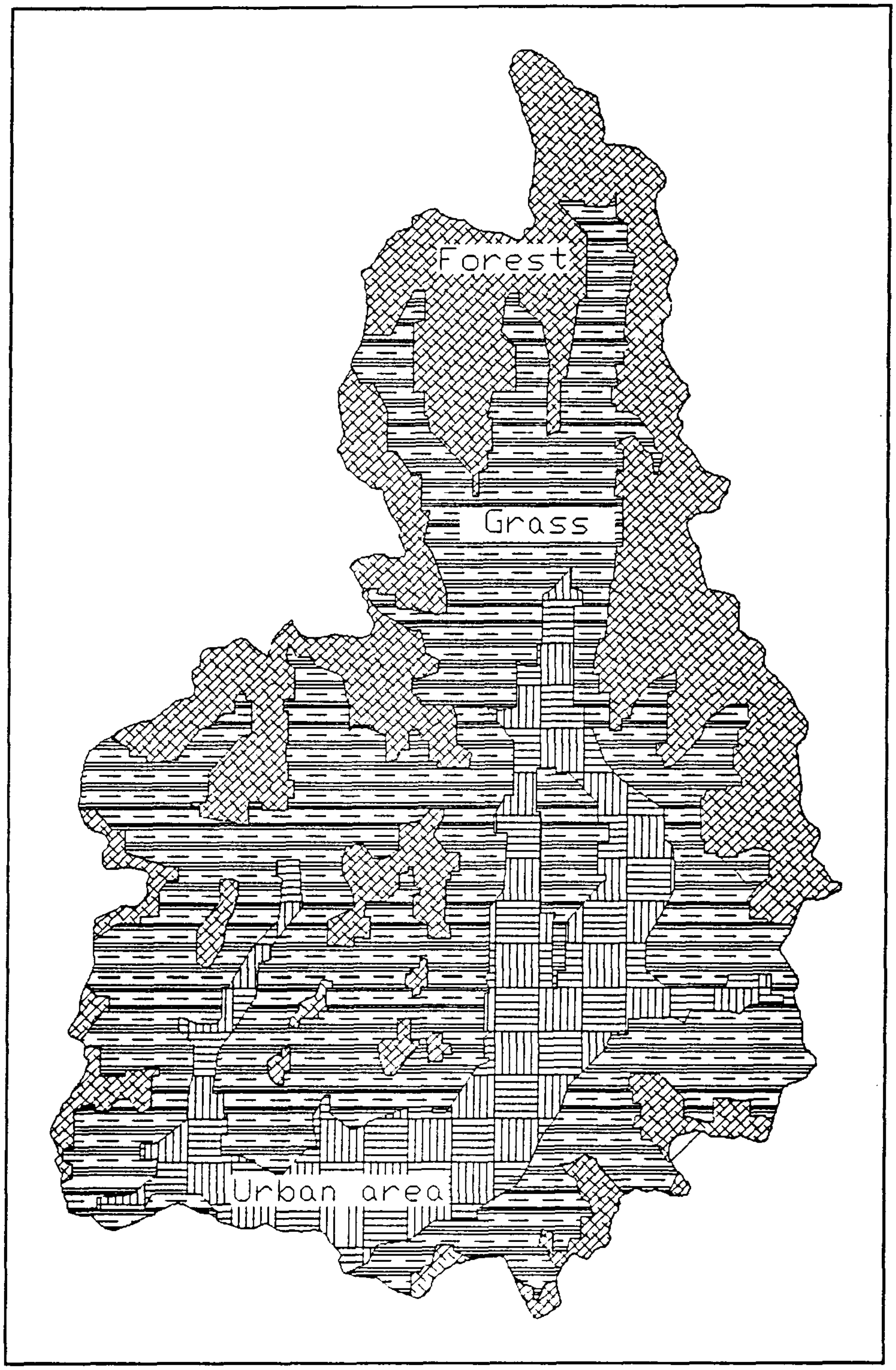

Figure 5.9a *Land use scenario 2. The land is covered with forest, grass and urban area.*

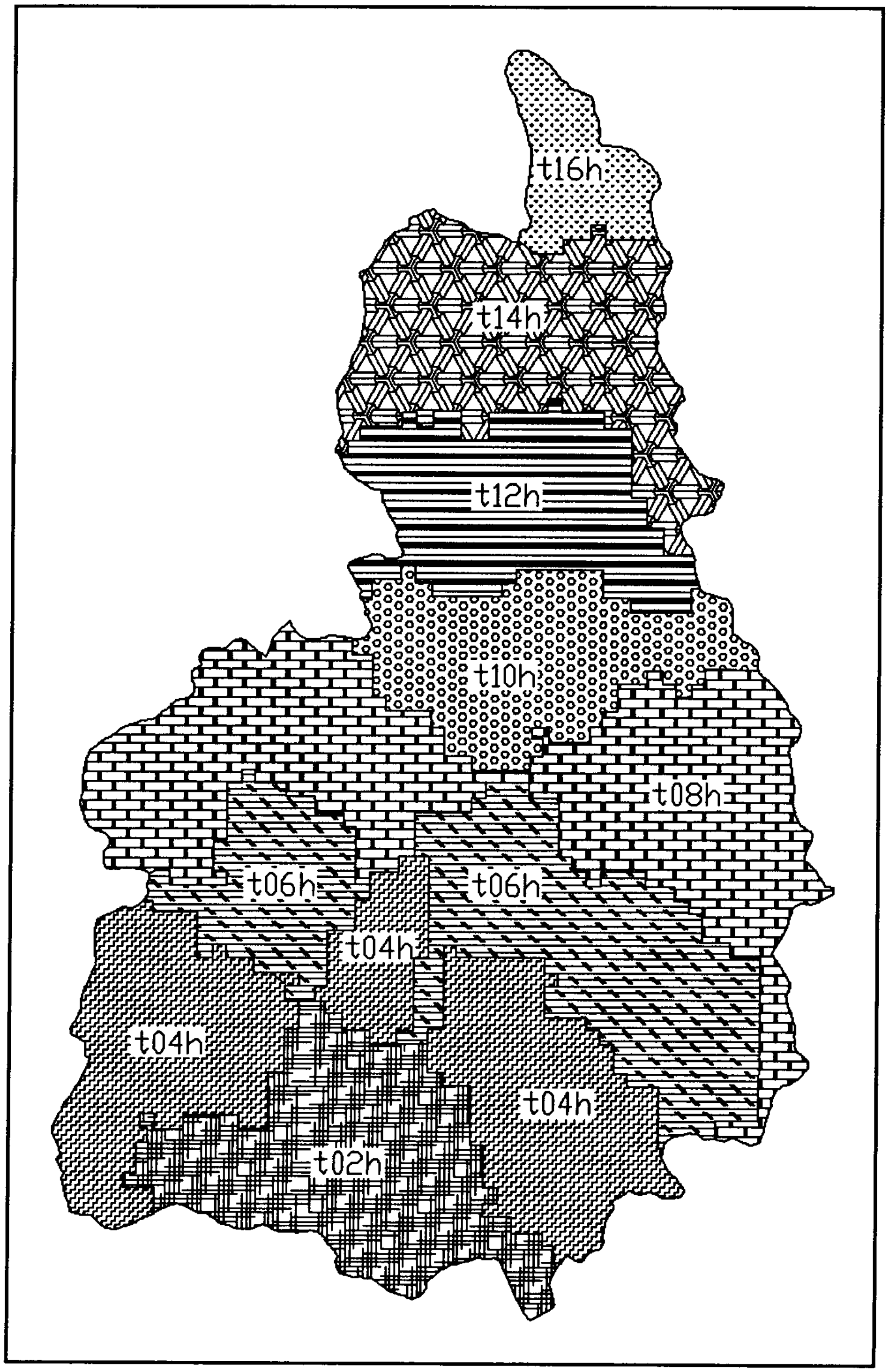

Figure 5.9b *Two-hour time-area map for the land use scenario 2.*

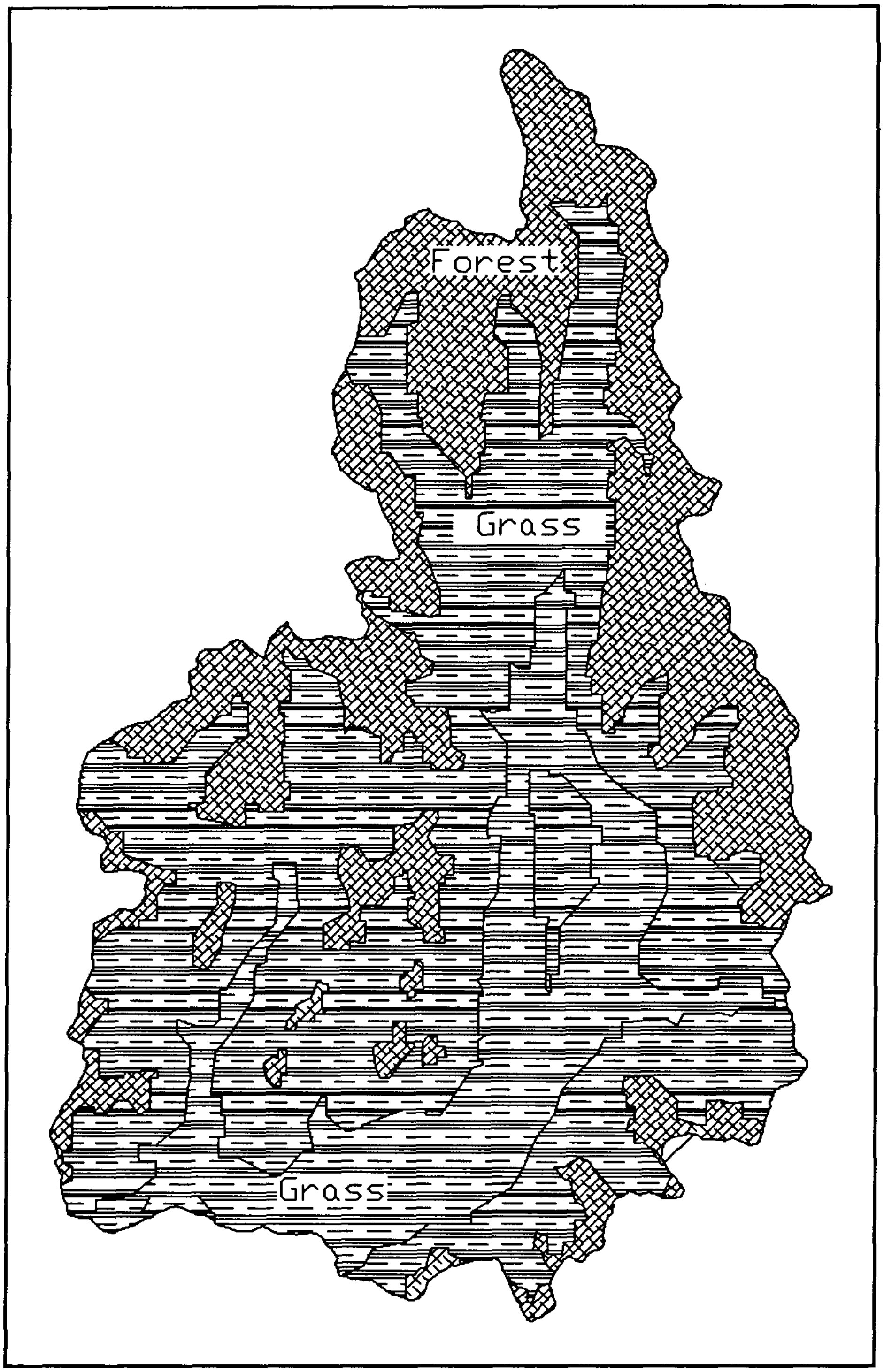

Figure 5.10a *Land use scenario 3. The land is covered with forest and grass.*

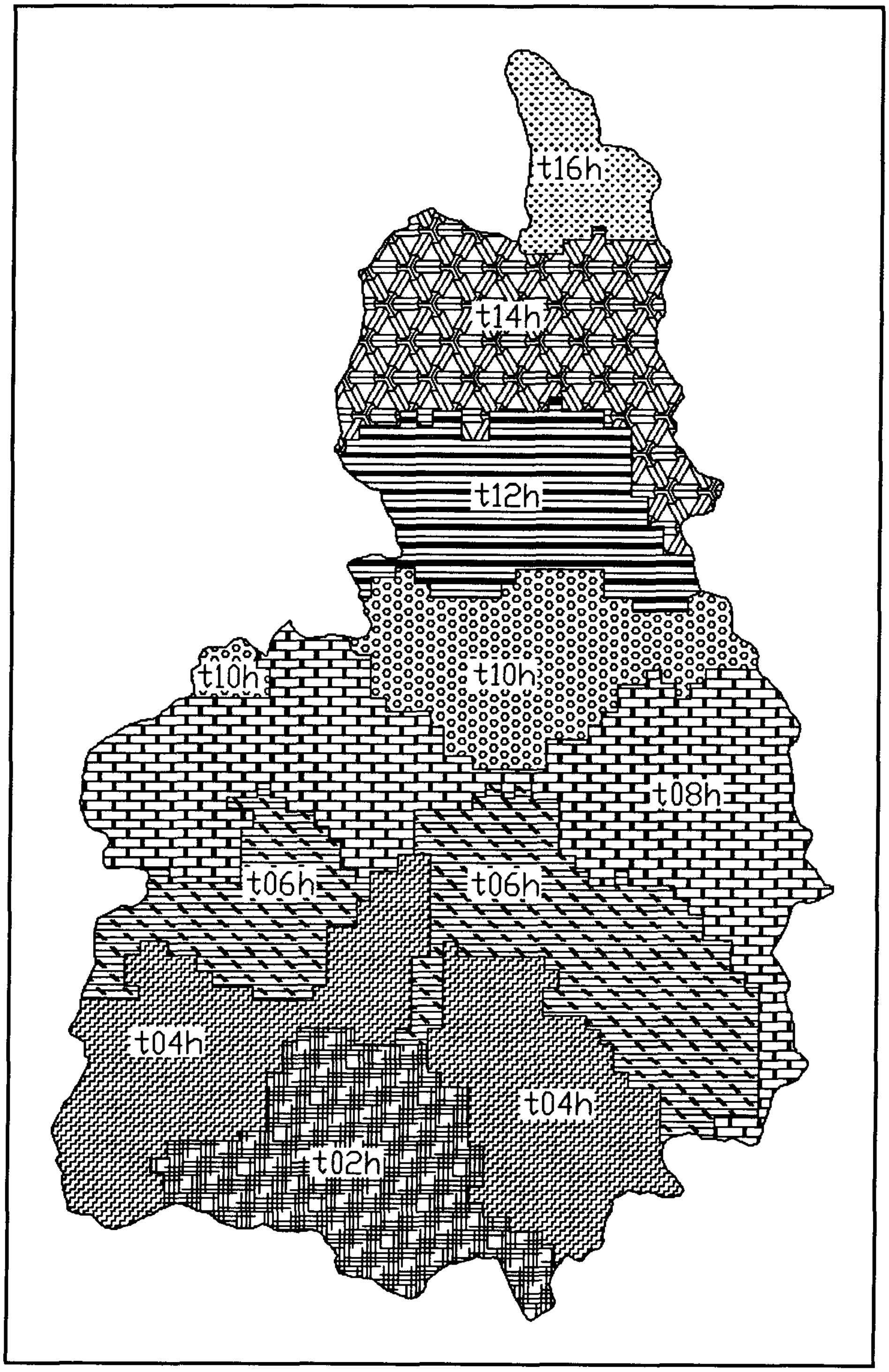

Figure 5.10 *Two-hour time-area map for the land use scenario 3.*

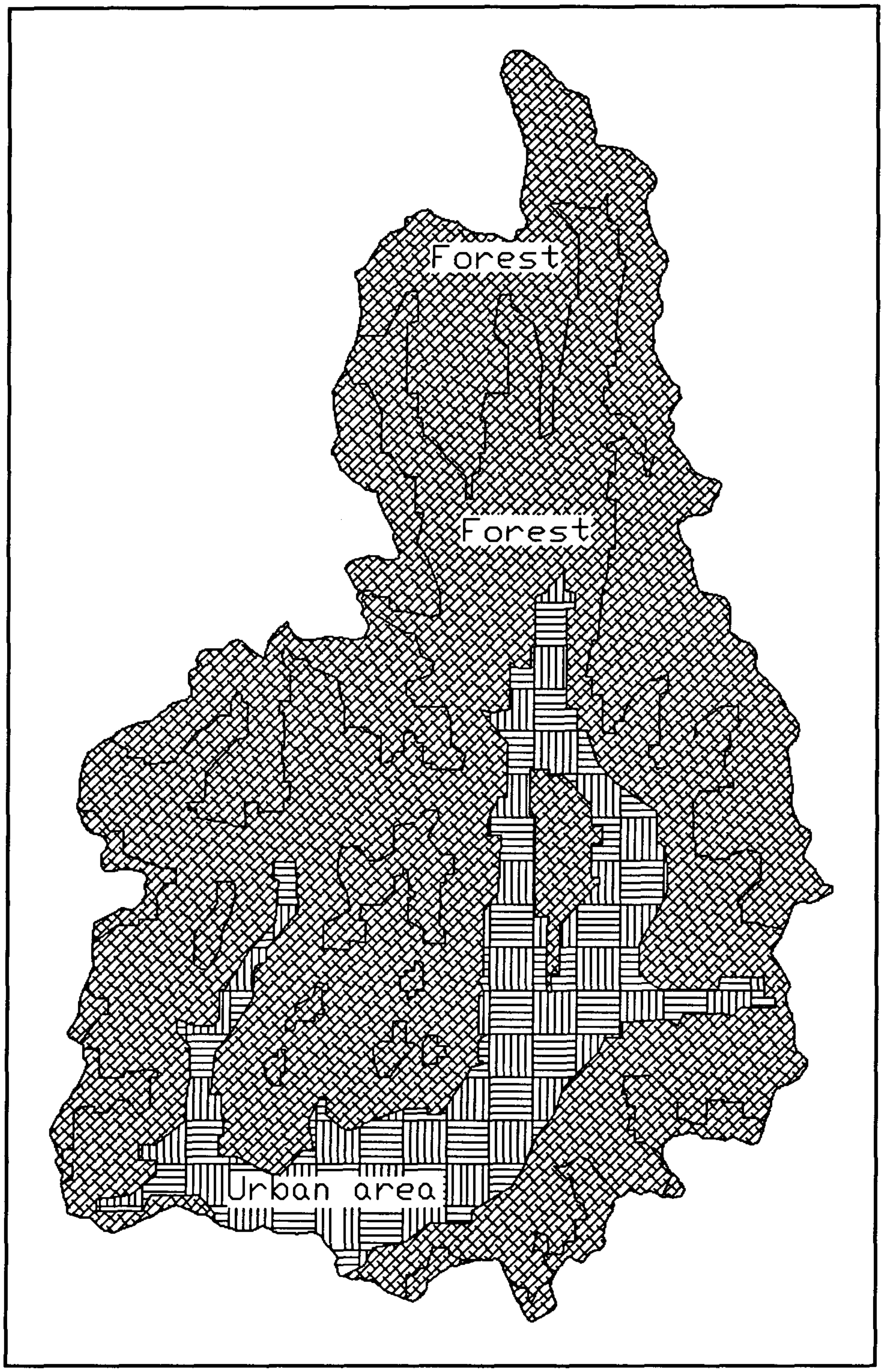

Figure 5.11a *Land use scenario 4. The land is covered with forest and urban area.*

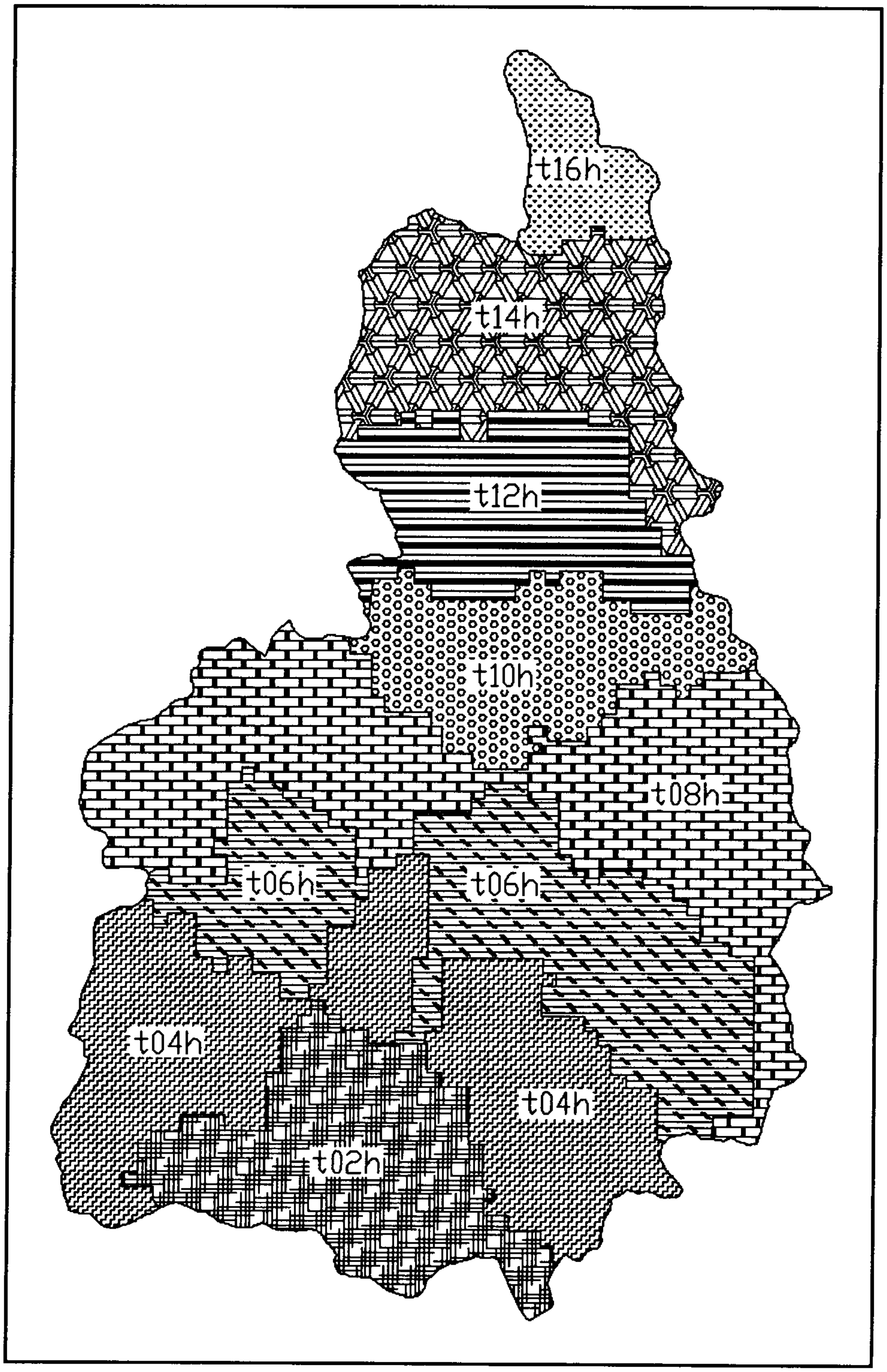

Figure 5.11b *Two-hour time-area map for the land use scenario 4.*

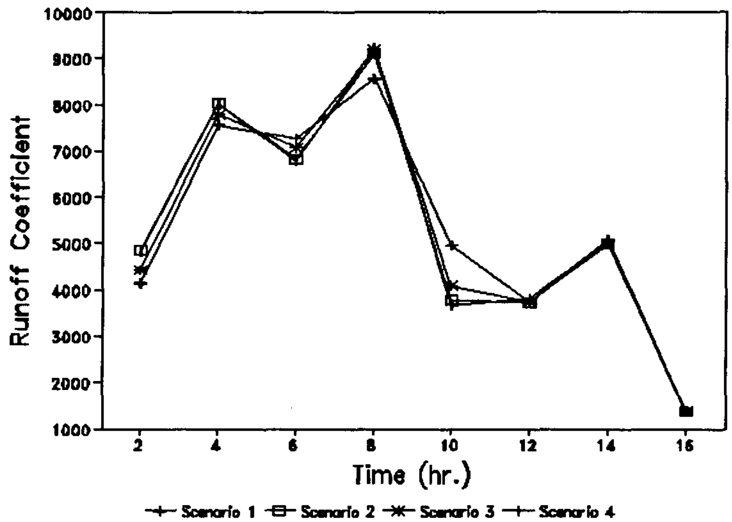

Figure 5.12 *Areas of 2-hour time-area for the four land use scenarios.*

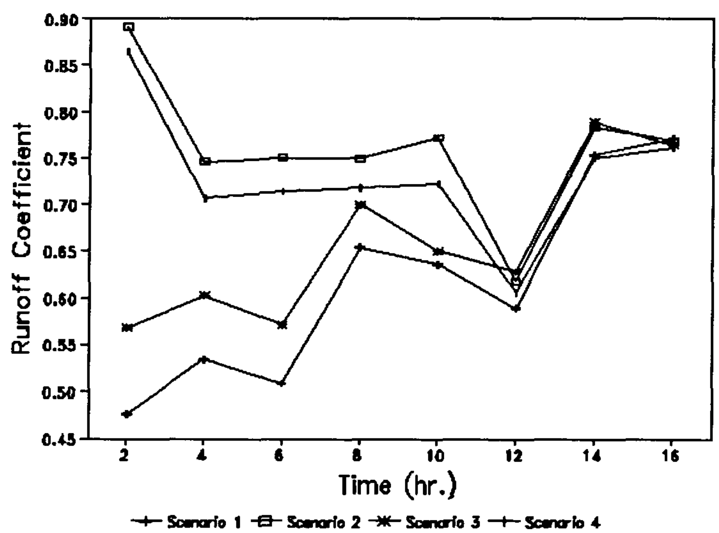

Figure 5.13 *Runoff coefficients on each area of time-area maps for the four scenarios.*

R = 16.6 hours

for scenario 3,

$$R/(R+T_c) = 0.50 \times 289.05/426.90 + 0.75 \times 137.85/426.90$$

$$= 0.58$$

R = 22.0 hours

for scenario 4,

$$R/(R+T_c) = 0.10 \times 76.44/426.90 + 0.75 \times 350.46/426.90$$

$$= 0.63$$

R = 27.2 hours

The parameters related to these scenarios are summarised in Table 5.1 and 5.2.

Table 5.1 *Regional $R/(R+T_c)$ and areas of individual land use for the four scenarios.*

	Forest		Grass land		Urban area	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Regional $R/(R+T_c)$	0.75		0.50		0.10	
Scenario 1	426.90	100	0	0	0	0
Scenario 2	137.85	32.29	212.61	49.80	76.44	17.91
Scenario 3	137.85	32.29	289.05	67.71	0	0
Scenario 4	350.46	82.09	0	0	76.44	17.91

Table 5.2 *Parameters and results of the model for the four land use scenarios.*

	T_c (hours)	R (hours)	$R/(R+T_c)$	Peak flow	
				Discharge (m^3/s)	Time (hours)
Scenario 1	16	48.0	0.75	666.8	28
Scenario 2	16	16.6	0.51	1715.1	22
Scenario 3	16	22.0	0.58	1246.4	24
Scenario 4	16	27.2	0.63	1214.9	24

The input rainfall intensity is given by using an uniform design storm with 200-year return period and duration of 16 hours. As shown in Figure 5.14 and Table 5.2, the peak flow increases and the lag time to the peak flow decreases as the watershed is developed. The land use scenario 2, a combination of forest, grass land and urban area, will cause the highest peak flow and shortest lag time to the peak flow, while forest tends to reduce peak flow and delays the time of arrival of peak flow. According to the relationship between the flood stage and the peak flow discussed in Section 5.2, it has been interestingly noted that keeping the existing forest is the only scenario not causing overbank flood for the storm with 200-year return period and 16-hour duration. By comparing the scenario 3 and 4, it can also be concluded that the watershed may respond to storms in the similar way though the land use scenarios may be different.

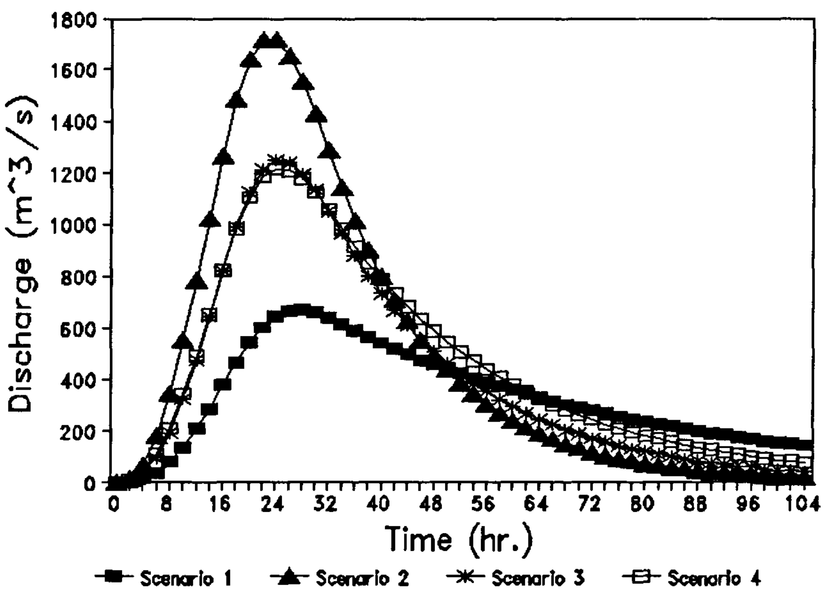

Figure 5.14 *Stormflow hydrographs simulated for the four scenarios of land uses.*

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The GIS based model described in this thesis has demonstrated usefulness of applying GIS technology to hydrologic modeling. With the proposed approach, the impact of land use practices, such as logging, road construction and urbanization, on the hydrologic response (i.e., stormflow), can be quickly evaluated so that proper land use scenarios can be adopted before any irrevocable mistake has been made to the watershed itself.

Time-area method is the key for the model. Unlike most of GIS based hydrologic models which mainly focus on model parameterizations, derivations of hydrologic characteristics of watershed, or interface between GIS and existing hydrologic models, this study took one step further to integrate the movement of stormflow with GIS by using the time-area method. Such integration provided the model with a greater power in handling the effects of complexities of soils, land uses and rainfall on the simulation of stormflow hydrograph.

Spatial and temporal variations of rainfall intensity have substantial effects on stormflow in a watershed. Examining design storms on computer will aid in providing early warning of anticipated flood conditions. In this study, four patterns of storms passing over Nitinat watershed were examined with respect to the stormflow responses to the storms. In fact, it is possible for the model to simulate the response to more complex storms moving at any velocities and in any directions. By processing rainfall intensity data in the digital elevation model (DEM) of GIS, the model is capable of forecasting floods in real-time with the rainfall information timely received from meteorologic radars, weather stations, satellites or airplanes.

The model was established with the combined characteristics of distributed and lumped models. It can be used not only for modeling stormflow in a well gaged watershed, but also for giving a reasonable simulation of stormflow in an ungaged watershed. Soil, land use and topographic maps are commonly available information for most watersheds, but they may be only hydrologically related information available for ungaged watersheds. By taking advantages of GIS in spatial information processing, the model can help users to achieve satisfactory simulations of stormflow hydrographs with these limited information in ungaged watersheds.

Because of the effect of watershed detention on stormflow, the assumption for the Rational Method, that maximum peak flow caused by a storm occurs when the duration of the storm reaches the flow time of concentration, is rarely true except for small and simple urban watersheds. In the watersheds with large storage capacity, peak flow is greatly attenuated and the time to peak flow is delayed. As a result, for a design storm with a given return period, peak flow increases with the duration of storm. Such increase, based on the results from the examination on the simulated stormflow in Nitinat watershed by using the model, may approach a stable level as the rainfall proceeds much longer than the flow time of concentration. Therefore, the maximum peak flow for a storm with a given return period will be underestimated if the Rational Method is applied to the watersheds with large storage capacity.

There are three models explaining the sources of stormflow generation: overland source, partial area and variable source area. It has been pointed out in Chapter III that variable area source is dominant in the study watersheds. Stormflow is conducted through widely existing soil channels in these watersheds and becomes overland flow near stream channels. Though roughly, this study has made the first attempt to automatically simulate the dynamic change of variable source area.

The digital elevation model (DEM) is recognized as a useful tool to automatically derive hydrologic characteristics of watershed. Many previous researches have been carried out for the automated delineations of these characteristics such as watershed boundaries and stream channels, but very few of them attempted to link the automatically derived hydrologic characteristics to hydrologic response. The delineation of flow time-area is an effort made in this study to establish such linkage so that GIS technology can be better integrated with hydrologic modeling.

There are many parameters that have frequently been employed to characterize watershed topography. These parameters, such as drainage density, main stream profile, slope, aspect, elevation of land surface, usually represent the long term interactions between hydrologic regime and watershed surface. The similarities of the these parameters between watersheds may determine the applicability of a hydrologic model from one watershed to another. Manual interpretation of these parameters could be very cumbersome, time-consuming and error-prone. The automated techniques used for this study provide a fast and more accurate way to characterize a watershed.

The results of the model testing in Jamieson Creek are very encouraging. Applications of the model to Nitinat watershed indicates that the maximum flood level for the storm with 200 years return period would exceed the present hatchery site elevation. Logging and urbanization in the watershed would substantially increase peak flow for a given return period.

6.2 Recommendations

The effects of soil, land use, rainfall intensity and topography on stormflow generation are reflected on the runoff coefficients assigned to each hydrologic response unit (HRU) in the model. Although the antecedent soil moisture also greatly affects stormflow generation, its spatial distribution is not involved in the current consideration of the model. Because antecedent soil moisture may vary greatly with watershed topography, a more detailed analysis of antecedent soil moisture distribution will benefit the improvement of the model accuracy. Further research may use the digital elevation model of GIS to relate antecedent soil moisture to evapotranspiration and solar radiation that are partly determined by aspect, slope and elevation of land surface.

The downhill searching program is able to trace the flow pathway for every point on a watershed. By reversing the searching direction of the program, this program will have the capability of delineating the boundary of drainage area for any point on the watershed. Potentially, the traced flow pathway for each point on the watershed provides the boundary conditions important for the finite element analysis in a numerical hydrologic model.

The derived contributing areas from DEM for points on a watershed are very useful data, from which many important hydrologic characteristics such as watershed boundaries, stream channels, drainage density and variable source area of stormflow can be obtained. Together with flow pathways and time-area data, the contributing area can be further used to simulate soil erosion and non-point source water pollution of the watershed because these derived results have indicated where, when and how much stormflow comes to a point of interest on the watershed.

It appears that a more comprehensive hydrologic model in conjunction with GIS can be established to simulate water quantity and quality in a watershed. Because both GIS technology and its applications to water resources management are still in their infant stage, many parameters and procedures unique to stormflow modeling have not been included in standard GISs. With the improvement of GIS technology, however, it is not impossible to establish a hydrologically oriented GIS with the power in both spatial data management and modeling specific for water resources management.

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