Surface Hydrologic Modeling and GIS: A Case Study of the Kaimai Hydropower Project Catchment, New Zealand

A thesis submitted in fulfilment of the requirements

for the Degree of

Doctor of Philosophy

in Earth Sciences

at the University of Waikato

by

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The
University
of Waikato
Te Whare Wānanga
o Waikato

1998

ABSTRACT

The recent trend towards spatial hydrologic modeling is due to advances in the field of geographic information systems (GIS). Spatially distributed models take into account the spatial variability within the catchment and allow users to define parameters for each sub-watershed or river section depending on the availability of the data. A study was conducted at the Kaimai Hydropower catchment, Tauranga, to identify the potential advantages and disadvantages of spatial hydrologic modeling for use in surface runoff estimation while emphasizing the importance of GIS data quality and discussing the latest developments in the field of GIS. This study has developed a number of techniques to improve the usefulness of GIS for surface hydrologic modeling. A black box runoff model was also developed in order to evaluate the effectiveness of spatial surface hydrologic model as an inflow prediction tool.

The Kaimai Hydropower scheme is a small storage-constrained scheme and it is very important that such schemes optimize their available water resources in the present competitive electricity marketing environment. River inflow forecasts are an important part of optimizing hydropower schemes. A black box type inflow prediction model was developed and used as an input to the Kaimai Hydropower scheduling software (HYMAX). HYMAX results indicated a 7% improvement in the operation of the hydropower scheme when HYMAX results were compared with the control room operation.

It is also important for the management of any hydropower scheme to see any impact of landuse change on their river resources. The Kaimai Hydropower catchment has undergone a landuse change from native bush to *pinus radiata* in several parts of the catchment since 1982. The analysis of electrical power output as a proxy for catchment water yield could not detect any reduction in annual or seasonal water yield. A slight increase in the water yield in winter and spring seasons after landuse change is attributed to the incremental nature of the landuse change.

The use of GIS in the field of hydrology contains many hidden errors and the user must be aware of the quality of the data before its use. Different types of GIS errors such as generalization, rasterizing error, sink artifacts (and their impacts on the surface hydrologic modeling) were studied and solutions proposed. The digital elevation model is the basic digital data set to be used in surface hydrologic modeling using GIS. A technique was developed to build a hydrologically sound digital elevation model, and this was then applied to develop a surface runoff model using the curve number (CN) approach of excess rainfall estimation within the GIS framework. The unit hydrograph was used to translate the time distribution of excess rainfall into a runoff hydrograph, and routed at the watershed outlet using the Muskingum method. However, the CN method failed in the study area because the region has a high infiltration rate coupled with deep percolation through joints and cracks. The subsurface geology, rather than land surface characteristics, were the dominant factor here, so surface classification methods such as CN could not support predicting quickflow volumes.

A map-based surface water flow simulation model, which is based on Geographic Information System (GIS) and object oriented programming (OOP), was evaluated after making necessary changes in its original code and applied to the study area to see its applicability as an inflow prediction tool. The selection of this model was based on its strength in addressing GIS and hydrologic modeling, as an integrated field in the area of runoff prediction involving time series data. The model gave a good match when compared with both observed and black box predicted inflows. It proved to be a good strategic management tool for planning purposes, but at present has limited use as an operational tool because of greater computational requirements involved. However, the map-based model is a good addition in the field of integrated spatial hydrologic modeling using GIS. It also solves many of the basic problems such as feature oriented map operations, dynamic segmentation of an arc, and spatial time series database development, which until recently were not possible in a GIS environment.

This study shows the effective use of black box and GIS techniques by applying them to the study area, and demonstrates the integrated surface hydrologic modeling using ARC/INFO GIS and OOP in an ARCVIEW GIS environment. The importance of the GIS data quality for hydrologic applications is explained by studying the different types of GIS errors, and techniques were developed to handle the errors to improve the quality of the digital data. This study has also addressed new developments in surface hydrologic modeling within a GIS framework; and hopefully some of the solutions presented here will be of value to future work in spatial hydrology and related fields.

DEDICATION

This work is dedicated to my father,

Mohammad Afzal Choudhry

Who taught me the value of education and whose continuous support, love & encouragement enabled me to complete this work

ACKNOWLEDGEMENTS

I would like to express my thanks to all those who assisted with the research presented in this thesis. In particular I would like to thank:

- Dr. Earl Bardsley, my chief supervisor for invaluable suggestions, advice and encouragement throughout the time of this research. I appreciate his help in evaluating the power scheduling software (HYMAX).
- Dr. Munir (Munro) Morad, my co-supervisor for his guidance, continuous encouragement, and discussions on GIS topics during this study.
- Associate professor Lex Chalmers, Geography Department for his help and support. Special thanks to him for upgrading the GIS softwares necessary for this research.
- Roger Burchett, Former Chief Executive Officer, The Kaimai Hydropower Project, Tauranga for providing me with logistic and financial support for this project.
- Kevin Osbaldiston, Steve Wickham, Brian Simmonds, Raewyn McCall, staff of the former Kaimai Hydropower Project, Tauranga for their assistance with data collection and field work.
- Simon Neale and Graeme Prestidge of Trust Power Ltd., Tauranga, for providing me with power output and price data.
- The former Kaimai Hydropower project, The Department of Earth Sciences and Geography are thanked for financial support towards conferences and running costs involved with this project.
- The Graduate Industry Fellowship (GRIF), Ministry of Science and Technology, New Zealand for their scholarship and financial support associated with this project.
- Dr. Murray Jorgensen, The Department of Statistics, for assistance with statistical analysis.
- John Radford, hydrology technician, for his assistance in streamflow gauging.
- Bruce Parkinson, computer support person for his help.
- Dave Evans, Environmental Manager, Tasman Forestry, Rotorua, for providing me the information regarding forestry development in the study area.

- The great hydrology group (Nick, Edmund, and Mike) with whom the days were spent in good humour, discussions and hard work. Good luck to you all with your research and jobs. Special thanks to Edmund Brown and Nick Brown for proof reading my thesis.
- Khalid Ilyas Moughal and Dr. Cliff J. Studman for their encouragement and guidance on accepting this project.
- Liddy and Geerten, Sabine and Harvey, Joseph, Gager, Jayanthi, Heiko, Barbra for their friendship and support throughout my time at the University.
- Cameron King for his assistance in rasterizing error data analysis.
- My parents, brothers and sisters for their support and understanding during my time at the University. Special thanks to my father and mother in law (Mr. Husny Sunkar and Mrs. Imlati Sunkar) for their love & support throughout my time at the University.
- Finally, I would like to thank my wife Niely for her patience and love during the time I have been involved with this study.

- And many others, your assistance is much appreciated.

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CHAPTER 1

INTRODUCTION

1.1 HYDROLOGIC MODELING

A hydrologic system was defined by Dooge (1959) as an approximation of the actual system, with the inputs and outputs of the system being measurable hydrologic variables, and the structure of the system being a set of equations linking the inputs and outputs. The construction and application of watershed models has been a prime focus of hydrologic research for many decades. Various models have provided frameworks in which to conceptualize and investigate hydrologic systems and the relationship between climate, landuse and water resources (Leavesley, 1994). These models perform the system transformations which link hydrologic input, such as precipitation, to catchment output such as streamflow. Hence models can be structured according to the treatment of randomness, spatial heterogeneity, and temporal variations in natural hydrologic processes (Chow *et al.,* 1988).

The principal purpose of utilizing models, as discussed by Linsley (1982) and Beven (1989), is to understand processes and predict future outputs. Process investigations include understanding the sensitivities of various factors influencing hydrologic responses and testing theoretical concepts of certain hydrologic mechanism. Future model predictions involve forecasting the change in hydrologic responses after climatic and/or landuse change.

1.2 EVOLUTION OF SURFACE HYDROLOGIC MODELS

Hydrologic models have evolved from simple linear models of rainfall-runoff relationships (Linsley, 1982) to spatially distributed complex models (Beven and Kirkby, 1979). Linsley (1982) and O'Connell (1991) review the history of hydrologic modeling in detail. Quantitative hydrology, immature at the beginning of the twentieth century, gradually evolved, as rational analysis has replaced empiricism (Chow *et al.*, 1988). The rational method developed by Mulvaney (1851) represented the first formal and longest used relationship for predicting discharge from rainfall. Research on catchment hydrology has greatly advanced through unit response studies, based on time variations, for example Nash (1958) and O'Donnell (1960), following the introduction of the unit hydrograph by Sherman (1932).

The topic of spatial variation also received some attention, although progress was limited by computational power. In recent years, the powerful computers and new modeling techniques have enabled progress in spatially distributed models like TOPMODEL (Beven and Kirkby, 1979) and Geomorphic Instantaneous Unit Hydrograph (GIUH) (Rodriguez-Iturbe and Valdes, 1979), Systems Hydrologique European (SHE) (Abbott *et al.*, 1986) and THALES (Grayson *et al.*, 1992). All these models incorporated spatial variation into catchment response but with different emphases.

1.3 SPATIAL AND LUMPED MODELING APPROACHES

The last decade has seen an increasing emphasis on the need to predict spatially variable hydrologic processes at quite fine resolutions. Many spatially distributed hydrologic models as mentioned above have been developed in recent decades. Unlike black box models that approximate watersheds as homogeneous with respect to topography, soil, vegetation and landuse and calculate hydrologic response as a dependent variable of meteorological input, distributed models divide the catchment into homogenous elements within which all the characteristics are assumed uniform, with differences among elements. Distributed models take into account the spatial variability within the catchment and allow user to define parameters for each sub-watershed or river section depending on the availability of the data. Distributed models are essentially lumped at finer scales, which implies that hydrologic response of a watershed is sensitive to the resolution of the cell size or elements (Wood *et al.*, 1988). Distributed models suffer the limitation of complexity and intensive calculations due to a large number of parameters involved in their equations. Lumped models are simple, objective and often provide good predictability for operational purposes like hydropower scheduling, but provide limited understanding of basic hydrologic processes. Lumped models describe the entire basin variation and temporal differences by altering coefficients. Both types of applications have their advantages and disadvantages; the preference of one type over the other simply depends on the problem in question, computational requirements and availability of data.

The recent trend toward spatially distributed modeling is largely due to the use of geographic information systems (GIS) in the field of hydrology (Abbott *et al.,* 1986). GIS is designed to visualize, store, and analyze the information about the locations, topology, and attributes of spatial features. In GIS, locational data and their map representations are dynamically linked, so that any changes made in the databases and model equations are reflected immediately on its map presentation. The linkage between the map and databases makes GIS an ideal and strong tool for spatial data visualization and analysis. The basic prerequisite for distributed hydrologic modeling is data preparation and estimation of model parameters. The time and expertise required for this can be prohibitive, especially if large areas are involved.

Recent advances in GIS and increasing availability of commercial and freely distributed data sets can reduce the time involved in parameter estimation, but can also produce undesirable results due to different types of GIS errors involved in the digital data like generalization, vector to raster conversion, resampling error, and sink artifacts. The users must be aware of the quality of the digital data before starting hydrologic modeling due to the fact that the GIS analysis cannot produce results better than the input data. The spatially distributed hydrologic models are inherently map-based and provide a productive area for application of GIS techniques using a digital elevation model (DEM) as the basic data set. Therefore, it is important to have a reliable digital elevation model of the area.

This study used both lumped and distributed (GIS) approaches of surface runoff estimation while emphasizing the importance of GIS data quality and discussing the latest developments in this field. Due to the growing use of GIS in the field of surface hydrologic modeling, this study also developed some techniques within a

GIS framework to improve the effectiveness of GIS for surface hydrologic modeling

1.4 OBJECTIVES OF THE STUDY

The main objective of the thesis is to show the effective use of GIS and black box approaches in the field of surface hydrologic modeling, which is accomplished by dividing it into seven specific objectives. These are:

1. To develop a black box inflow prediction model as a requirement for the Kaimai Hydropower optimal scheduling software (HYMAX);
2. To study the effects of landuse changes on river resources of the Kaimai Hydropower project catchment;
3. To review the applications, new developments and limitations of GIS use in hydrologic modeling;
4. To study the effects of different types of GIS errors in surface hydrologic modeling and provide possible solutions;
5. To develop a procedure for hydrologic sound digital elevation model (DEM);
6. To evaluate the applicability of the curve number (CN) approach of runoff estimation using GIS in the study area;
7. To evaluate the map-based surface flow simulation model as a tool for inflow prediction of the Kaimai Hydropower scheme and compare the results with the black box surface runoff model.

1.5 THESIS OUTLINE

This section briefly explains the structure of the thesis. The thesis consists of ten chapters and three appendices and a brief explanation about each chapter is mentioned in this section. It should be noted that most of the objectives of the thesis are independent and have been presented as scientific papers in different international conferences and submitted to different international journals independently for publication. The remaining chapters are presented in paper form in the thesis. The words in capital letters are the GIS programs or functions used.

Chapter 2 describes the Kaimai Hydropower scheme, its topography, landuse, hydroelectric development, hydrology and geology of the area.

Chapter 3 discusses the importance of optimizing the hydropower scheme especially storage-constrained schemes like the Kaimai and briefly describes the power scheduling software "HYMAX". This chapter further explains the development of a black box inflow prediction model, which is an essential requirement for the power scheduling software and validation. A quantification is given of the improvements in the Kaimai Hydropower operation as a result of HYMAX use.

Chapter 4 explains the effect of landuse change from native forest to ***pinus radiata*** plantations in the Kaimai Hydropower catchment and discusses different statistical analyses used on electrical power output as a proxy for the catchment water yield, in order to detect any impact of landuse change on the operation of the hydropower scheme.

Chapter 5 reviews GIS use in the field of hydrologic modeling. This review consists of three parts: i) a summary of past efforts and current trends in using GIS to perform hydrologic analysis. ii) a discussion of the errors involved in using digital data and their effects on surface hydrologic modeling results. iii) an explanation of the concerns of GIS uses in hydrologic modeling.

Chapter 6 describes the different sources of GIS errors and their effects on surface runoff modeling and provides means of controlling them. Finally, the application of the proposed methods in the study area is discussed.

Chapter 7 describes the importance of the digital elevation model (DEM) in hydrologic modeling and discusses the natural closed catchments and DEM artifacts, and describes a new automated method of distinguishing between DEM artifacts and true closed catchments. This chapter also explains the role of surface description (breaklines) in building a hydrologically sound DEM. The application of the new DEM method in delineating watershed and stream network is also explained.

Chapter 8 describes the development of a surface runoff model using ARC/INFO GIS to evaluate the applicability of the widely used curve number method of excess rainfall estimation. The unit hydrograph approach was used to translate the time distribution of excess rainfall into a runoff hydrograph for each subwatershed and routed through the network to the principal drainage lines using the Muskingum method. Finally, this chapter discusses the reasons for the failure of the curve number approach in the study area.

Chapter 9 evaluates the map-based surface flow simulation model, which was developed using object oriented programming "AVENUE" and ARCVIEW-GIS software as a host environment. This chapter further discusses the new developments like time-series data handling, dynamic segmentation of an arc and feature oriented map operations in the field of GIS. A comparison of the map-based and the black box model results is carried out to see the applicability of map-based model as an inflow prediction tool for the study area.

Chapter 10 describes the general conclusions about each objective and recommendations for the future study.

Appendix 1 explains the data collection, streamflow gauging and initial data analysis.

Appendix 2 describes the sensitivity analysis of the black box model parameters.

Appendix 3 explains the conceptual design of the map-based model.

1.6 LIST OF PUBLICATIONS

The following section explains about the chapters which were presented in different international conferences. All the chapters mentioned below along with chapters 5 and 9 have been submitted to different scientific journals and are under review.

Chapter 4

- *The effects of landuse changes on river resources of the Kaimai Hydropower catchment, New Zealand*, Presented at an international conference on modeling and simulation (MODSIM'97), Organized by the international association for mathematics and computers in simulation, Tasmania, Australia, 8-11 December, 1997, pp. 440-443.

Chapter 6

- *DEM errors and their effects on surface runoff modeling,* Presented at 4th international conference on computer methods & water resources, Organized by the American society of civil engineers (ASCE), USA, Byblos, Lebanon, 16-18 June 1997. 8pp.
- *DEM accuracy and its importance in hydrologic modeling,* Presented at an international symposium on water resources education, training and practice: opportunities for the next century, Organized by the American water resources association, Keystone, Colorado, USA, June 29-July 3, 1997, pp. 764.
- *GIS errors and surface hydrologic modeling: problems and solutions,* Journal of survey engineering, Vol. 124 no.3, ASCE.

Chapter 7

- *A new method of building DEM for hydrologic modeling,* Presented at an international conference on modeling and simulation (MODSIM'97), Organized by the international association for mathematics and computers in simulation, Tasmania, Australia, 8-11 December 1997, pp. 444-449.

Chapter 8

- *Rainfall-Runoff modelling of Opuiaki river catchment using GIS*, Presented at 24th hydrology & water resources symposium, Organized by the New Zealand hydrologic society and the institution of engineers, Australia, Auckland, 24-28 November 1997, pp. 435-438.

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CHAPTER 2

STUDY AREA

2.1 INTRODUCTION

The Kaimai Hydropower catchment covers an area of approximately 350 km^2, 14-km southwest of Tauranga City. There are three hydro lakes in the catchment namely Lake Mangaonui, Lake Matariki and Lake Mclaren, with areas of 181.4 km^2, 192.8 km^2 and 347 km^2 respectively. Based on the geology and topography, the catchment can be divided into the northern Mamaku Plateau (which comprises the bulk of the area), the lower eastern Kaimais and the southern Whakamarama Plateau. Figure 2.1 shows the digital elevation model and location map of the main rivers, hydro lakes and hydropower stations within the study area. The Opuiaki River with a catchment area of 88 km^2 provides an approximate boundary between the north western Mamaku Plateau and the eastern Kaimais, while the Mangakarengorengo River separates the northern Mamaku Plateau from the southern Whakamarama Plateau. The Opuiaki River sub-catchment (as marked in Figure 2.1) has been used as a sample study area for analysis purposes in this study.

2.2 LAND USE

Most of the hydropower catchment is covered by native forest, with smaller areas of exotic forest and scrub. A variety of native trees grow in the gorges and valleys of the study area, particularly in the more inaccessible areas. In the upper gorge of the Mangapapa River there is a reserve of scattered kauri, growing at its most southerly natural limit. Immediately north of the kauri is a stand of hard beech in a very rugged section of the gorge. Bordering the edges of Lake Matariki are dense stands of tanekaha. In the headwaters of the Opuiaki there are thick stands of rimu, totara, miro and tanekaha. Downstream in the valley, the bush has been cut over and secondary growth now predominates. Intermixed are the occasional pine and scrubby thickets of bushlawyer, supplejack, mangemange and tee tree. These thickets are common in cut over areas and make for difficult access. Exotic forestry has rapidly replaced mixed secondary and native growth in the far southwest, with deer farms and horticulture common at lower altitudes. Dairying and exotic forestry predominate in the southeast. A map of study area's landuse and topography is contained in Appendix 4 (see pocket at the back of thesis).

2.3 HYDRO-ELECTRIC DEVELOPMENT

The Kaimai Hydropower development comprises a system of tunnels, dams and canals that direct the water through a progression of cascade type power stations (see Figure 2.0). The water resources were first developed in 1915 with the opening of hydro station at Omanawa falls with the capacity of 150 KW (capacity was increased to 750 KW in 1921). In 1925 the Mclaren falls station, with a capacity of 2.7 MW at 25.3 meters head, was commissioned. These stations have been superseded by the Mangapapa scheme. Lloyd Mandeno station was commissioned in September 1972 with only diversion of the Mangapapa River. The diversion of the Omanawa River and the Ruakaka stream was completed in July 1974, the Ngatuhoa and Awakotuku streams on December 1974 and finally the Opuiaki River on December 1976. Lloyd Mandeno station has the capacity of 15.4 MW. The 6 MW Lower Mangapapa station opened in 1979, followed by the 20 MW Ruahihi station in 1981 (due to failure in feed canal, station was recommissioned in June 1983). The scheme is owned by the Trust Power, New Zealand. Figure 2.2 shows the hydro lakes, their surface area, storage and elevations. All the hydro lakes in the catchment have very limited storage capacities which can last only few hours.

2.4 HYDROLOGY

The mean annual rainfall is closely related to the elevation of the Kaimai Ranges. In the upper Kaimais annual rainfall averages 2.5 m, reducing to 1.25 -1.5 m in the Tauranga Region (Davis, 1985). Data analysis showed that rain in the Ruahihi area has averaged 1.944 m per year over the last 28 years, with a maximum of 2.624 m in 1971 and minimum of 1.056 m in 1982. Mean annual temperature of the Kaimai – Mamaku region range from 10 –13°C and winds are predominantly from a westerly direction (Kennedy, 1994). Main rivers in the northern Mamaku Plateau are the Opuiaki, Mangapapa and Omanawa. Those in the lower eastern Kaimais are the Te Aruhu and Ngamuwahine, which join to form the Mangakarengorengo River. All the rivers are tributaries of the Wairoa River which flows to the sea at Tauranga.

The ability of Ignimbrites to store rainwater and release it over a long period is well known. From tritium analysis, a residence time of 40 years for groundwater in the study area was calculated, which suggests that the Ignimbrites store large volumes of water, providing a constant base flow even in drought conditions. This is important for the operation of the hydro schemes as the lakes themselves are small and provide little storage. Dell (1982) also calculated a residence time of 50-100 years for groundwater in the Mamaku Plateau. Morgan (1986) found a number of springs and seepages, especially at contacts and in the lower less welded zones of the Mamaku and Waimakariri Ignimbrites. It is quite common to find swampy zones in the area.

Cowbourne (1985) stated that the catchment area is too small for the water volume produced after allowing for evaporation loss. Penstock leakage is precluded and Cowbourne suggests "the area marks an exit point of an extensive hydrologic system involving the Mamaku Plateau and perhaps the Kaimai Ranges". Figure 2.3 shows a typical hydrograph of the catchment for the period of September 25, 1997 to January 01, 1997, showing a high baseflow component. However, the presence of high baseflow indicates a significant groundwater catchment, suggesting the groundwater catchment extend some distance beyond the topographic catchment boundaries.

2.5 GEOLOGY

The Kaimai Ranges are rugged, bush-covered hills with summit heights between 570 - 850 m and the catchment is mostly composed of Mamaku Ignimbrites which vary in their degree of welding and weathering. The Mamaku Ignimbrite was erupted from the Rotorua Caldera (Wilson *et al.,* 1984, Healy, 1992). The Mamaku Ignimbrite is the youngest of the large, welded sheet forming Ignimbrites from Taupo volcanic zone. The Mamaku Ignimbrite was originally dated at 0.14 Ma using zircon fission track dating techniques (Murphy and Seward, 1981). However, Houghton *et al.* (1995) determined a fission track age of 0.22 ± 0.01 Ma, and Shane *et al.* (1994) dated independently at 0.23 ± 0.01 Ma using the isothermal plateau fission track method on glass.

The Upper Mamaku Ignimbrite is generally a fine-grained, light pinkish grey, moderately to poorly welded rock. The Lower Mamaku Ignimbrite is a light grey, fine grained, moderately soft rock containing glassy grey or brown orange pumice. A sequence of pumiceous lacustrine or fluviatile sediments separates the Lower Mamaku Ignimbrite from the underlying Waiteariki Ignimbrite. The paleoenvironment of these sediments is interpreted as a meandering river (flood plain) system associated with lakes and the sequence is widespread throughout the northern Mamaku Plateau. The underlying Waiteariki Ignimbrite is an densely welded, hard, black-grey to reddish brown, glassy dacitic Ignimbrite which is rich in both, crystal and pumice. A layer of ash generally in excess of up to 8 m covers the plateau and overlies the upper Ignimbrite and a deep weathering into a silty clay is characteristic. The regional dip of the Mamaku Ignimbrite is 2 – 4 degrees towards north [(Healy, 1992), (Briggs *et al.,* 1996)].

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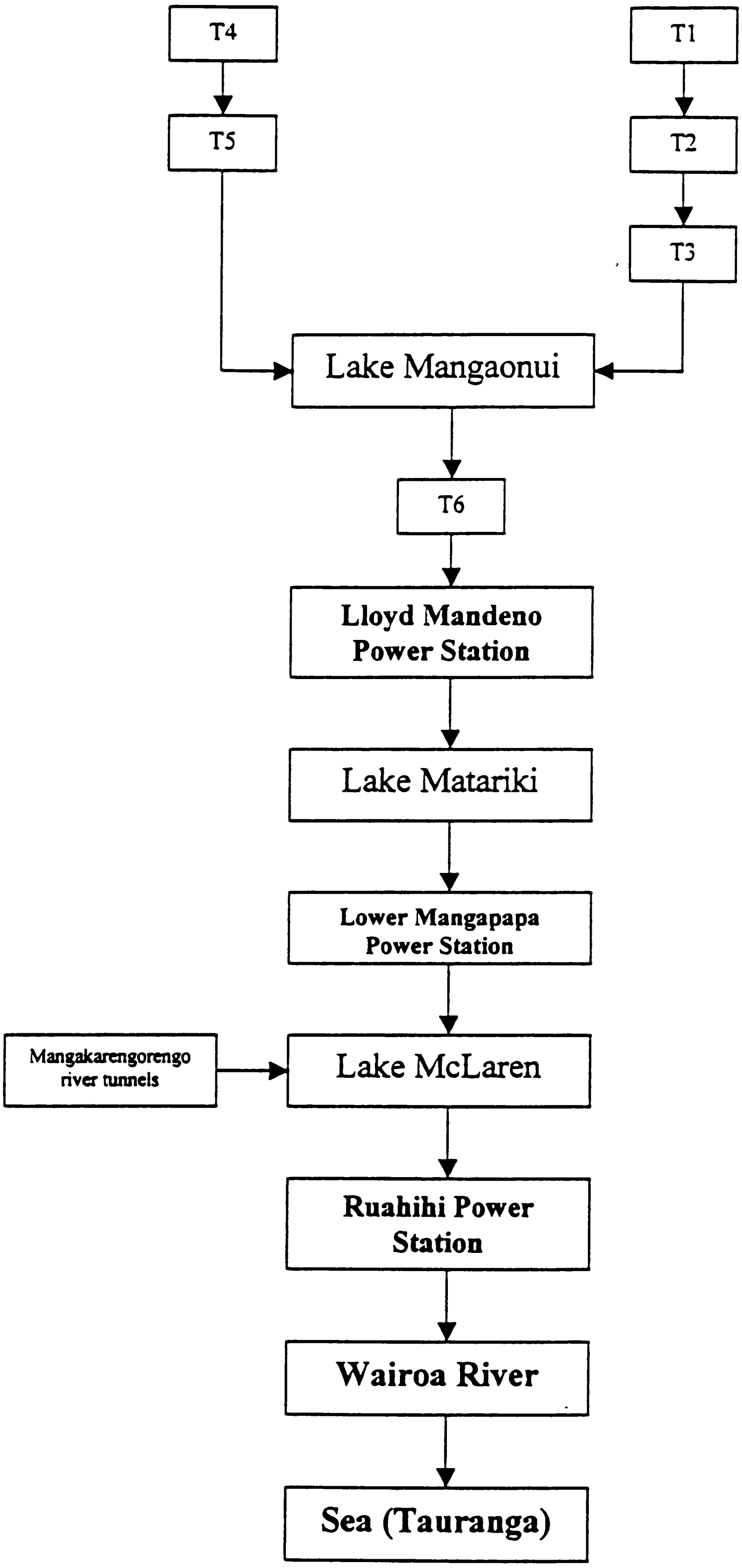

Note: (T1, T2, T3, T4, T5, T6 represents hydro tunnels for Lloyd Mandeno Power station).

Figure 2.0 Schematic diagram showing the dynamic links of the cascade type Kaimai Hydropower scheme.

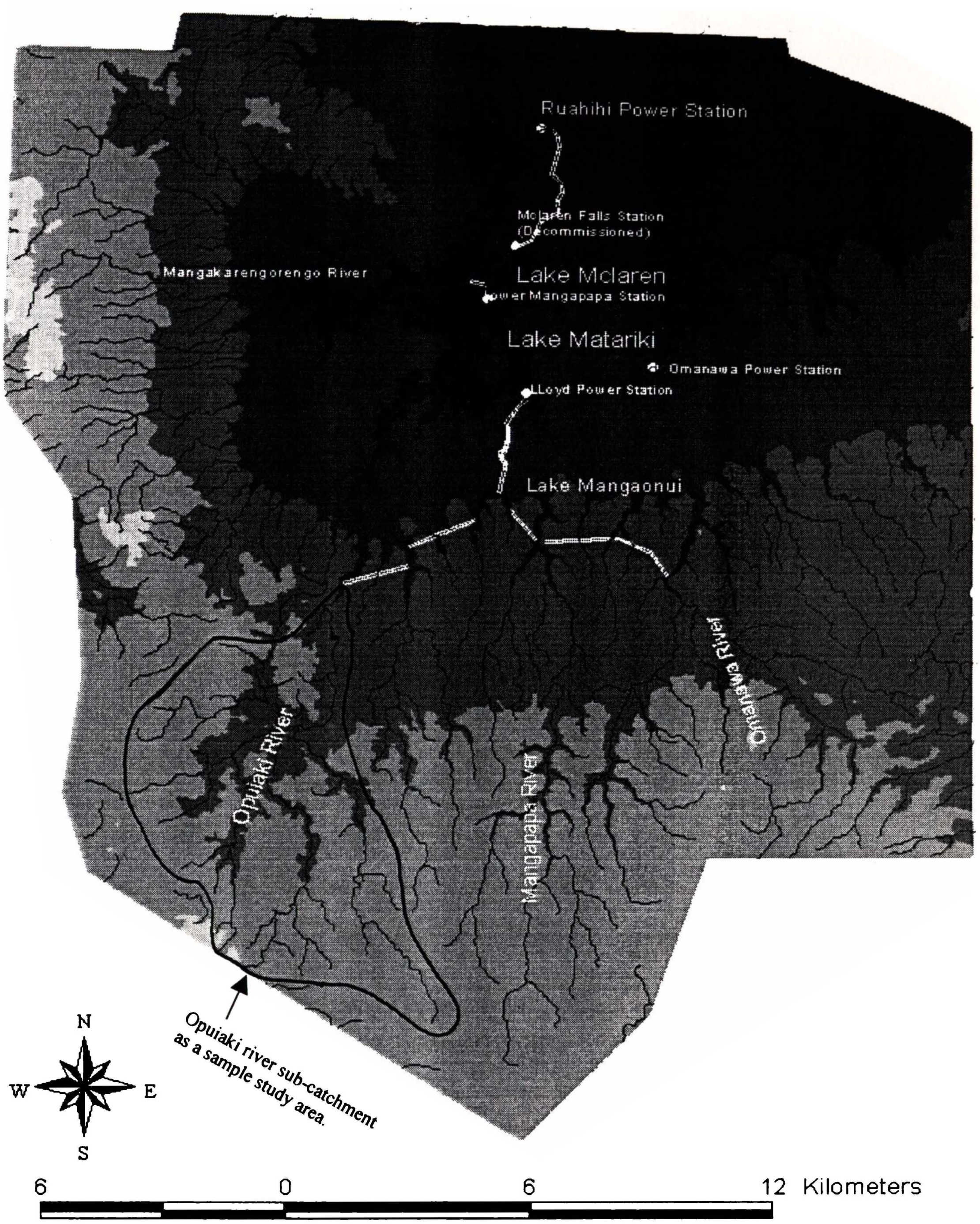

Figure 2.1 Digital Elevation Model of the Kaimai Hydropower catchment. Darker areas show the lower elevations.

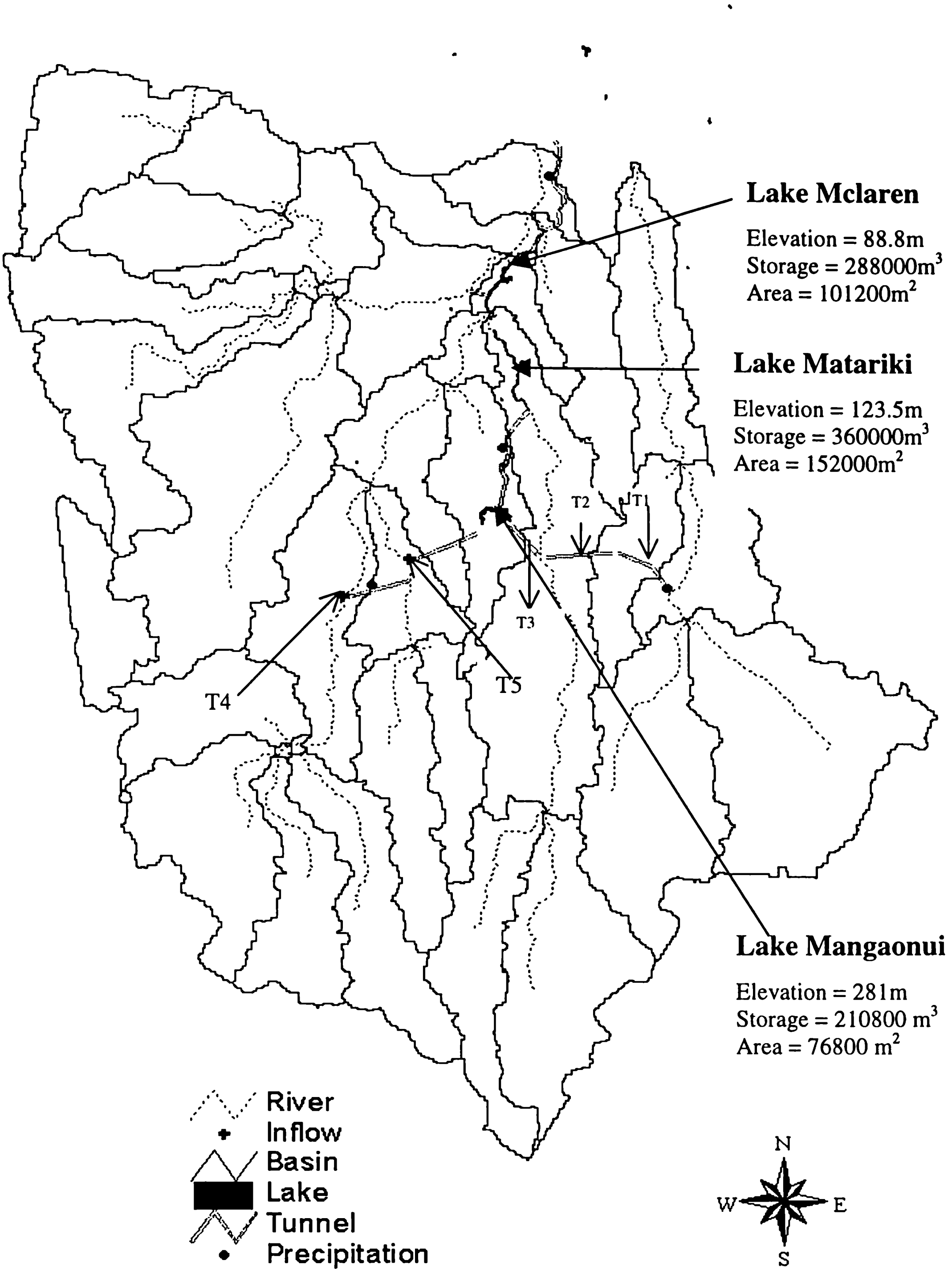

Figure 2.2 The storage, elevation and surface area of all the Kaimai Hydropower lakes.

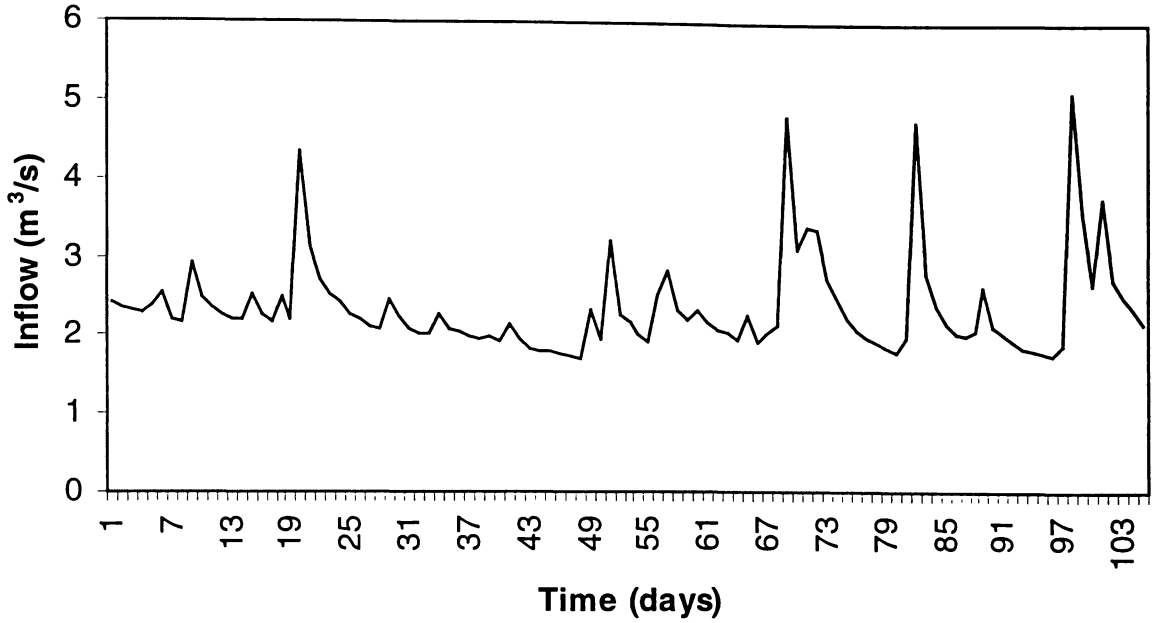

Figure 2.3 A typical hydrograph at T4 streamflow gauging station.

CHAPTER 3

INFLOW FORECASTING AND POWER SCHEDULING OPTIMIZATION

ABSTRACT: Commercial power scheduling optimization of New Zealand hydropower schemes can be very useful in the current environment of competitive power pricing for every half-hour interval. River inflow forecasts are part of the optimization for power generation scheduling when storage is limited. A black box inflow prediction model for the Kaimai Hydropower scheme catchment was developed and tested as a predictive tool which included rainfall forecasts from the NZ Meteorological Service. The model gave good prediction when compared with the observed data. The inflow prediction model was used as an input to the income optimizing power scheduling software (HYMAX) over the winter of 1997. Income produced from the power scheme increased by 7.0% over control room operation for the period of June 24 to 31 August 1997. More data for the summer season is required to find out the exact improvement in the income of the hydropower scheme for that period. However, HYMAX always showed an improvement in income of the Kaimai Hydropower scheme when compared with operators-generated income in its absence. There is a possibility of further improvement in the operation of the Kaimai Hydropower scheme by using HYMAX as an independent real-time predictive tool.

3.1 INTRODUCTION

Before October 1996, the electricity pricing in New Zealand was set by the Electricity Corporation of New Zealand (ECNZ) for the day depending on which station it was running. There was little incentive for small hydro schemes like the Kaimai Hydropower to produce electricity in relation to daily demand. As of 1st October 1996, a new power pricing system, called free spot market, came into being. Under the new pricing, every power plant bids separately per half-hour interval for their power production even if it is operating under the umbrella of a larger organization. There are heavy fines for not meeting the bid. In the new competitive environment, there is a need for small hydro schemes like Kaimai Hydropower to optimize their available resources to maximize income with respect to fluctuating half-hour tariffs. River inflow forecasts are part of the optimization for generation scheduling for storage constrained hydro schemes in order to ensure water is available to meet the power requirements.

Integrated optimization of power scheduling with inflows forecast can provide profit increases to hydropower operations. Studies in New Zealand and overseas have reported the optimization of hydro schemes in different contexts [(Boshier *et al.* 1985), (Halliburton and Sirisena, 1983), Reznicek and simonovic, 1983), Riddell, D. C. (1983), Tejada-Guibert (1990), Broughan, *et al.* (1993)] but little is known about the optimization of a single cascade system like the Kaimai Hydropower scheme where the optimization is directed purely towards profit maximization. The integrated power scheduling system is the computer interface to data management, forecasting, current system status, and optimization routine. Figure 3.1 shows a schematic diagram of a real-time optimization of the Kaimai Hydropower system.

3.2 OPTIMAL POWER SCHEDULING

An optimization algorithm "HYMAX" was developed by Dr. W. E. Bardsley (Department of Earth Sciences, The University Of Waikato) to maximize income from the Kaimai Hydropower project, Tauranga, New Zealand under conditions of non-spillage operation. The basis of "HYMAX" is a special purpose mixed integer-linear programming optimization algorithm for selecting the optimum generating time sequences for small hydropower cascades. The algorithm selects a good on-off sequence of the turbines and their half-hour optimal discharge settings for maximizing the profit under the fluctuating half-hour power prices. The optimization works within a water management framework, with prior specification of desirable end-point water storage volume for the three lakes at the end of a midnight-midnight 24-hour period. The goal is to seek maximum dollar returns from the available water, subject to the constraints of inflows, available stored water in all three lakes, and need to avoid too much on-off generation switching which decreases efficiency. HYMAX makes this decision about the optimal running of the hydro scheme in a real time situation and reduces the human error in the operations process. The software also allows the user to specify which turbines are available at a particular time, which is useful for overhauling and maintenance of the scheme.

3.3 INFLOW PREDICTION

3.3.1 Background to model prediction

Rainfall-runoff models assist in decision making situations, ranging from real-time inflow prediction to flood forecasting. The methods used in estimating runoff from rainfall can be classified as black box and distributed models. Black box modeling uses empirical equations to relate runoff and rainfall, mathematical equations and time series methods fall into this category. Tsykin (1985) developed a simple time series equation "Tsykin equation" which was applied on various catchments throughout Australia to estimate daily runoff. He found his equation gave better results than the time-series equations of other forms. Boughton (1984) and Haan (1972) developed simple conceptual models using three and four parameters in their model equations respectively and found their model results satisfactory. Many authors [(Gan *et al.,* 1990), (Chiew and McMohan, 1993), (Amorocho 1963, 1967), (Bidwell, 1970), (Chiu and Huang, 1970), (Hsu, N. S. *et al.,* 1995), (Bender and Simonovic, 1994)] developed black box models which they found useful for different operational purposes by fitting the data without making any explicit assumptions regarding the internal structure of the system.

In contrast to black box models, distributed models use many spatial parameters in their equations to attempt to simulate the hydrologic processes. Examples include [(Freeze and Harland 1969), (Beven *et al.*, 1987), (Abbott *et al.,* 1986 a, b)]. Data limitations and the difficulty in relating theoretical equations that describe hydrologic processes on small laboratory scales to spatially heterogeneous and time varying systems in a real catchment may not justify the use of these models to estimate runoff (Grayson *et al.,* 1993). Chiew *et al.* (1993) compared six rainfall-runoff modeling approaches by simulating flows at different time intervals (daily, monthly and yearly) in eight unregulated catchments of Australia. They found that the simple black box models gave comparable results to that of complex conceptual models. They further stated, the simpler methods may be preferred to estimate catchment runoff as it is much easier to use simple approaches than a complex conceptual model.

3.3.2 Model utilized

In this research, a three parameter, single store, black-box rainfall-runoff model (Figure 3.2) was developed for 24-hour stream inflow prediction of the Kaimai Hydropower scheme which was used as an input to the Kaimai Hydropower scheduling software. The model parameters were estimated by minimizing a fit criterion defined as the sum of the absolute differences between observed and predicted inflows. The minimization algorithm adopted was that of Rosenbrock (1960) and the parameter estimation procedure was applied to discharges recorded at half-hour intervals. Initially, rainfall weighting were used as variables with the optimization technique but there was little improvement in fitted results suggesting that a simple spatial average of the rainfall would be sufficient. It was thus decided to remove the weights from the equation for simplicity. The rainfall used in the model is a forecast from the New Zealand Meteorological Services.

The inflow prediction for Lake Mangaonui, Lake Matariki and Lake Mclaren from tunnel (T4 & T5) inflows was obtained using the relationships mentioned in the Appendix-1. T4 and T5 are the name of the inflow stations as shown in Figure 2.2

The model equations used are:

$$\hat{Q}_t = \beta S_t + \gamma \qquad (3.1)$$

$$\hat{Q}_{t+1} = \beta S_{t+1} + \gamma \qquad (3.2)$$

$$S_{t+1} = P(S_t + R_{t+1}) \qquad (3.3)$$

$$S_t = \frac{\hat{Q}_t - \gamma}{\beta} \qquad (3.4)$$

Where,

S_t = Current storage in a single water store at the start of the half-hour interval t.

γ = Baseflow constant (the baseflow constant is the contribution of baseflow into the system, and is assumed not to change).

t = Half-hour interval

R_t = Forecast rainfall in half-hour time interval

$\hat{Q}_t$ = Predicted inflow discharge (available over the half-hour time interval t) used for first calculation and is the current inflow measured from recording apparatus.

P = Proportional loss (for this single store model, the proportion loss represents the proportion of the water in the store which is lost from store per time interval to evaporation and ground water and does not go into model-generated discharges).

β = Scale parameter (the scale parameter is introduced in the model equation to adjust rainfall for any spatial or topographic variations).

Substituting for S_t in (3.3) gives

$$S_{t+1} = P(\frac{\hat{Q}_t - \gamma}{\beta} + R_{t+1}) \tag{3.5}$$

and substituting for S_{t+1} in (3.2) gives the recursive discharge prediction equation

$$\hat{Q}_{t+1} = P(\hat{Q}_t + \beta R_{t+1}) + \gamma(1-P) \tag{3.6}$$

Following the fitting procedure to obtain numerical estimates for the parameter values, the recursive discharge prediction equation for the T4 inflow station is

$$\hat{Q}_{t+1} = 0.9951(\hat{Q}_t + 0.0407 R_{t+1}) + 0.0105 \tag{3.7}$$

$$= 0.9951\hat{Q}_t + 0.0405 R_{t+1} + 0.0105 \tag{3.8}$$

The recursive discharge prediction equation for T5 inflow station is

$$\hat{Q}_{t+1} = 0.9982(\hat{Q}_t + 0.0096 R_{t+1}) + 0.00535 \tag{3.9}$$

$$= 0.9982\hat{Q}_t + 0.0096 R_{t+1} + 0.00535 \tag{3.10}$$

Both model equations for T4 and T5 inflow stations were validated using independent sets of data. Figures 3.3 and 3.4 show the comparison of validated inflow predictions and observed inflows at T4 and T5 streamflow gauging stations.

The inflow prediction shows a good match with the observed data suggesting the model usefulness to be as a predictive tool. The results of a sensitivity analysis of the model parameter values are given in Appendix-2.

3.4 EVALUATION OF THE POWER SCHEDULING OPTIMIZATION SOFTWARE (HYMAX)

The power scheduling optimization software for the Kaimai Hydropower scheme (HYMAX) was evaluated in order to estimate the increase in income (if any) of the hydropower scheme through its use. The real power of HYMAX is its ability as a real-time operational tool. The software was developed in 1997 and was made available in June to the Kaimai Hydropower scheme. In order to find any improvement in the operation of the Kaimai Hydropower scheme through HYMAX's use, the performance of the operators of the hydropower scheme needs to be evaluated by looking that how well the operators would have run the scheme in absence of the HYMAX. The HYMAX software including the inflow prediction model as input was installed at the Trust Power Ltd., Tauranga (Owner of the Kaimai Hydropower scheme) in first week of the June 1997. The person in charge (Mr. Simon Neale) used HYMAX as a learning tool for approximately two weeks and started instructing the operators about HYMAX decisions regarding the operation of the scheme in the last week of June 1997 (Mr. Simon Neale, Pers. Com.).

An inspection of operating history revealed a significant shift in the operating sequence of the power station from June 25 1997 as shown in Figure 3.5. The change is measured by using the cumulative kilo watt hours (kwh) data (midnight to 5am) of the Ruahihi power station. After 25 June 1997, producing lower kwh during the time period (midnight to 5am) but higher power production (kwh) the rest of the time (5am to the following midnight). The overall Ruahihi power production as explained in Figure 3.6, remains the same, showing that there was no significant change in the hydrology of the area, but simply a change in operating mode. Price data analysis also showed consistently higher prices after 5am over the period of the transition to the new operating mode, so the change of mode was not simply an effect of the operators responding to a different daily price structure. The six days (30 June, 3, 4, 5 and 21 August and 2 September 1997) with very high electricity prices were excluded from the analysis to avoid any unrealistic income estimation.

As shown in Figure 3.6 and Figure 3.7 there was no significant change in the hydrology and power prices for the analysis period (4 June to 31 August 1997), so any change in the operating mode of the Kaimai Hydropower scheme appears to be due to the influence of the optimizer.

It was important to find out the performance of the operators for the analysis period, by estimating what income the operators would have achieved using their own operating decisions for the hydropower scheme. Two prediction functions to evaluate the performance of the operators were developed, one for the winter season using power production and price data (4 –24 June 1997), and one for the summer season using 1 March to 30 April 1997 data. The winter seasons operators' performance predictor is explained by the following equation, which is used to estimate the dollar amount generated by the operators in absence of HYMAX's use:

Predicted operators return (\$) for the day = $1.039593(X_1)-9112.579542(X_2)-1637.8234$

Where X_1 is a function of total power output and electricity price values for the day. X_1 represents an ideal income under normal operating conditions, based on a hypothetical hydropower scheme with few real-world constraints. In the hypothetical scheme, the turbines are assumed to always run at the most efficient rate (or be switched off), regardless of flow conditions. For a given power station with a total specified energy output in a particular day, the income for that hypothetical station is defined by running the turbine(s) at the optimal rate for half-hour with the next highest price, and so on until the specified energy output is matched. X_1 is then obtained as this income summed over the three hypothetical stations. In the event of high flow situations when there would be energy "left over" from the half-hour partitioning process, the station income is defined to be the product of total energy generated and the mean of the 48 half-hour prices for the day concerned. X_2 is the mean absolute deviation between consecutive half-hour price values. The operators' function using the 4-24 June 1997 data is shown in Figure 3.8 showing a strong correlation with correlation coefficient (r) of 0.99. The data for the period of 25 June to 31 August 1997 (winter) was used to generate income of the operators driven hydropower scheme in the absence of HYMAX use. The increase in dollars amount in the operation of the Kaimai Hydropower was quantified by calculating the cumulative residuals from June operator function for the period of 4 June to 5 October 1997 (Figure 3.9). It can be seen that cumulative residuals show a steady increasing trend after June 25 1997, supporting the benefit of HYMAX use. Due to commercial sensitivity, the dollar amount used in Figure 3.9 is arbitrary and does not reflect any real increase in the income of the hydropower scheme.

Data analysis showed that the operators generated income would be 7.0% less than the income generated using the HYMAX. In other words, there is an improvement of 7.0% in the income of the hydropower scheme for the analysis period achieved by using the optimizer (HYMAX).

A summer prediction function by using the power output and price data for the period of 1 March to 30 April 1997 was also developed. The equation of the summer operator function is as follows:

$$\text{Predicted operators return (\$) for the day} = 1.0572(X_1)-3362.106(X_2)-1598.18$$

The coefficients of the summer prediction function suggest that the operators performed better in the summer season when the summer income was compared with the winter season in the absence of HYMAX use. One possible explanation may be the fact that they do not have to handle load constraints in summer. In the absence of the summer power output and price data, operators' summer prediction function was applied to the data of 1 September to 5 October 1997, to check the results. The results showed estimated operators income of the hydropower scheme which was 4.7% less than actually achieved. However, to verify an accurate degree of income improvement during summer (using the summer prediction equation) more data is required for this summer, provided it is known that the optimizer (HYMAX) is being used.

3.5 CONCLUSION

A black box inflow prediction model for the study area was developed and tested as a predictive tool by including a rainfall forecast from the New Zealand Meteorological Services, model gave a good prediction when compared with the observed data. The inflow prediction model was used as an input to the power scheduling software (HYMAX) in order to evaluate the performance of the Kaimai Hydropower scheme. The data analysis for the evaluation of HYMAX concluded that there is clear evidence in the improvement of the operation of the Kaimai Hydropower scheme by using the power scheduling optimization software. The winter season data analysis showed a significant improvement in the income of the Kaimai Hydropower scheme by 7.0%, achieved through instructing the operators about HYMAXs decisions. This improvement may be less in the summer season, and more data is required to quantify the actual increase in the income for the summer season provided HYMAX is being used in decision making.

HYMAX always showed a significant improvement over the control room operation for the analysis period. HYMAX use has demonstrated the benefit of optimizing the storage constrained schemes like the Kaimai Hydropower scheme in a competitive power-marketing environment. It is worth noting that all these improvements in operation of the hydropower scheme are by instructing the operators about HYMAXs decisions. As mentioned earlier, the real power of HYMAX is its ability as a real-time prediction tool. The data analysis results indicated there is still a possibility of some improvement in operation of the Kaimai Hydropower scheme by using HYMAX as an independent real-time prediction tool.

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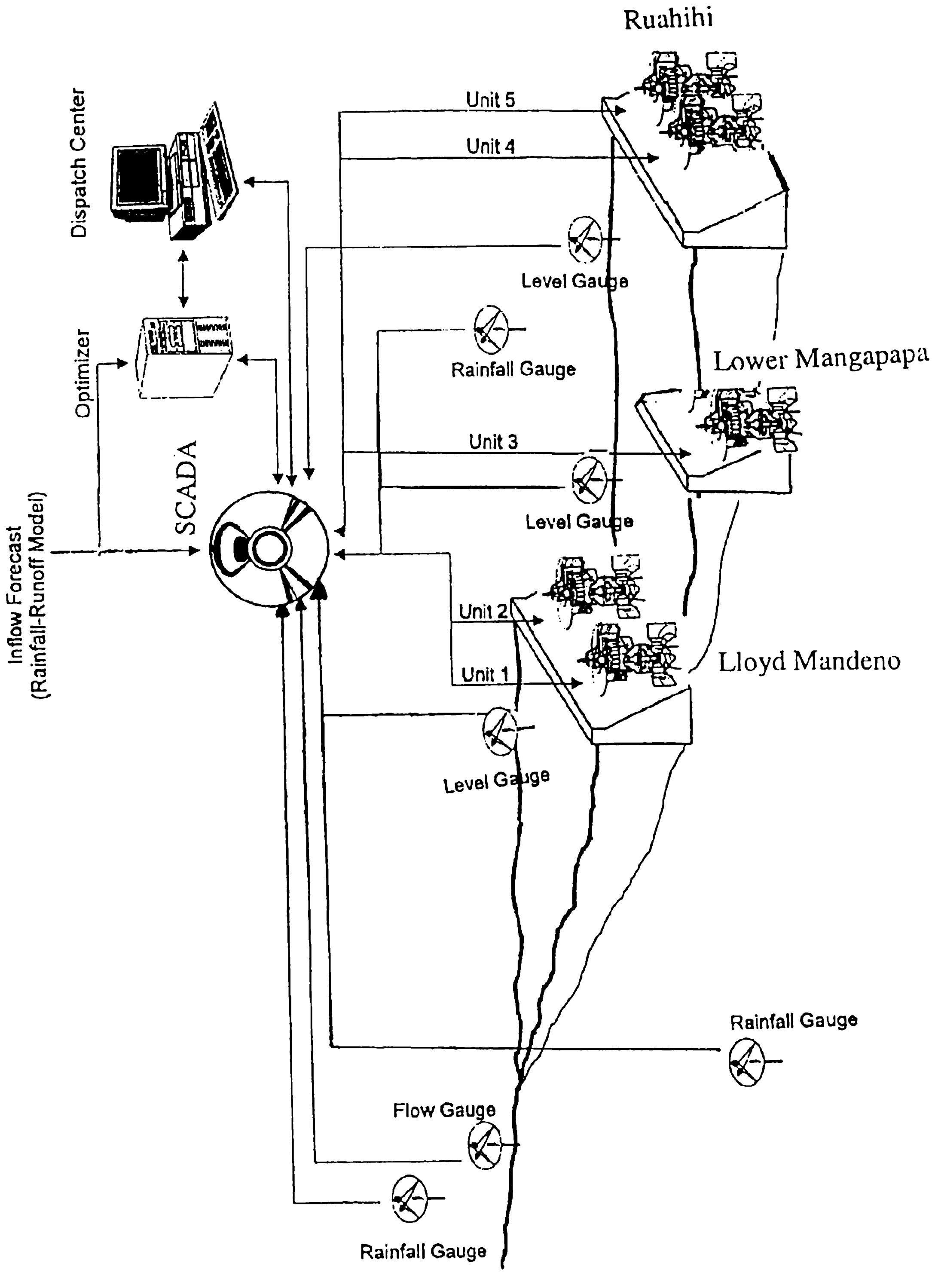

Figure 3.1 Schematic diagram of the Kaimai Hydropower real-time optimization system, (After Worley Consultants, 1996).

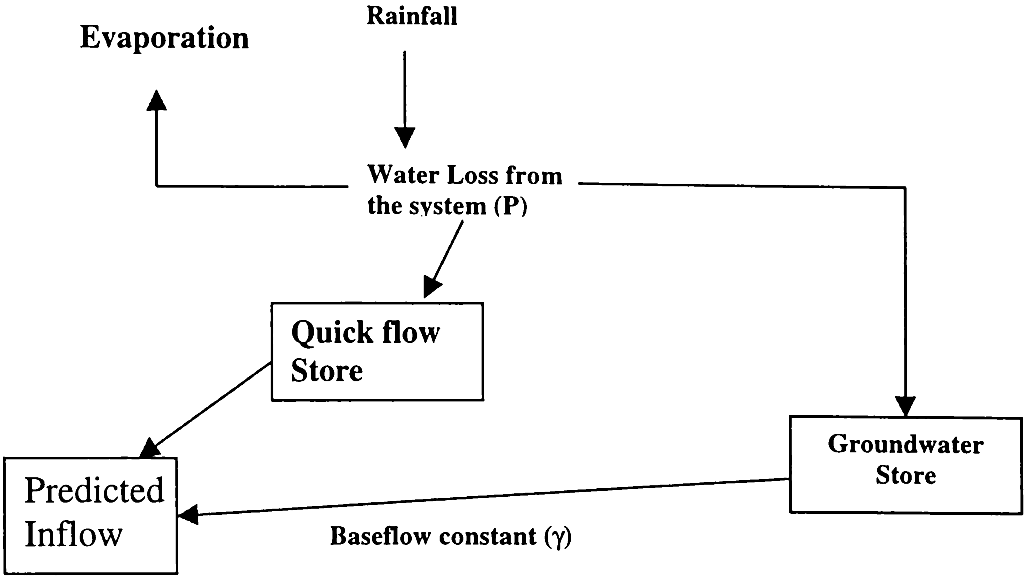

Figure 3.2 Structure of the inflow prediction model.

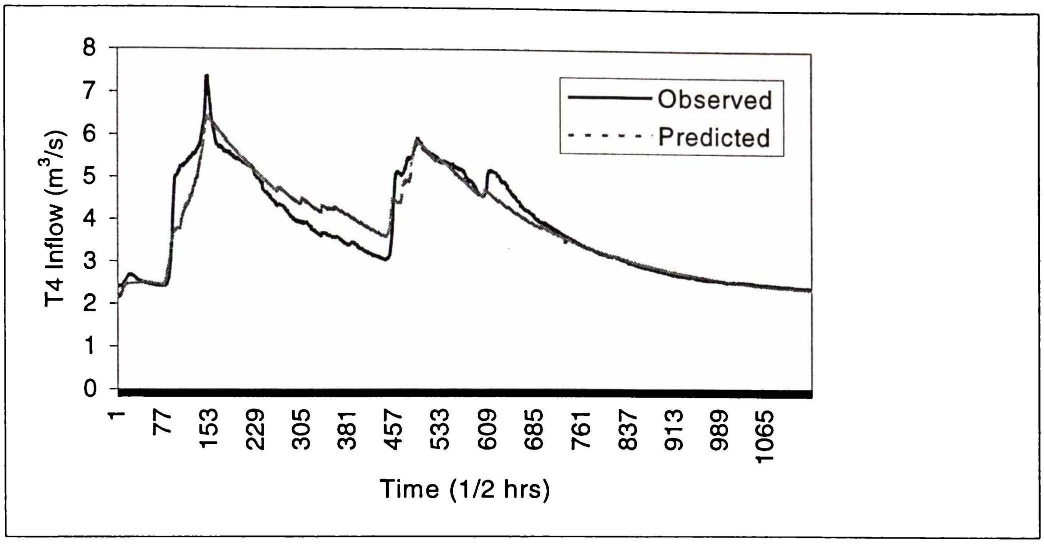

Figure 3.3 Inflow prediction of T4 streamflow gauging station.

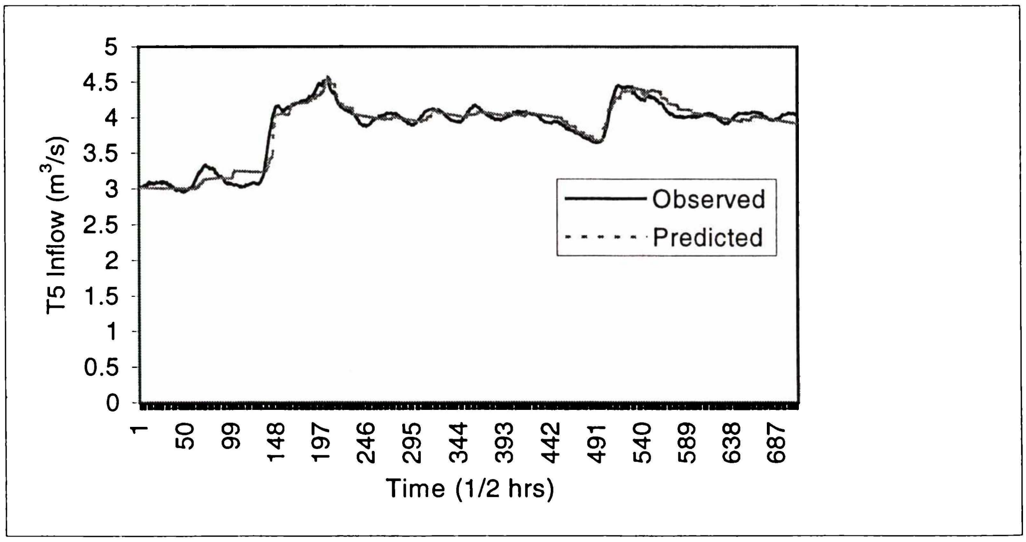

Figure 3.4 Inflow prediction of T5 streamflow gauging station.

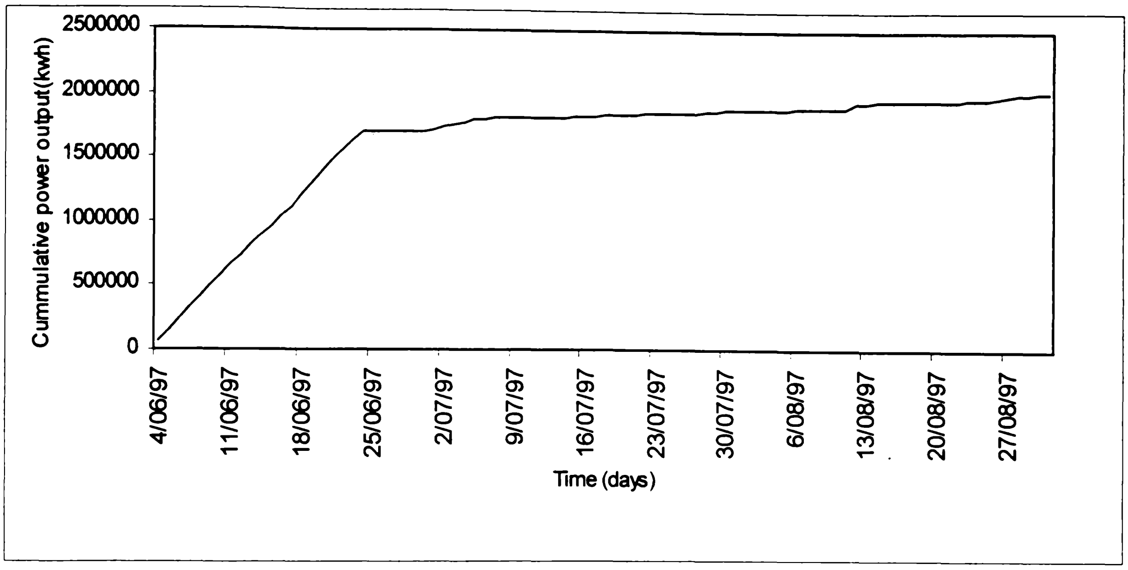

Figure 3.5 Change in operating mode of the Kaimai Hydropower scheme from 25 June 1997 by using midnight to 5am data.

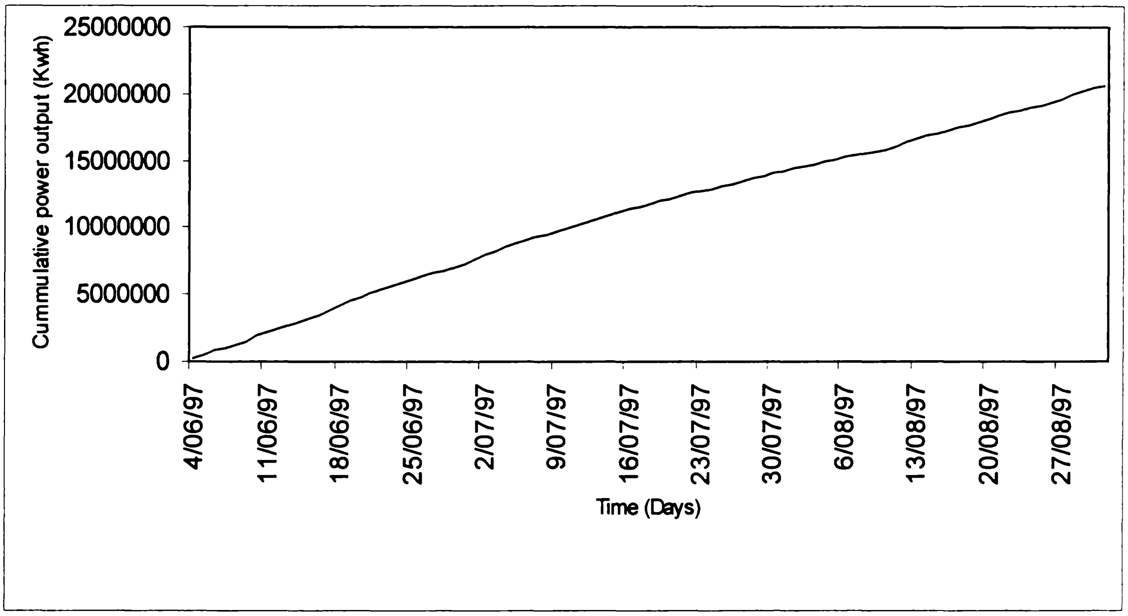

Figure 3.6 Overall production of the Ruahihi power station using data for the full day.

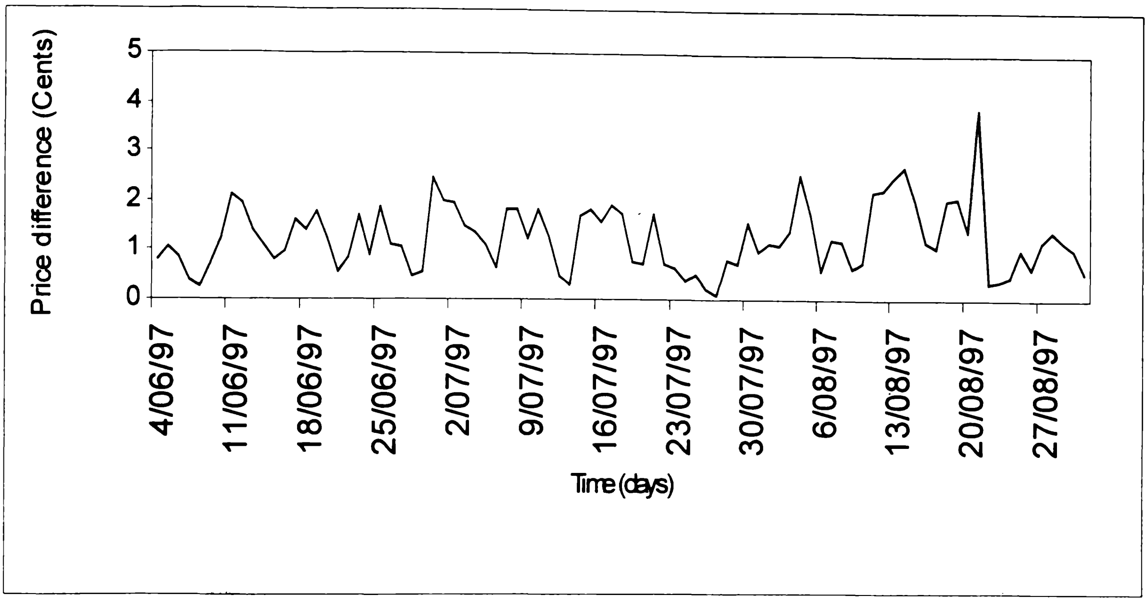

Figure 3.7 Electricity price variations for the period of 4 June to 31 August 1997 by using the data showing the difference of mean of the first 5 hrs and mean of the last 19 hrs for the day.

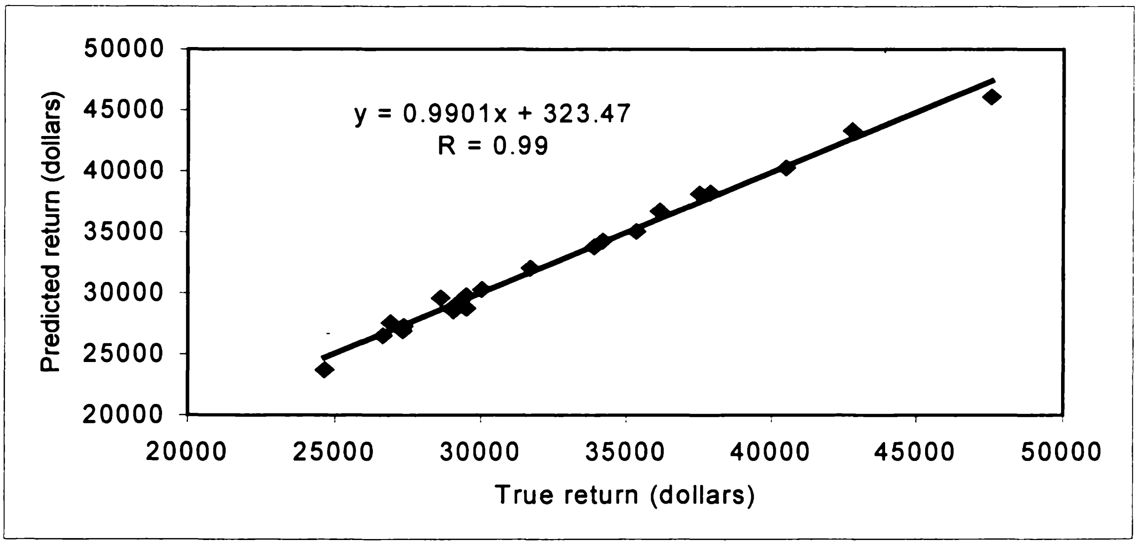

Figure 3.8 Operators function equation. for the period of 4-24 June 1997, showing the strong correlation..

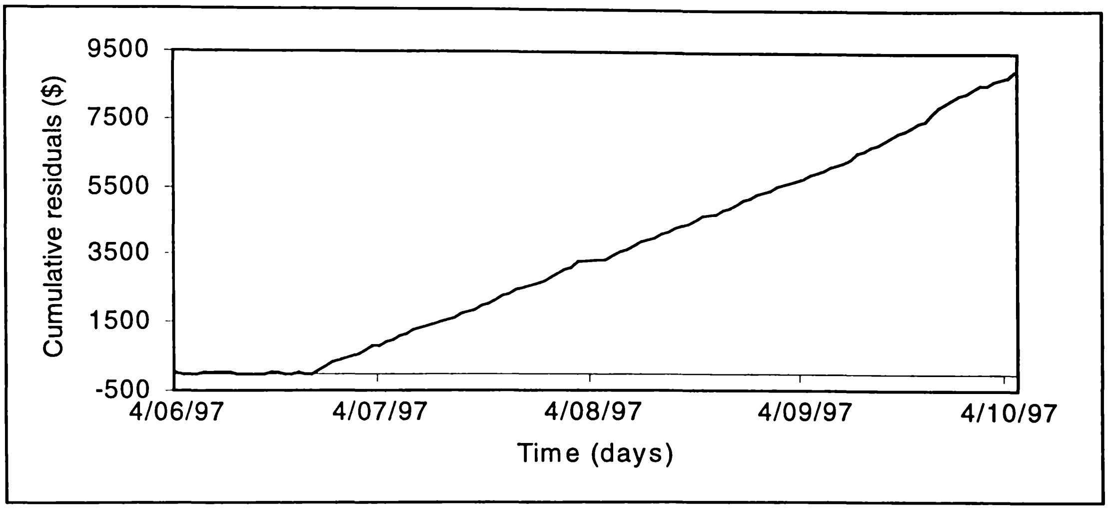

Figure 3.9 Cumulative residuals (dollars) from June operator function for the period of 4 June to 5 October 1997 (excluding high price days; 30 June, 3,4,5 and 21 August and 2 September 1997).

CHAPTER 4

THE EFFECT OF ESTABLISHING PINUS RADIATA ON WATER YIELD

ABSTRACT: *The Kaimai hydropower catchment experienced progressive landuse change from native forest to pinus radiata plantations since 1982. However, there was no detectable reduction in annual or seasonal water yield, on the basis of analysis of electrical power output as a proxy for catchment water yield. The minimal impact is attributed in part to the fact that fully developed radiata pine and the native forest vegetation appear to have similar water loss characteristics. Also, the incremental nature of the landuse change meant that at any one time only a small proportion of the catchment was in a clear-felled state, causing a small water yield increase after landuse change for winter and spring seasons.*

4.1 INTRODUCTION

Forestry has contributed substantially to the economic growth of New Zealand over the past 60 years, with 50,000 ha of afforestation every year on average. Most of the country's forested areas consist of exotic forests (of non-native species), covering more than 1.3 million hectares (The Ministry of Forestry, 1994). The introduction of plantation forests on land previously under pasture has served to protect many unstable areas from erosion (Fahey, 1994). Although hydrologists agree that large-scale conversion of one vegetation type to another could influence stream flow characteristics, more information is desirable about the magnitude of these changes in New Zealand (Fahey and Rowe, 1992).

The purpose of this paper is to study the effect of landuse change on water yield of the Kaimai Hydropower catchment, New Zealand. Several parts of the catchment have undergone changes in landuse since 1982 (see chapter 2 for study area details).

4.2 PREVIOUS STUDIES

Studies in New Zealand and overseas agree that water yield tends to increase after forestry felling, and decreases after planting. Jackson and Fahey (1993) in their study near Nelson, New Zealand, observed that forest harvesting increased the frequency of flood peaks by three-fold. However, as Bosch and Hewlett (1982) concluded, the association between forestry harvests and water yield appeared to depend on rainfall, and is therefore more marked in high rainfall areas. The spatial distribution of forest vegetation within a catchment was also found to be important, as forested areas affect flow levels differently according to their location. Forests in groundwater recharge areas of a catchment may have a greater impact on the flow regime than forests in the discharge areas (Jackson and Fahey, 1993). Tables 4.1 and 4.2 list a number of further studies on the effect of land clearance and afforestation on water yield.

The magnitude of water yield also varies with the type of vegetation in the catchment. Dons (1986) and Fahey (1994) concluded that the extensive conversion, in New Zealand, from native forest and scrub to radiata (Monterey) pine has not altered catchment water yields significantly because of their water-interception similarities. Dell (1982) reported that due to the Mamaku region's geology, the higher groundwater recharge rates, and interception similarities, there should be no major variations in water yield when converting from native to exotics. These conclusions correspond with similar findings reported earlier by Pearce and Rowe (1979), who had observed minimal change in evapotranspiration loss, when converting indigenous mixed forest to *pinus radiata* because of interception similarities of both species.

4.3 DATA ANALYSIS

The OVERLAY and EDITTOOLS functions of the geographic information system ARC/INFO were used to investigate the spatial extent of landuse change in the Kaimai Hydropower catchment. Approximately, 6323 ha (out of a planned total of 10635 ha) have been planted todate with pine trees since 1982 in the Kaimai – Mamaku region. In other words 60% of the planned forest region has experienced landuse change. In the absence of stream flow data for the study area, power generation data were utilized to estimate monthly average natural river discharges.

Table 4.3 compares seasonal and annual rainfall for the period 1968-81 (before afforestation was introduced) and 1982-95 (following the landuse change). On the basis of an unpaired t-test (statistical analysis), there was no significant difference before and after landuse changes were examined. River discharge data were not available before 1981, so it was not possible to compare rainfall records with the power records for that period.

The Lloyd Mandeno and Lower Mangapapa power stations had river discharge values available from 1981; and similar data was available for the Ruahihi power station since 1984. The river discharges and rainfall data were divided into two periods, 1982-1989 and 1990-1995, for the Lloyd Mandeno and Lower Mangapapa stations, 1984-1989 and 1990-1995 respectively for the Ruahihi station. It was assumed while making this comparison, that the period 1982-89 was a time when the area had been clearfelled initially and the trees were young, and 1990-95 was a time when the trees had started growing and were making hydrologic impact in the catchment. As the Lloyd Mandeno station had the longest available annual records of discharges and rainfall, water loss for that period was estimated for the lake Mangaonui catchment by grouping the data into three periods 1975-81 (before landuse change), 1982-89 (during landuse change) and 1990-95 (after landuse change). Seven years of simple water balance showed a water loss of approximately 50% (1m/year). Similar results were achieved by calculating the discharge to rainfall ratios for the comparison period. By using the evapotranspiration (ET) value of 1.0 m/year for the study area [(Wells, 1974); (Pearce, 1980); (Dons, 1981); (Dell, 1982)], very little water remained for groundwater recharge. Tritium analysis of the water in the study area showed that the water is 40 years old, which explains the presence of high baseflow indicating a significant groundwater catchment, suggesting the groundwater catchment extend some distance beyond the topographic catchment boundaries.

Finally, the Ruahihi discharges were utilized because the other power station experienced bypassing during high flow conditions. A regression analysis was carried out between rainfall and Ruahihi discharges estimated from power generation data on annual, seasonal and average seasonal values. Initially no impact was detected. The data was then reanalyzed using the test for variable intercept under different scenarios of separate slope and intercept, common slope and separate intercept, common slope and intercept. These analyses revealed that there was a significant increase in outflows for the spring and winter seasons. This is because of high rainfall in spring and winter as compared to other seasons. The regression analysis results for the winter and spring seasons are shown in Figures 4.1 and 4.2.

4.4 CONCLUSION AND DISCUSSION

Several previous studies have noted that the magnitude of the effects of forest changes on streamflow depends on the rainfall regime, the percentage of the catchment area affected by forest changes, and the location of the forest changes within the catchment, especially with regard to stream locations and spatial distribution of the precipitation. The magnitude of water yields also varies with the type of vegetation in a catchment.

The analysis of electrical power output as a proxy for catchment water yield could not detect any reduction in annual or seasonal water yield of the Kaimai Hydropower catchment. The minimal impact is attributed in part to the fact that fully developed *pinus radiata* and the native forest vegetation appear to have similar water loss characteristics as reported above. Also, the incremental nature of the landuse change meant that at any one time only a small proportion of the study area was in a clear-felled state, causing a small water yield increase after landuse change for winter and spring seasons. The increase in spring and winter outflows can be attributed to the impact of the immediate decrease in interception loss due to clearfelling. The average total power production for the year 1984-89 (159.28 GWH) was compared with the 1990-95 (162.42 GWH) data (as all the hydro stations were functional in 1984). The slight increase in the systems average total power production before and after landuse changes (159.28 GWH and 162.42 GWH respectively) can also be attributed to increases in spring and winter quick flows, as the baseflow component is fairly constant.

Based on the data analysis, it is concluded that there is no evident reduction in annual and seasonal discharges. In the future, provided the present structure of the hydropower generation system and catchment rate of incremental landuse change remain the same, there may be little or no impact of landuse changes on river resources of the Kaimai Hydropower catchment. However, it is recommended, where possible, incremental catchment landuse change is the more desirable option.

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Location	Area Cleared (%)	Precipitation (mm)	Water Yield Increase (mm/yr)	Reference
Western Australia	100 (Native)	1200	570	Williamson *et al.*, (1987)
Western Australia	100 (Native)	-	120	Ruprecht & Schofield (1989)
South Africa	50-60 (Exotic)	1475	280	Smith (1991)
Puketurua, NZ	100 (Manuka)	1565	172	Waugh (1980)
Hunua Range, NZ	100 (Manuka)	1880	179	Herald (1979)
Moutere 8	100 (Gorse)	1069	168-180	Duncan (1980)
Moutere 13	100 (Gorse)	1069	283-302	Duncan (1980)
Maimai 5	100 (Native)	2625	550	Rowe & Fahey (1991)
Maimai 8	95 (Native)	2827	260	Rowe & Fahey (1991)
Maimai 13	90 (Native)	2625	200	Rowe & Fahey (1991)
Maimai 7	100 (Native)	1930	650	Pearce *et al.*, (1980)
Maimai 9	80 (Native)	1930	540	Pearce *et al.*, (1980)
DC 1	83 (Big bush)	1305	373	Pearce *et al.*, (1982)
DC 3	74 (Big bush)	1305	331	Pearce *et al.*, (1982)
DC 4	94 (Big bush)	1305	420	Pearce *et al.*, (1982)

Table 4.1 Studies on impacts of land clearance on water yield.

Location	Features	Water Yield Decrease (mm/yr)	(%)	Time (Yrs)	Reference
South Africa	98% *pinus radiata*	350	-	12	Wyk (1987)
South Africa	57% *pinus radiata*	200	-	16	Wyk (1987)
U.S.A.	Coweeta catch.	660	-	-	Bosch and Hewlett (1982)
Around the world (International experiment)	Conifers (in catchments of 0.01-24 km^2), pine and eucalypt forests	40 mm per 10% change in forest cover	-	-	Bosch and Hewlett (1982)
Maimai 8, NZ.	95% *pinus radiata*	260	-	7	Rowe & Fahey (1991)
Maimai 13, NZ.	90% *pinus radiata*	200	-	2	Rowe & Fahey (1991)
Maimai 5, NZ.	100% *pinus radiata*	730	-	7	Rowe & Fahey (1991)
Hunua Ranges, NZ.	100% *pinus radiata* (.15 km^2)	-	30%	7	Herald (1979)
Moutere, NZ.	100 % *pinus radiata*	182-195	-	8-10	Duncan (1980)
Moutere, NZ.	100% *pinus radiata*	-	70%	-	Duncan (1993)
Moutere, NZ.	20% of the 1.4 km^2 *pinus radiata*	104	-	8-9	Smith (1991)
Nelson, NZ.	Tree and gorse	-	41%	6	Duncan (1980)
Purukohukohu, NZ.	Pine-trees replaced pasture,0.34 km^2	410	-	7	Dons (1981)
Tarawera, NZ.	28% of the 906 km^2 *pinus radiata*	379 (of which 225mm was attributed to decrease in rainfall)	-	17	Dons (1986)

Table 4.2 Studies on impact of afforestation on water yield.

Seasons	Mean Monthly Rain (mm), 1968-81	Mean Monthly Rain (mm), 1982-95
Spring (Sep – Nov)	178 ± 19.1	196 ± 33.5
Summer (Dec - Feb)	145 ± 28	152 ± 32
Autumn (Mar – May)	198 ± 39	162 ± 34
Winter (June – Aug)	215 ± 18.4	194 ± 28.5
Annual	2268 ± 257	2065 ± 284

Table 4.3 Seasonal and annual comparison of monthly rainfall.

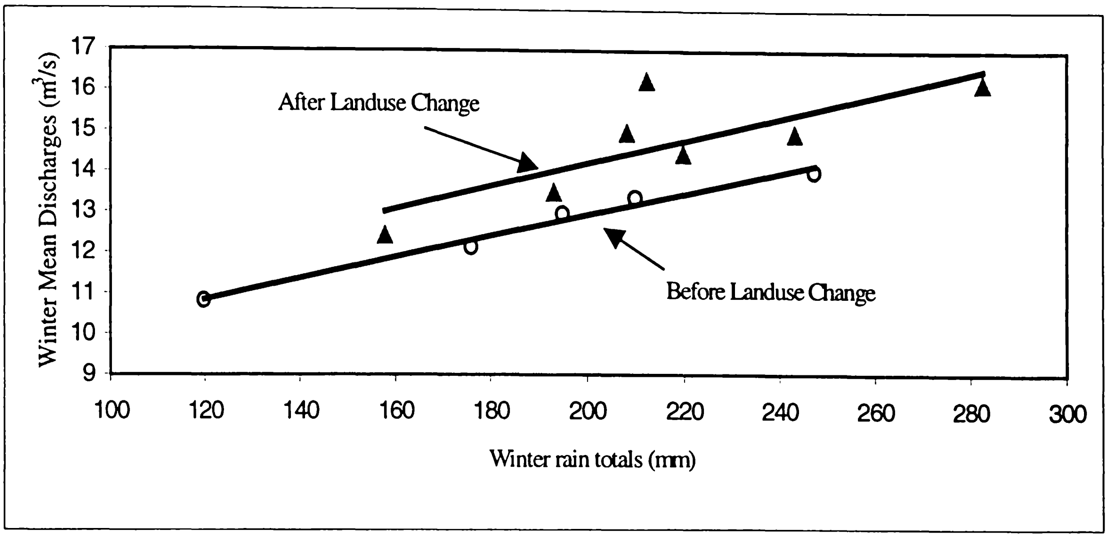

Figure 4.1 Regression analysis of Ruahihi discharge data before and after landuse changes (winter).

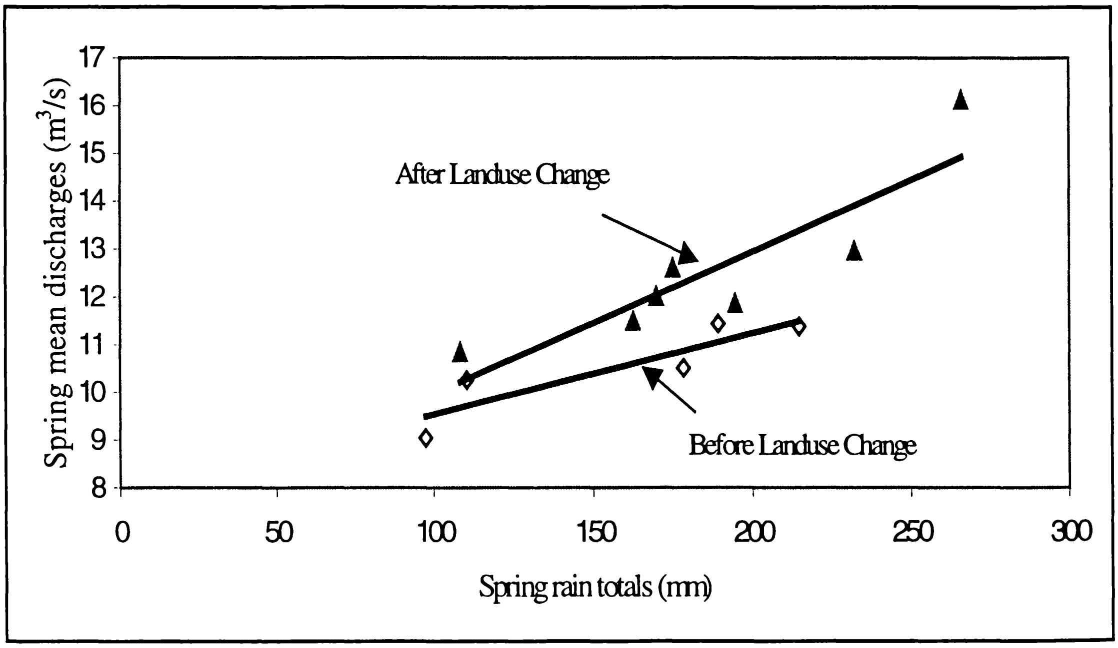

Figure 4.2 Regression analysis of Ruahihi discharge data before and after landuse changes (spring).

CHAPTER 5

HYDROLOGIC MODELING AND GIS – AN OVERVIEW

ABSTRACT: Researchers have used GIS as an aid for hydrologic modeling where there is a requirement for digital representation of spatial watershed characteristics. This paper overviews i) past efforts and current trends in using GIS to perform hydrologic analysis. ii) errors involved in using digital data and their effects in hydrologic modeling results. iii) limitations of GIS use in hydrologic modeling. Despite of the few concerns of GIS use in hydrology at present, spatial aspects of hydrology are likely to become integrated into a GIS framework in future.

5.1 GEOGRAPHIC INFORMATION SYSTEMS

Over the last decade the use of GIS has grown significantly in hydrologic and environmental studies. Different workers have used GIS differently according to their needs. Consequently many definitions of GIS have developed. The purpose of this study is to review the term "GIS", its application in the field of hydrology, advantages and limitations of its use in hydrology, and the latest developments in the field of spatial hydrologic modeling using GIS. Another aim of this paper is to provide bibliography for the users in the field of hydrologic modeling using GIS.

A comprehensive GIS can be considered as an organized collection of computer hardware, software, geographic data and techniques designed to efficiently capture, store, update, manipulate, analyze and display all forms of geographically referenced information (GRID/UNEP, 1993). The food and agriculture organization of United Nations (1988) defined the term "GIS" as a computerized information storage, processing and retrieval systems that have hardware and software specifically designed to cope with geographically referenced spatial data and the corresponding attribute information.

The term GIS can be defined as internally referenced, automated spatial information system designed for data management, mapping and analysis (Berry, 1990). Berry points out that spatial information is either spatially aggregated e.g. (soil classification schemes) or geographically referenced. This later class of data is spatially coherent, resulting in maps. These mapped data can be managed by automated or non-automated means and spatial reference may be external or internal to the spatial information system. According to Berry, an externally referenced system uses a computer to store information on various geographic units, however, the location of each unit is indicated as a separate map. By contrast, internally referenced systems have an automated linkage between the data (thematic attribute) and the location of the data (spatial attribute). These digital maps form the basis of true GIS systems.

The above description by Berry as a natural resource specialist differs from water resource scientists (Johnson *et al.*, 1988). According to them, GIS are computer software and hardware systems dedicated to development, processing, archival and retrieval of spatially distributed data. GIS software and hardware tools can be integrated into a flexible, adaptive, interactive computer graphic based data manager supportive to modeling of watersheds. The essential difference between Berry and Johnson's definition perhaps is better understood if it is viewed in terms of the elements of Decision Support System (DSS) in water resources as defined by Labadie (1989). Labadie's view is that the three fundamental subsystems of DSS are, the dialogue subsystem, data subsystem and model subsystem. Berry's definition implies that GIS is a DSS complete with its three element whereas, Johnson's definition suggests that GIS has only two of the three elements, namely data and a dialogue subsystem not the model subsystem. This in Berry's term would imply that GIS is an externally referenced rather than an internally referenced spatial information system and hence is not a true GIS system by definition. In one respect, Berry and Labadie agreed that a true GIS is also a true DSS.

The difficulty of having a model subsystem within GIS for scientific, engineering applications was due to GIS limitations in fulfilling complex programming and computation requirements of an engineering model subsystem in the 1980s. The latest advancements in the field of GIS technology have overcome most of the problems of the past. At present, GIS allows the entire mapping, numerical and modeling operations using the concepts of object oriented programming (OOP). GIS technology now is capable of handling time series data, feature oriented map operations and allows dynamic segmentation of an arc (Ye, 1996), (Chen, 1996). GIS is now complete decisions support system (DSS) and can be used to perform hydrologic modeling.

5.2 OVERVIEW OF CURRENT GIS TECHNOLOGY

A GIS system consists of a spatially referenced database and a set of instructions and operations that can operate upon that database. Current computer based GIS's have evolved from three precursor technologies. One of these is traditional cartography and associated mechanical map analysis techniques. Long before computers, cartographers had developed sophisticated concepts of spatial analysis and data representation. They also devised effective but extremely labor intensive methods of implementing spatial data analysis functions such as overlay/intersection and proximity calculation. Computerization has made these types of operations entirely practical.

Another ancestor of GIS is the group of Computer Aided Design (CAD) systems that emerged in the 1960's. Most of the early systems were oriented toward electrical CAD. Development of these programs led to rapid advances in computer database design, and also forced the developments of routines for placements, interconnection and routing operations. These functions have later become adopted to and particularly useful for hydrology - GIS. The third foundation of GIS is the field of computer graphics. During the 1960's and 1970's researchers made progress in the area of graphics display, without which GIS would be far less useful. Even more important to the modeler/scientist, efficient routines were coded for the implementation of the cartographers' spatial data analysis functions. These were oriented toward using the efficient database organization pioneered by the CAD researchers. Examples of these routines are the point-in-polygon, polygon intersection and vector rasterization operations.

The database portion of a GIS can be implemented as either a grid based (raster) or vector based format. A raster database consists of a set of uniformly shaped cells, each of which is assigned a discrete value for each data attribute. The vector format consists of sets of points that define the polygon boundaries of regions with the same value for a particular attribute. Each format has advantages and disadvantages. Raster database structures are very simple, and calculations upon them are quite straightforward, while vector database have a complex structure and require sophisticated algorithms to perform data analysis. Vector data, however, can be stored very compactly compared with raster data and can be displayed very precisely. Raster data displays exhibit the characteristic "stair steps" caused by the rectangular shape of each cell.

The software component of a GIS consists of a large number of spatial data analysis functions. Some of these are map overlay, proximity analysis, area/perimeter/volume calculation, routing/path analysis, production of summary statistics, filtering and edge detection, and map algebra (for example, calculating a weighted average of several attributes to form an index). Also part of GIS software are utility packages such as database import/export routines to convert among various GIS programs and between GIS and other external applications such as spreadsheets and CAD packages. Some GIS programs even provide the capability of using these functions, along with control statements from the computer's operating system, as a programming language. These "meta languages" provide the ability to develop compact, easy to understand, physically meaningful resource analysis models.

Specific data sets for use on GIS's come from a number of sources. Data may already have been prepared by another work group, and can be used immediately, or after a format conversion or reference system transformation. The number of existing databases is increasing rapidly as GIS use become more common. For new study areas, data entry functions of the GIS must be used. Most packages include digitizing, data verification, rasterization, and geo-referencing functionalities. The hardware needed to support GIS includes a high quality color monitor for display, a large disk drive to hold the large spatial databases used, a powerful processor to perform the sophisticated spatial data functions of the GIS, and a pointing device (usually a mouse). As of 1997, computer technology has advanced to the point where a quite powerful system costs as little as $5,000 and can fit on a desktop. Optional equipment includes a digitizing tablet for data entry, a printer/plotter for report generation, and a mass storage device for data backup.

5.3 ADVANTAGES OF GIS USE IN HYDROLOGIC MODELING

GIS is of value to spatial hydrologic modeling in two general ways. First, it is generally accepted as an important productivity tool, although many users are not aware of the extent of features that are available. Of even greater importance is the capability of GIS to help better understand spatial hydrologic models and systems. Future advance in hydrology depends upon new insights and conceptual breakthroughs, some of which may emerge as a result of the improved visualizations of hydrologic systems provided by GIS.

GIS allows one to enter spatially oriented data by using digitization routines, or by accepting existing digital databases developed by others. These data are becoming more available all the time, often from third-party data providers not linked to GIS organizations. This capability allows flexible and varied use of existing data resources in which a single database can be used for modeling, planning and documentation. Once GIS data is entered, the user can call upon a variety of pre-programmed data analysis functions. Scale changes, data re-classification and transformation and interpolation are each available with a single command. Proximity analysis, data layer overlay and combination, neighborhood operations, and a complete set of arithmetic and logical operators are available. A GIS can also be programmed to substitute a probability distribution function for a nominal value within a mapping unit. This allows the model to represent better the variability inherent in natural spatial systems. All together, these features allow one to integrate and combine multiple database, and provide the ability to handle large amounts of diverse, complex data with multiple attributes.

Specifically with respect to spatial hydrologic modeling, all of these productivity tools expedite model development and implementation to proceed rapidly. The GIS can serve as a platform for fast experimenting with new ideas and concepts. Many GIS implementations include the capability to program in a meta-language consisting of control statements and built-in high level spatial data manipulation functions. This allows models to be written concisely with considerable reduction in statement numbers over standard programming techniques. Since the complexity, coding time and debug time of a computer program is proportional to a power of the program length, a hydrologic model can be implemented in a fraction of the time that it would take in a standard scientific programming language.

Even more importantly to the modeler, GIS helps one to better understand and analyze models and systems. A key feature of GIS is high quality, meaningful display and output. The intuitively satisfying, easily interpreted map and data layers that comprise GIS data structures make models implemented with GIS easy to understand. The user has the ability to visualize and clearly understand results, see spatial relations, and in general view data in an intuitive and creative manner. The spatially oriented data structures and operations ensure that there is no loss of spatial meaning at any point in the modeling process. Input, intermediate values, and output are all continuously geo-referenced and their inter-relationships are preserved. Also one can always keep track of the processes and output at any point in the study area. The modeler is not limited to just the total system output, but also can interrogate the GIS to determine what processes are occurring, and what outputs are generated, at any location in the area. All the parameters and processes remain fully distributed within the system/model. This is vital since hydrologic systems are distinctly non-linear, and using averaged values and lumped processes can lead to significantly distorted results.

5.4 TIME AND SPACE

Integration of time series data within the GIS spatial framework was one of the challenges of GIS use in hydrology. The latest advancements in spatial hydrologic modeling using GIS have overcome this problem (Maidment, 1996). At present, time and spatial domains can be considered for hydrologic modeling, depending upon the nature of the data structure used (vector or raster). Raster format using digital elevation model cells as spatial units is very useful for certain kinds of hydrologic analysis by eliminating the time dimension e.g. mean annual flow. The numbers of DEM cells within an analysis region are usually very large, so the numbers of time periods that can be analyzed are relatively small. If the time dynamics have to be considered, vector data structure based on points, lines and polygons is important. It requires in concept a 3-D data structure, which can be reduced to 2-D data structure in the following way. The feature attribute table of the GIS data layer defines the geographic properties of the spatial units and gives each a unique identifying number. This table will have geographic attributes making up its columns or fields for which the values in each spatial unit are displayed in rows. The values of a particular computed variable such as precipitation or soil moisture storage can be defined by means of a related timetable. The conventional method of constructing such a table is to define a new field for each time interval and keep the rows for the sequence of spatial units (Figure 5.1), but the advent of OOP languages such as AVENUE in ARCVIEW software, has made possible the reverse arrangement, namely the use of time as the index on the rows of the table for which there is a new field for each spatial unit. The item name in this field is the feature identification number of the spatial unit attached to an arbitrary prefix such as SU to mean spatial unit (Maidment, 1996).

From a hydrologic modeling perspective, the most important aspect of OOP is that objects created for one application can serve as building blocks in other applications. Although in an OOP language state, behaviour and interface are used jointly to define an object, they can also be defined independently from one another. This capability can be used to support the design of an efficient, generic GIS database management system, whose tasks differ according the type of data used.

In the context of hydrologic analysis, an object in a hydrologic model could represent the physical characteristics of a stream section or a river basin, while the behaviour of the object would be the hydrologic processes occurring in that stream section or river basin. Since the state and behaviour of an object are independent in an object-oriented model, they can be treated separately: where state variables are stored and managed in a GIS database; and behaviour are determined subsequently by the hydrologist through selecting an appropriate model to work with the model's objects. The concept of state and behaviour independence is, therefore, essential to the design of a GIS database that could be shared by different external models. Figure 5.1 and 5.2 shows the feature attribute table (FAT) in ARC/INFO and how that FAT has connected with time series data sets respectively in an OOP environment.

The smooth treatment of time variation within GIS was a critical problem that has strongly limited its applicability in the past. This limitation is now over and models of spatially distributed and time varying systems can be readily constructed within GIS rather than simply using the GIS as a repository for spatial data feeding an external time varying model. Models using the similar concepts, investigating different hydrologic phenomena, have been developed recently by [Ye (1996), Shiba *et al.* (1996), Ackermann (1996), Costa *et al.* (1996), Fedra and Jamieson (1996)].

5.5 GIS APPLICATIONS IN HYDROLOGIC MODELING

Maidment (1993) classified the use of GIS in hydrology in the following taxonomy:

i) Hydrologic inventory and assessment
ii) Hydrologic parameter determination
iii) Loosely coupled GIS and hydrologic models
iv) Integrated GIS hydrologic models

The sections below will discuss the application i), ii), and iii) as one part and the last part of this section concentrate on iv) which is the area of most interest for hydrologists.

The most common current application of GIS to hydrology is in hydrologic risk assessment and siting studies. Siting involves projects in which there are certain known constraints and/or requirements in the siting of a facility. A GIS can apply Boolean operators upon multi attribute data to find rapidly all areas that are suitable or unsuitable for the facility. Risk assessment projects are similar, but generally arithmetic operators to generate an index for any part of the watershed. This index is generally a weighted and summed representation of all relevant fields of the multi-attribute data. Examples are the DRASTIC groundwater pollution susceptibility index (Halliday and Wolfe, 1990) and the suitability and capability models of land management (Johnston, 1987). A number of researchers have used

GIS for parameter generation to support hydrologic modeling. They generally use existing modeling techniques or implementations outside of the GIS. The GIS is used merely as a data management tool. For example, Muzik (1988) used a GIS system to automatically calculate a lumped watershed curve number (CN) from digital soils and landuse databases. Berry and Sailor (1987) used GIS to calculate CN values and estimate the overall catchment time of concentration by using topographic database (Digital Elevation Model).

Several researchers have gone further toward hydrologic modeling within a GIS. White (1988) used GIS to calculate curve numbers and combined this information with rainfall amounts to get distributed values for runoff (rainfall excess). Steube and Johnston (1990) used a GIS to determine watershed boundaries and estimate total runoff which would arrive at an outlet, thereby fully implementing the CN method within a GIS. GIS has also proved convenient for generating input data sets for models solved by finite difference/finite element (FD/FE) techniques. Choudhry *et al.* (1997e) developed a runoff model using ARC/INFO-GIS and demonstrated the advantage of spatial rainfall in the runoff modeling. Wolfe and Neale (1988) describe how a GIS system was used to develop the input data set for a finite element surface hydrologic model (FESHM). This model is composed of two parts, each requiring different levels of discretization. The first is runoff generation, which is calculated for each unique soil cover complex, also referred to in the model as the hydrologic response unit (HRU). This discretization is easily accomplished using the overlay capability of GIS upon the commonly available land use and soil map layers. The other part of FESHM is the routing of runoff amounts, for which the study area is discretized by identifying component subwatersheds. This can be accomplished by using the routing and topographic functions of a GIS upon a digital elevation model of the study area. Finally, a GIS is used to resolve the fact that topographic/watershed boundaries do not necessarily coincide with HRU boundaries, since an HRU in this model is defined solely by soil and land use. Calculations using overlay functions are used to determine the runoff amounts contributed to each subwatershed by the fragments of HRU's that fall within their boundaries. Vieux *et al.* (1988) also used a GIS to generate an input data set for an existing finite element groundwater model.

In general, all researchers mentioned above found the GIS to be effective in providing a means of handling data that is spatially variable and spatially referenced. Thus results are all very useful, but they actually exploit a relatively small portion of the 'productivity' capabilities of a GIS and almost none of the 'better understanding' potential.

Current hydrologic research using GIS emphasizes on spatially distributed and time varying models by taking the advantage of OOP. Ye (1996) developed a surface runoff model using OOP, which took into account the distributed nature of the state variables and topographic characteristics in a GIS framework. This model allows all regular model functions such as construction, simulations, modifications and result processing to be activated directly from the model maps. This model enhanced the ability of GIS to perform feature oriented map operations. It combines the three basic elements of a spatial hydrologic simulation model which are i) equations that govern the hydrologic processes ii) maps that define the study area iii) database tables that numerically define the study region and model parameters. Choudhry *et al.* (1997d) evaluated Ye's model for their study on inflow forecasting for the Kaimai Hydropower catchment, NZ. They found this model to be a good tool for strategic planning and management with limited applicability as an operation tool for rapid forecasting purposes when compared with the black box model. Despite of its limitation as an operational tool, this model has contributed significantly towards the use of GIS in hydrologic modeling by overcoming the issue of handling time-series data using GIS and feature oriented map operations.

Shiba *et al.* (1996) used object oriented hydrologic modeling system to scale up the results of runoff model. They also investigated the distributed nature of the topographic characteristics using GIS and lump slope systems using cluster analysis techniques. Ackerman *et al.* (1996) developed an integrated simulation and optimization system of river power plants and reservoirs using object oriented-GIS programming and successfully applied this to the Mosel catchment in Germany. Similar approach were used by Costa *et al.* (1996) for integrating GIS and time series analysis for water resources management in Portugal.

Diaz and Brown (1997) developed an object-oriented model (AQUARIUS) for efficient allocation of water in river basin. This model incorporated a non-linear optimization technique for selection of the model parameters. They reported that water systems could be interpreted as objects of a flow network in which they interact, and the model considered each component or structure of a water system as an equivalent node or structure in the OOP environment.

Models developed using OOP and computer graphics capability like GIS allow interactive use of model to examine what if scenarios. Fedra and Jamieson (1996), Chen (1996) report the successful application of OO-GIS showing the applicability of integrated spatial hydrologic modeling. The above mentioned review shows the beginning of new era in which hydrologists will be able to take the full advantage of GIS for hydrologic modeling which will enable them to understand hydrologic processes in a better way.

5.6 FURTHER READING

The application of GIS in hydrologic modeling is a growing area and hundreds of researchers have worked or working in this new field. It will be difficult to discuss each and every study. Readers are referred to the following publications for GIS applications in spatial hydrologic modeling:

For runoff modeling, [(De roo *et al.,* 1989), (Shamsi, 1993), (Sasowsky and Gardner, 1991), (Sharda *et al.,* 1993), (Djokic and Maidment, 1993), (El Kady, 1992), (Hendrix and Buckley, 1992), (Wolf and Nale, 1988), (Lanfear, 1992), (Johnson *et al.*, 1988), (Hill *et al.,* 1987), (Drayton *et al.,* 1992), (Terstriep and Lee, 1989), (Meyer *et al.*, 1993), (Chang and Muzik, 1991), (Stuebe and Johnston, 1990), (Leu and Wang, 1991), (Tarboton, 1992), (Shea *et al.,* 1993), (Ross and Tara, 1993), (Hodge *et al.,* 1988), (De Vantier and Feldman, 1993), (Smith, 1993), (Brilly *et al.,* 1993), (Chairat and Delleur, 1993), (See *et al.*, 1992), (Ryberg and Douglas, 1997), (Mark, 1988), (Swayne *et al.,* 1992), (Bhaskar *et al.,* 1992), (Lepink *et al.*, 1993), (Myhre, 1991), (Ross and Tara, 1993), (Willeke, G. E., 1992)].

Studies on the application of non-point source pollution, spatial decision support systems and groundwater modeling are reported in [(Vieux and Needham, 1993), (Hamlett and Peterson, 1992), (Russell and Kimsey, 1989), (Hession and Shanholtz, 1988), (Terstriep and Lee, 1991), (Males and Grayman, 1992), (Schoolmaster and Marr, 1992), (Walsh, 1993), (Hamlett *et al.*, 1992), (Mckinney *et al.*, 1993), (Watts and Moreau, 1992), (Ross *et al.*, 1990), (Terstriep and Lee, 1991), (Tong, 1992), (Horn and Grayman, 1993), (Boswinkel, 1989), (Hoodgendoorn and Boswinkel, 1990), (Bateleaan *et al.*, 1993), (Halliday and Wolfe, 1991), (Baker and Panciera, 1990), (Gupta *et al.*, 1996), (Hahn, 1996), (Michl, 1996), (Newwell, 1990), (Gilliland and Baxter-Potter, 1987), (Roo *et al.*, 1989), (Srinivasa and Arnold, 1994), (Lull and Potts, 1990)].

Further review of GIS application to hydrologic modeling can be found in the following publications:

- IAHS publication number 211 and 235 are special issues on application of GIS in hydrology and water resource systems.
- Proceedings of annual conferences on GIS by environmental system research institute (ESRI).
- International journal of water resources planning and management, special issue on GIS, Vol. 119 no.2, 1993.
- Update water resources, special issue on GIS, no. 87, 1992.
- International journal of geographic information sciences.
- Water resources bulletin, special issue on GIS, Vol. 28, 1991.

Few other applications of GIS in hydrologic modeling are also listed in the bibliography.

5.7 SOURCES OF ERRORS IN HYDROLOGIC APPLICATIONS

There are many sources of GIS errors including generalization of the digital data, vector to raster data conversion, change of scale. These errors may occur because of the lack of understanding about the source of the data or not having enough knowledge about the functions of the GIS software. All these errors will propagate through the hydrologic models used and may have considerable effect on the outcome of the hydrologic modeling using GIS. A digital elevation model (DEM) is the basic digital data set necessary to perform spatial surface hydrologic modeling. Several characteristics about the surface hydrology of a particular area can be determined using DEM. Processing DEM data to extract hydrologic features is now a common procedure. However, users of such data often perform this task without carefully considering the accuracy of the data and how it could affect the reliability of extracted hydrologic features. Many studies on using DEM to extract hydrologic features are reported in the literature: [(Jay and Chu, 1996), (Mark, 1982), (Marks *et al.*, 1984), (Band, 1986), (Hutchinson, 1989), (Goodchild and Mark, 1987), (Vieux, 1995), (Wood and Fisher, 1993), (Tabios and salas, 1985), (Garbrecht and Martz, 1996), (Guercia *et al.*, 1996)].

The generalization of spatial data sets is arguably a fundamental problem in GIS research, because of the complex nature of the interaction between scale, cartographic representation and error (McMaster and Shea, 1992). Most spatial data sets held in digital form are ultimately derived from paper maps or from remotely sensed data. The generalization effects contained in them will rise from manual and automated generalizations. Generalization effects can manifest themselves in different ways length and angularity change, elimination of features, or by displacement of features. Ultimately, a combination of these will affect GIS analysis, particularly in the field of watershed or hydrologic modeling. This is a matter of considerable significance. If the results from combining two or more data sets are a reflection of the quality of the data, rather than of the situation in the real world in which the data is supposed to represent, then all subsequent interpretations and actions based upon them are liable to be flawed to some degree (Herbert *et al.* 1991).

Manual generalization effects embedded in paper maps are imported into GIS when the paper maps are converted into digital form. Defining the magnitude and nature of generalization in different classes of geographical data is very important for hydrologic modeling purposes. Joao *et al.* (1993) discusses this issue in detail. Most geographic data is available in vector or raster format. Conversion of vector maps into raster maps result in some degree of rasterizing error. Resampling errors occur when higher resolution data is converted into lower resolution data. Resampling errors increase the attribute/classifications errors. Interpolation errors occur when point data is converted into map data. Choudhry *et al.* (1997a, b, c), in their studies on GIS errors, reported that over-generalization of the data produced results which are significant for hydrologic modeling. In a study area of 88 km^2, 3.67 km^2 was lost while generalizing the data at 50m weed tolerance. They further mentioned that the level of error increased with the increase in cell size while converting data from vector to raster format. They emphasized the need of error free digital data for hydrologic modeling.

Most of the geographic data in map form exist as a vector representation of natural features. For many hydrologic applications, it is easier to process raster data than vector data. Conversion of vector map into a raster map results in rasterizing error as stated earlier. The obvious source of error is because each grid cell only contains a single value of attribute, it is only the dominant or mean value that is carried in the cell. This kind of classification error typically occurs when the size of grid cell is large than the features or more than one feature falls in the same cell. Carver and Brunsden (1994) developed a relationship between line complexity, raster size and rasterizing error. [(Heuvelink and Burrough, 1989), (Hunter and Beard, 1992), Wang *et al.,* 1990), (Breght *et al.,* 1991)] also discussed the rasterizing error in their studies.

Potential accuracy is defined as the expected evidence in the geographic location of an object from its true ground position (Arnoff, 1989). Selecting specified samples of points in a prescribed manner and comparing the position coordinates with an independent and more accurate source of information usually tests potential accuracy. The attribute accuracy refers to the problem of whether the attributes attached to the points, lines, and areas of geographical data are correct or not. In a landuse map, for example, a wheat field may wrongly be classified as potato field. Attribute accuracy is a major concern when remotely sensed data is classified. The accuracy levels achieved so far in the range of 60-85% and are specific to each area of study. Tan and Shih (1991) investigated the errors of manual digitizing for data entry in GIS. Their results showed that maps digitized by multiple participants as well as by participants without previous digitizing experience tended to have a larger geographical error. Dunn *et al.* (1990) discussed the issues of positional accuracy and measurement error in digital databases of landuse. They used an epsilon band model of digitizing accuracy to make estimates of the level of positional uncertainty and measurement error that was due to digitizing polygon outlines. They further discussed the errors due to conversion of vector data into raster format.

Walsh *et al.* (1987) studied how to determine and measure input errors and their consequences in the context of a geographical information system (GIS). Lodwick *et al.* (1990) developed methods to measure the attribute error and sensitivity analysis associated with map based suitability analysis. The use of these methods included understanding the relationship of attribute error in the output map generated by errors in the input maps for a given geographical analysis. Studies have been conducted which demonstrate the need to avoid the errors associated with the digital data, examples include [(Burrough, P. A., 1986), (Clarke, K. C., 1985), (Goodchild, M. F. *et al.,* 1992), (Goodchild, 1982), (Piwowar, J. M. *et al.*, 1990), (Van der Knapp, W. G. M., 1992), (Lodwick *et al.,* 1990)]. Obviously, GIS can not produce output resolution better than the input and users must know the errors associated with the data before its use. This is true particularly when data is being used for hydrologic modeling purposes because a very small magnitude of error can produce erratic input for spatial hydrologic modeling.

5.8 LIMITATIONS OF GIS USE IN HYDROLOGIC MODELING

GIS use in hydrologic modeling is rapidly increasing and many past issues such as handling time series data are no longer relevant. GIS certainly offers a number of benefits to researchers or users working in hydrology. However, there are still some limitations to GIS use in hydrology:

1. Distributed parameter hydrologic models attempt to represent the spatial behaviour needed to address integrated catchment management issues and are, in principle, compatible with the structure of GIS. The algorithms in the distributed parameter model are often based on an understanding of processes at the scale of laboratory or small plots where characteristics of a certain parameter are well defined. This includes, for example, saturated hydraulic conductivity and the soil water retention curves. These parameters are considered as having constant value when applied to larger catchments or sub-catchments. Unfortunately these

parameters have been developed for research catchments that are orders of magnitude smaller than application areas. This difference in scale requires simplifying assumptions that undermine the validity of the original model. Furthermore, the fundamental premise of original model for use as a predictive tool is questioned (Grayson *et al.*, 1993).

2. Statistical analytical capabilities available within current GIS are still limited (Fotheringham and Rogerson, 1994). Attempts have been made recently to add functionality to systems through the linking of spatial statistical packages to a GIS as reported by [(Bailey, 1994), (McCord and Oslon, 1989)]. Schlagel and Newton (1996) developed a GIS based statistical method to analyze spatial change and successfully applied this method to a subset of the landuse data collected as part of a rural clean water program. Increased statistical and mathematical functionality is needed in GIS to be able to support improved representations of variable surfaces and processes, particularly non-linear and probabilistic ones.
3. Simple assumptions incorporated into the various functions of GIS has brought limitations in some hydrologic analysis and modeling results, as mentioned by Neemani *et al.* (1993). Simple overlays (combining different data layers) are not able to account for spatial covariance in the data or multivariable interaction that are important in modeling or interpreting processes. Nemani *et al.* (1993) warn that "since process models are inherently complex and nonlinear, the way in which continuous geographic information is aggregated has far reaching effects on model output". These problems only be overcome when the user has a greater understanding of the structure and assumptions of the hydrologic models or analysis techniques used, allied with a good knowledge of the nature of GIS functions and data models (McDonell, 1996).
4. Most hydrologic measurements are point-based and spatial interpolation using statistical techniques introduce errors. Spatial data for some hydrologic variables like topography and soils is available but new sources of spatial data are still needed at the catchment scale. Remote sensing is being used extensively as a source of hydrologic data [(Giles *et al.*, 1994), (Hogg *et al.*, 1993), (Sorman *et al.*, 1993), (Sharma and Singh, 1992) but there are still resolution limitations to the remote sensing data.
5. The integration of hydrologic processes (surface and groundwater flow) is not yet solved very well in GIS systems. This in part reflects the fact that integration of

hydrologic processes across scales of space and time is not well understood. A map can be drawn at any scale, but it is unclear to which extent models can be applied at different scales (Maidment, 1996).

5.9 CONCLUSION

GIS has advanced to the extent where it can be used for integrated surface hydrologic modeling for strategic planning, management and other environmental applications. GIS technology has overcome the problem of handling time series data but it still has limitations like resolution of spatial data, scale, different sources of GIS errors and integration of surface and sub-surface models. The literature discussed in this paper emphasizes that the user must have a good understanding of both GIS and hydrology before doing hydrologic modeling using GIS. There are many hidden dangers of GIS use in hydrology or other scientific fields. One should not take the modeling results at the face value of colorful maps. However, if we compare the present state of GIS with few years back, it may be that the time is not very faroff when GIS and spatial hydrology will be regarded as an integrated field.

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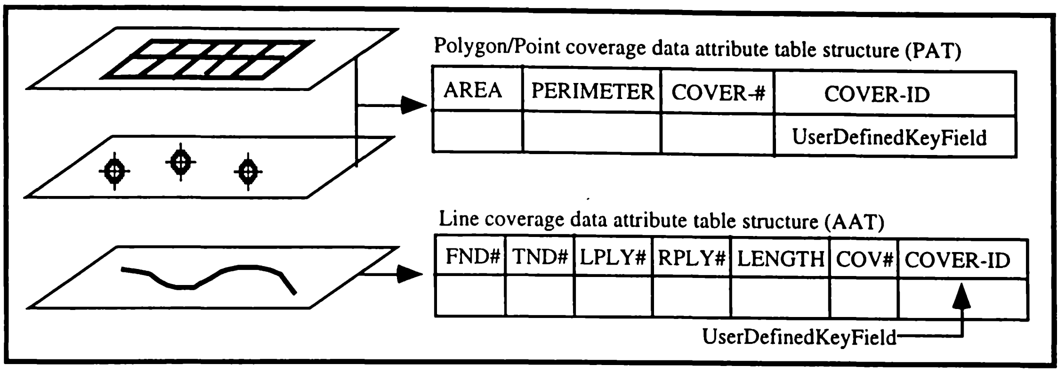
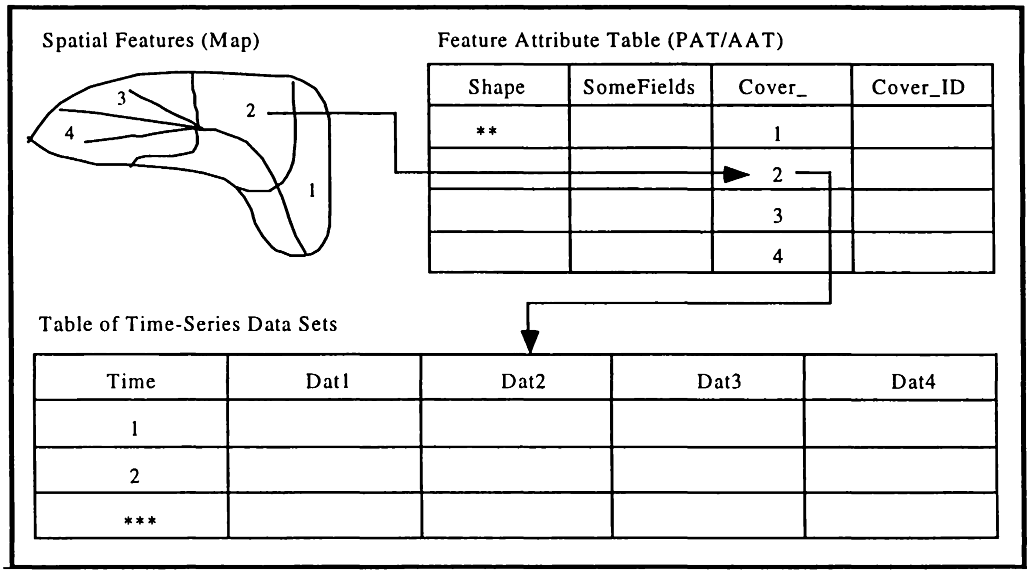

Polygon/Point coverage data attribute table structure (PAT)

AREA	PERIMETER	COVER-#	COVER-ID
			UserDefinedKeyField

Line coverage data attribute table structure (AAT)

FND#	TND#	LPLY#	RPLY#	LENGTH	COV#	COVER-ID

Figure 5.1 Feature attribute table in ARC/INFO (After Ye, 1996).



Feature Attribute Table (PAT/AAT)

Shape	SomeFields	Cover_	Cover_ID
**		1	
		2	
		3	
		4	

Table of Time-Series Data Sets

Time	Dat1	Dat2	Dat3	Dat4
1				
2				
***				

Figure 5.2 Connection between maps and spatially referenced time-series data (After Ye, 1996).

CHAPTER 6

GIS ERRORS AND SURFACE HYDROLOGIC MODELING: PROBLEMS AND SOLUTIONS

ABSTRACT: *The first step in surface hydrologic modeling using GIS is to obtain a digital elevation model (DEM) of the study area. Accuracy of such hydrologic modeling using GIS depends on the accuracy of the DEM. This chapter concentrates on three serious issues and points out solutions for the users of GIS for hydrologic modeling: i) the process by which geographical data, when modified as a result of generalization, produces effects (e.g. changes in length or displacement of features) which have implications on the accuracy of the data. ii) the error involved in the conversion of the data from vector to raster format and importance of cell size selection in building a DEM. iii) the anomalous creation of sinks or peaks in the digital model, which may result in inaccurate flow direction, flow length and flow accumulation within the catchment. The major problem with ARC/INFO GIS is that this widely used software provides very little support to the user in term of both understanding the extent of these effects and in offering means of controlling them. This chapter proposes methods to control these errors within ARC/INFO and illustrates the application of the proposed methods at the Kaimai Hydropower catchment in New Zealand. The results show the importance of data accuracy and the need for accurate DEM in the field of hydrologic modeling.*

6.1 INTRODUCTION

Topography is an important factor in determining the streamflow response of catchments to precipitation. This factor is now widely taken into account in spatially distributed hydrologic modeling through the use of Digital Elevation Models (DEM). Automated drainage identification, watershed segmentation and catchment parameterization from DEM has emerged as an attractive source of topographically derived data for distributed and semi-distributed hydrologic modeling as mentioned in Mark (1988), Wolock & McCabe (1995), Wolock &

Price (1994). However, existing DEM data extraction procedures have limitations and are sometimes based on simplistic assumptions like generalization of the data, vector to raster data conversion and false flow direction because of sinks, that can lead to inaccuracies in the output.

Generalization of spatial data sets is arguably a fundamental problem in GIS research, because of the complex nature of the interaction between scale, cartographic representation and error (McMaster and Shea, 1992). Most spatial data sets held in digital form are ultimately derived from paper maps or from remotely sensed data. The generalization effects contained in them will rise from manual and automated generalizations. The generalization effects can manifest themselves in different ways, for example, by length and angularity change, by elimination of features or by displacement of features. Ultimately, a combination of these will affect GIS analysis especially in the field of watershed or hydrologic modeling. This is a matter of considerable significance. If the results from combining two or more data sets are a reflection of the quality of the data, rather than of the situation in the real world in which the data is supposed to represent, then all subsequent interpretations and actions based upon them are liable to be flawed to some degree (Herbert *et al.*, 1991). Manual generalization effects embedded in paper maps are imported into GIS when the paper maps are converted into a digital form. Defining the magnitude and nature of generalization in different classes of geographical data is very important for modeling purposes.

GIS data is usually available in raster or vector format. The conversion from one type to the other is often necessary for many GIS analyses (Van der Knapp, 1992) and it is important for the user to be aware of the level of error associated with such data conversion. The selection of cell size is also very important while converting the vector data into raster data (DEM) which is a pre-requisite for most of the hydrologic applications. The conversion process or the creation of DEM may create sinks in the DEM, which may have undesirable effects on hydrologic modeling results. The objective of this paper is to analyse the various types of GIS errors like the above-mentioned, which may affect the results of hydrologic modeling requiring topographical input. The most widely used GIS software (ARC/INFO) was selected for this study because a major problem with ARC/INFO is that it provides very little support to the user in term of both understanding the extent of the effects of GIS errors and in offering means of controlling them. The functions used in this study are ARC/INFO terminology and it may differ with other available GIS softwares, but concepts will be similar.

6.2 DATA ANALYSIS

In order to generalize the digital data, weed and proximal tolerances are usually used. It is important to define both of these before going into further details of data analysis. A detailed description is available in any GIS text such as Burrough, (1986).

WEED TOLERANCE is the distance in ground units used to reduce the number of vertices along the individual arcs.

PROXIMAL TOLERANCE eliminates points falling within the specified distance of other points.

The proximal tolerance is available with the "CREATETIN" function and not as an independent command for generalizing the data like weed tolerance. It was decided to use only weed tolerance as the "GENERALIZE" function uses only this tolerance. In order to assess the effects of generalization, which is important for the accurate representation of Triangular Irregular Network (TIN) or DEM, both visual representation and quantitative analysis can be used. Nevertheless, visual representations as reported by Wood and Fisher (1993) are more common. In this study, both visual representation and quantitative analysis are used. The visual representations include comparing contour lines before and after weeding, converting contour lines into grids and then converting back into contours to see the weeding effects. The quantitative analysis includes calculating the number of sinks, total area lost and the frequency distribution of slope angles.

6.2.1 Visual representation

Weed tolerance of 4, 10, 20 and 30 m was introduced to the sample data. The generalized results are presented in Figure 6.1. Contour data did not change the original shape at 4 m but the effects are prominent at 10, 20 and 30 m weed tolerance. A contour at 10 m tolerance seemed reasonable but the effect of generalization was prominent at the edges of the contours, as well as the islands, which start becoming triangular in shape. This effect was very strong at 20 and 30 m tolerance where islands appeared only as small lines and at greater weed tolerance islands simply disappeared which eventually will create false interpolation for constructing a DEM of the study area.

Four TINs (tin4, tin10, tin20 and tin50) were created using weed tolerances of 4, 10, 20 and 50 m . The TINCONTOUR function was used to convert grids into contour lines. As this command uses linear interpolation on each side of the triangle, the results were very dependent on one measurement at a distant location, resulting in uneven contour lines. Results are presented in Figure 6.2. Weed tolerance of 4 m produced contour lines more or less similar pattern to the original data but at other tolerance levels the contour lines differ significantly. The contour maps derived from tin10, tin20 and tin50 showed lines and islands that were not present on the original contour map.

6.2.2 Quantitative analysis

6.2.2.1 Comparison of sinks

Six TINs (tin-org, tin4, tin10, tin20, tin30 and tin50) were generated using original data and weed tolerances of 4, 10, 20, 30 and 50 m. The number of sinks were compared to see the effect of generalization. Errors in DEM are usually classified as either sinks or peaks. A method to remove them is discussed in section 6.4.

Analysis show that as the weed tolerance increases, the numbers of sinks also increase. This is not desirable for hydrologic modeling purposes. Removal of sinks is an iterative process. When a sink is filled, the boundaries of the filled area may create new sinks, which then need to be filled. More sinks will result in a false calculation of the flow direction and accumulation, which eventually will delineate false stream networks and watersheds. As a result, the hydrologic modeling will produce anomalous results. Results are listed in Table 6.1.

6.2.2.2 Comparison of the area lost

The area lost because of generalization was estimated by calculating the total number of cells of all the above mentioned TINs. It was found that the area lost was a function of the increase in weed tolerance and was maximum at the maximum weed tolerance level. 3.67 km^2 out of total catchment area of 88.18 km^2 was lost due to the over generalization of the data. A large area lost simply shows false introduction of catchment parameters in any hydrologic model that can be avoided by using the right weed tolerance. Table 6.2 explains the results of all the six TINs.

6.2.2.3 Slope angle distribution

All the above mentioned TINs were converted into lattices (lat-org, lat4, lat10, lat20, lat30 and lat50) in order to see the frequency distribution of slope angles. The slope angle distribution showing percentage of the flat area for each slope class is given in Table 6.3. All slope angle classes are given in degrees, the other columns show the percentage of flat area in a given slope class. The class 0-4 degrees is of more important for this analysis since the landscape having slope angles between 1-4 degrees favors a large proportion of infiltrated precipitation (no runoff) when other factors are constant. As the bed dip or topographic slope steepens, surface runoff increases (Baker *et al.*, 1990).

A field survey conducted by Bakker *et al.* (1996) in the study area confirmed that a large percentage of flat area is present in the study area. It is evident that as generalization increases the estimated natural flat area will reduce as shown in Table 6.3. The reason for the reduction in flat area with increase in weed tolerance is because as generalization of the data increases, contours of higher elevation will start intersecting with contours of lower elevation and will create false triangulation which will eventually result in an anomalous topography of the area.

6.3 RASTERIZING ERROR

Natural topographic data is more easily represented by vectors than rasters. Although vector maps are more accurate than raster maps, it is far easier to do hydrologic modeling with raster maps than with vector maps. The row cell structure of the maps creates a common two-dimensional matrix, which is conveniently handled in any computer program. Conversion of a vector map into a raster map results in rasterizing error. The obvious source of error is because each grid cell can only contain a single value of an attribute, it is only the dominant or mean value that is carried in the cell. This kind of classification error typically occurs when the size of the grid cell is larger than the features of that cell, or more than one feature falls in the same cell. It is recommended that in order to minimize the rasterizing error, the cell should be small enough so the smallest mapping unit will be greater than 50% of any cell. However, to apply this standard to large project areas, the resulting database could contain millions of cells. With too many cells, the computational advantage of converting vector to raster maps can become insignificant.

Hydrologists, cartographers, geographers, soil scientists have addressed the data conversion problems in different studies [(Bregt, A. K., *et al.*, 1991), (Burrough, P. A., 1986), (Carver, S. J. and Brunsdon, C. F., 1994), (Clarke, K. C., 1985), (Goodchild, M. F. *et al.,* 1992), (McCloy, K. R., 1995), (Piwowar, J. M. *et al.,* 1990), (Van der Knapp, W. G. M., 1992)]. It is important to know the level of error embedded in the data for an accurate interpretation of the results. The objective of this part of the study is to see the degree of error associated in rasterizing a vector polygon coverage for a range of grid sizes and also to find the optimal grid size for the study area. Finally, a model will be presented which will describe the effect of grid size on polygon area displacement. This eventually has a significant hydrologic importance because different landuses are associated with the different sub-watersheds or polygons. A false displacement of sub-watersheds may result in false parameters for hydrologic modeling depending on the polygon landuse, soil type and other related parameters, which is undesirable for planning, management and operational purposes.

6.3.1 Measurement of rasterizing error

A sample 18 km^2 (6 km x 3 km) grid was chosen from the New Zealand Land Resource Inventory (NZLRI) vector coverage of the study area. This coverage served as the base or reference coverage for the study. It was assumed that the base coverage is free from errors and all the converted coverages should represent the base coverage. The base vector coverage was rasterized using different grid sizes (1, 5, 10, 25, 50, 100, 250, 500, 750 and 1000 meters) and these grids were converted back to the vector polygon coverages to compare the area displaced with respect to the base coverage.

The analyses showed the lowest and highest total displaced area for the 5m and 1000 m grid conversion respectively. It was interesting to note the coverage created using a 1m grid did not have the lowest value of displaced area. This could be the result of an inherent error at this resolution scale or might be a function of the grid size being less than the fuzzy tolerance value, which was 1.5m in this case. It was decided to exclude the 1m grid from further analysis. A cubic polynomial equation was fitted to the data describing the effect of grid size on the displaced area. The model clearly shows the increase of displaced area with the increase in cell size. Area displaced at 10m and 1000m grid was 0.04% and 68.66% respectively. Figure 6.3 explains the model equation, where x is the grid size in meters and y is the area displaced in km^2. The relationship was tested on different sets of data, where it showed similar results and proved its validity. The relationship was also tested on a smaller grid size of up to 50m to see whether the polynomial relationship exists at this scale. It was found that the same relationship exists at the lower scale.

The numbers of polygons in the base coverage (26) were compared with all other coverages obtained using different grid sizes. On comparison, it was found that the polygon coverage produced using a 10 m grid had exactly the same number of polygons (26) as the base coverage but conversly the coverage produced using a 1000m grid had only 9 polygons. This also illustrated the increase in error with increase in grid size. Figure 6.4 and 6.5 show the overlay of the coverages produced using 10 m and 1000 m grid with the base coverage respectively. Figure 6.4 shows an exact match with the base coverage, but the area displacement is significant in Figure 6.5 using 1000 m grid size. False displacement of area can result in false information of the catchment parameters, which eventually will lead, to false hydrologic modeling results. Computer storage (bytes) of different grid sizes were compared to find the optimal cell size for the study area. Analysis showed that the optimal cell size for the catchment area is 10 m. It was decided to use the 10 m grid for converting vector data into raster format and for creating a DEM of the area.

6.4 SINK ERROR

The first step in the distributed hydrologic modeling using GIS is to obtain a DEM of the study area. The second step is to use the FLOWDIRECTION command to determine the flow path which water will take when it hits the Earth's surface. One problem with DEM is their inaccuracies. Usually, the creation of DEMs often results in many spurious sinks. It is necessary, however, to find out first whether these sinks are natural closed catchments or processing artifacts. A sink is a cell (or set of spatially connected cells) whose flow direction cannot be assigned one of the eight valid values in a flow direction filter. This occurs when all neighbouring cells are higher in elevation than the processing cell, or when two cells 'flow into each other' creating a two-cell loop. Sinks therefore have no defined flow direction. Filling sinks is a repetitive procedure. When a sink is filled, the boundaries of the filled area may create a new sink, which then needs to be filled in turn. Natural sinks are closed catchments as they constitute a closed hydrologic system that does not have any flow direction. In closed catchments, water drains towards an inland convergence point located within the basin, and not on the basin border as usually occurs. The importance of DEM accuracy especially in the sense of "sinks" might be small for most general purposes but crucial for hydrologic modeling (in which the lowest cell constitute a pour point).

The FILL function raises the elevation of the terrain in the sink until the water is able to flow out of it. The FILL function of GRID modeling fills all the sinks up to some user-defined value without distinguishing between DEM errors and closed catchments. Thus it is vital to locate the natural sinks as this will have implications on surface hydrologic modeling results. A program (see floppy disk at the back of thesis) has been written to overcome this problem using the GRID hydrologic model. This methodology is an iterative process and distinguishes between true closed catchments and DEM errors. This program corrects the DEM by assigning NODATA to the sink cells. Sink cells are the bottom cells of those fillings with area and depth greater than threshold values specified by the user. The proposed method was successfully applied to the DEM of the area. DEM errors were filled in order to get an accurate flow direction. Hutchinson (1989) also developed a method of removing spurious sinks and is available as a TOPOGRID function in ARC/INFO. The proposed method differs from the TOPOGRID function in that the spurious sinks are removed, and there is the added advantage of simplicity and flexibility for the user to locate and fill sink areas automatically in the catchment.

6.5 DISCUSSION

Data analysis demonstrates the need for an accurate digital data in the field of hydrologic modeling. Over-generalizations of the data produce effects, which can be significant in hydrologic modeling. Sometimes, data need to be generalized if it includes many nodes as a result of digitizing. The extra nodes can create false triangles of the landscape if the level of generalization is not determined. A weed tolerance of 4 m was used for the whole study area as it represents the original data well. This tolerance level was selected by clipping three areas of dense contours, and the distance between the contours (not to be confused with contour interval) was measured using ARCTOOLS. The minimum distance between the contours was found to be approximately 4.5 m, so the selection of the 4m weed tolerance ensured, data would not intersect and produce false triangles. A subroutine can be written outside ARC/INFO for automating this task but this was beyond the scope of this study.

Data analysis showed the level of error will increase with the increase in grid size. However, there is a trade off between accuracy and resolution required, depending on the nature of the study and system used. A 10 m cell size was used for the study area for building DEM or for converting vector data into raster format. The processing of digital data for building DEM creates sink errors. It is important to find out which sink cells are DEM artifacts and which are natural true closed catchments. This problem of distinguishing between DEM errors and closed catchments was solved by proposing a new method within the ARC/INFO. This study focused on the capabilities available within widely used GIS software ARC/INFO. Another aim was to provide a simple solution that could address the wider community of GIS users. Finally it can be recommended that hydrologists using GIS must know the accuracy of the data before starting their analysis. They may be following the right modeling procedures but the inherited errors in the data can produce undesirable results in their applications.

6.6 CONCLUSION

Most distributed or semi-distributed hydrologic model use DEM as the basic digital data for modeling purposes. The accuracy of DEM is very important for the accuracy of hydrologic modeling results. A study on different GIS errors like generalization, data conversion and sinks was conducted in the Kaimai Hydropower catchment, Tauranga, New Zealand using ARC/INFO GIS software. The conclusion of the data analysis was in three folds: i) as the level of generalization increases, the information loss also increases which can be significant for surface hydrologic modeling applications. ii) the conversion of data from vector to raster format clearly indicates that as the grid size increase the area displacement also increases, which can introduce false parameters in the hydrologic models. iii) a method that distinguishes between DEM processing errors and natural true closed catchments is developed and proposed for hydrologic studies.

The Methodologies proposed in this study will be equally applicable for other GIS software. This study has addressed the important problem of data accuracy within GIS and hopefully some of the solutions presented here will be of value to workers in spatial hydrology and related fields.

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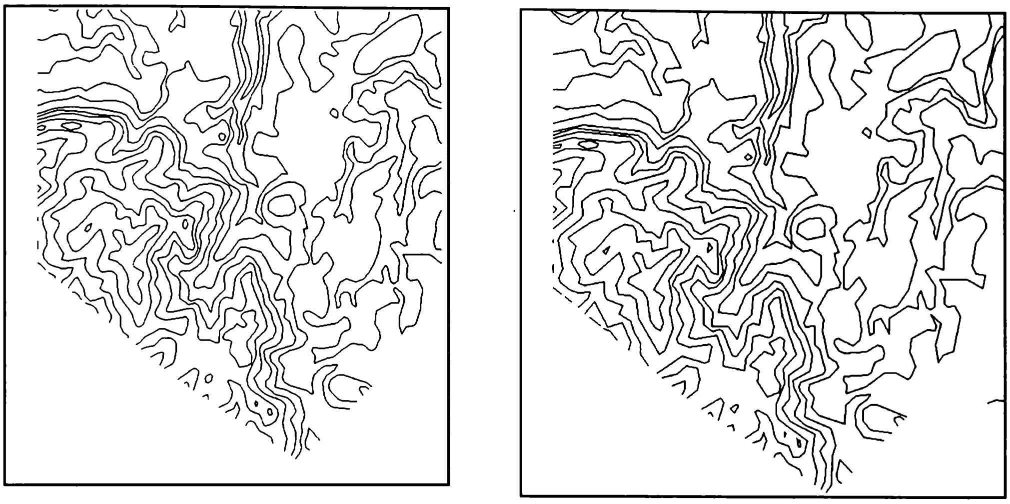
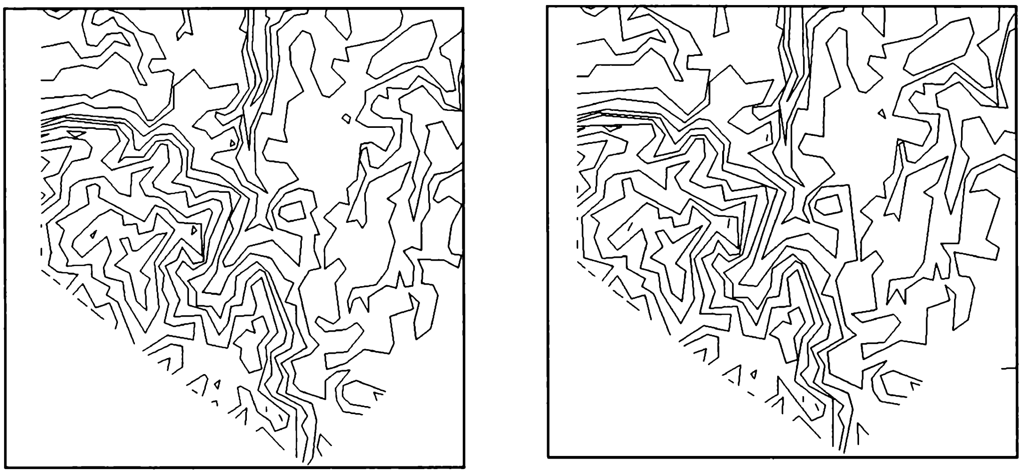


4 meter weed tolerance

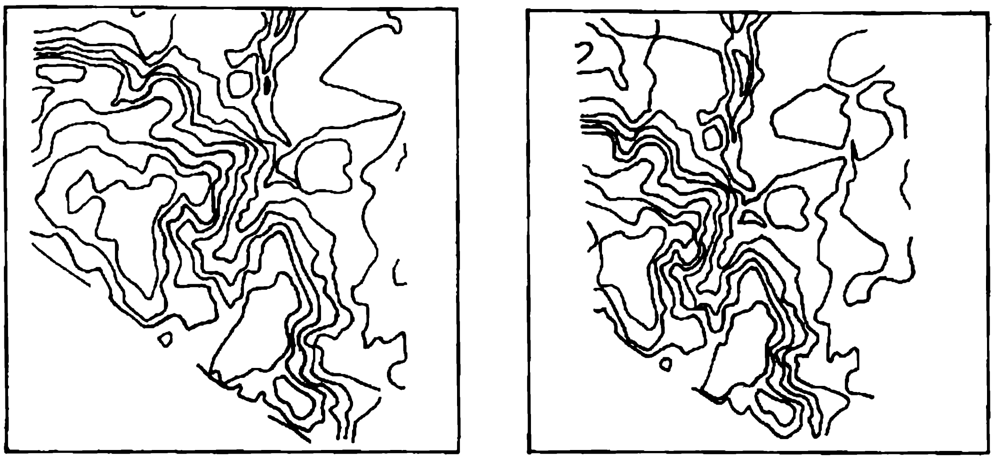
10 meter weed tolerance



20 meter weed tolerance

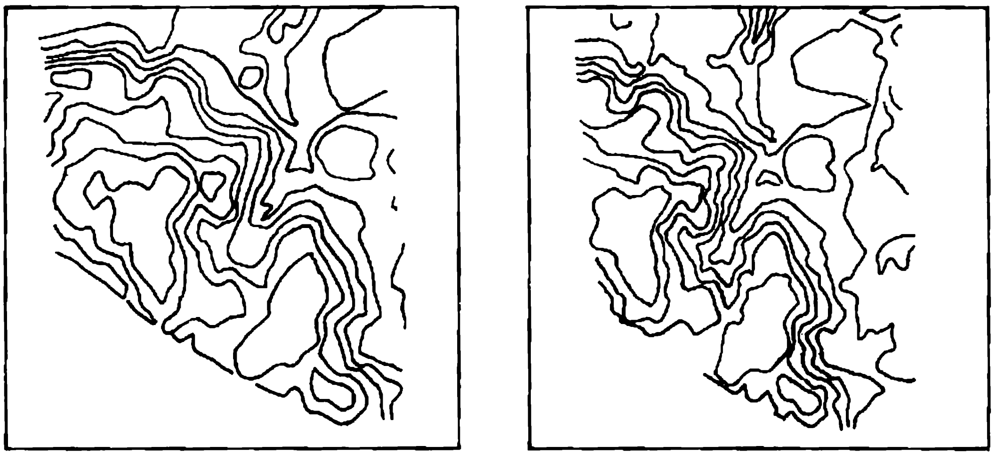
30 meter weed tolerance

Figure 6.1 The effect of weed tolerance on contour generalization.



4 meter weed tolerance

10 meter weed tolerance



20 meter weed tolerance

50 meter weed tolerance

Figure 6.2 Contours generated using TINCONTOUR function.

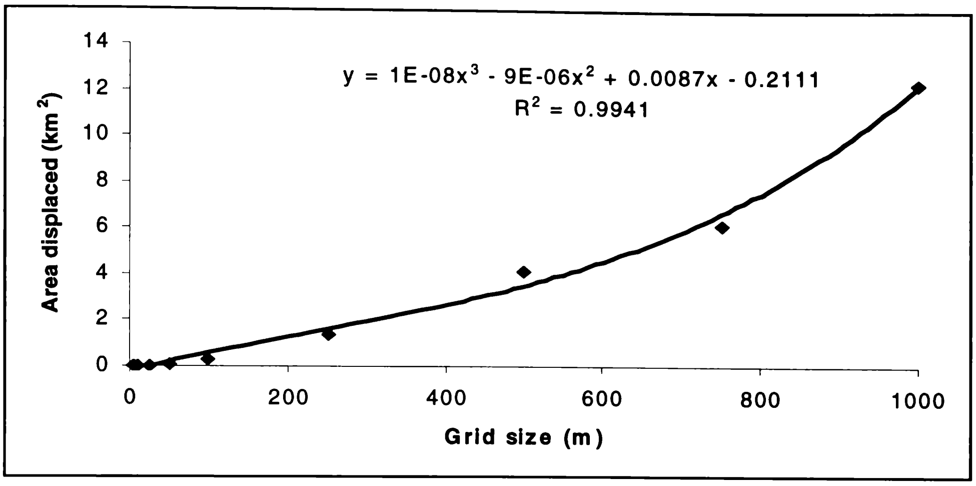


Figure 6.3 Model describing the effect of grid size on displaced area.

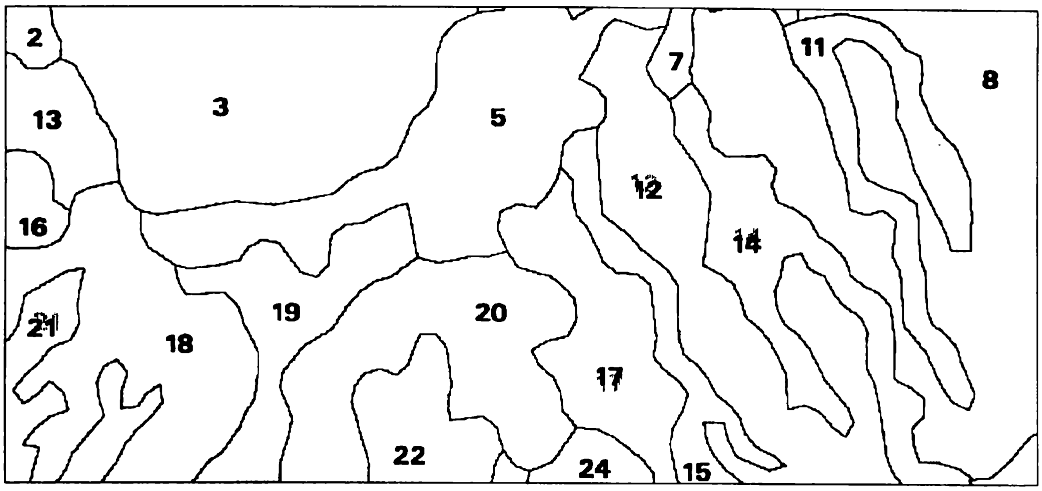


Figure 6.4 Overlay of the polygon coverage produced using 10m grid with base coverage.

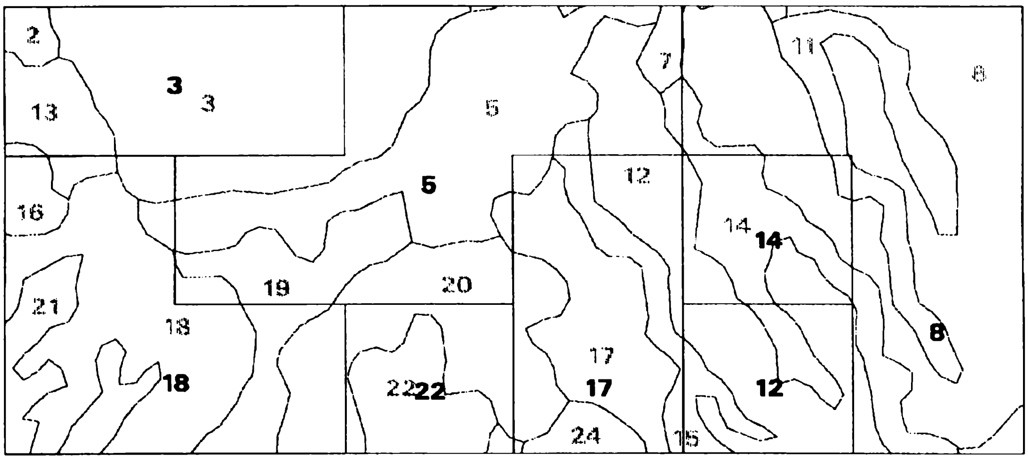


Figure 6.5 Overlay of the polygon coverage produced using 1000m grid with base coverage.

TIN	Number of Sinks
Tin-Original	181
Tin4	183
Tin10	192
Tin20	197
Tin30	233
Tin50	293

Table6.1 Comparison of sinks with different weed tolerances.

TIN	Total Number of Cells	Area Lost (Km^2)
Tin-Original	881799	-
Tin4	881798	NIL
Tin10	859668	2.14
Tin20	858656	2.24
Tin30	847651	3.34
Tin50	844300	3.67

Table 6.2 The area lost with generalization process.

Slope Class (Degrees)	Lat-Original (%)	Lat4 (%)	Lat10 (%)	Lat20 (%)	Lat30 (%)	Lat50 (%)
0-4	51.15	51.10	48.93	48.86	47.2	45.3
5-9	14.34	14.34	14.32	14.38	14.77	16.54
10-14	11.20	11.21	11.16	11.36	11.5	12.19
15-19	8.90	8.91	8.89	8.91	9.04	9.25
20-24	6.35	6.36	6.33	6.30	6.52	6.05
25-29	4.06	4.06	3.97	3.90	3.85	3.62
30-34	2.21	2.214	2.158	2.11	2.40	2.91
35-39	0.995	0.994	0.946	0.912	0.858	0.75
40-44	0.395	0.394	0.375	0.352	0.327	0.269
45-49	0.145	0.144	0.134	0.123	0.115	0.095
50-54	0.045	0.045	0.045	0.045	0.043	0.0415
55-59	0.032	0.032	0.031	0.031	0.030	0.043
60-64	0.051	0.050	0.052	0.052	0.051	0.063
65-69	0.049	0.049	0.049	0.050	0.053	0.049
70-74	0.053	0.055	0.053	0.054	0.045	0.04
75-79	0.021	0.020	0.021	0.0198	0.018	0.015
80-84	0.003	0.003	0.002	0.001	0.0019	0.0005

Table 6.3 Slope angle distribution showing percentage of the flat area in each slope class.

CHAPTER 7

DELINEATING WATERSHED FEATURES FROM DIGITAL ELEVATION MODELS: THE ROLE OF BREAKLINES IN HYDROLOGIC MODELING

ABSTRACT: Digital elevation models (DEMs) are widely used to delineate the topographic characteristics of hydrologic features. However, during the building of DEMs, spatial errors often propagate through the hydrologic model. Therefore, the accuracy of any DEM-based hydrologic model depends on the accuracy of the DEM used. This chapter examines the role of 'breaklines' (which define and control surface behavior in terms of smoothness and continuity) in building DEMs for hydrologic modeling, and proposes a new methodology which uses soft breaklines to improve the quality of these models. The new technique has showed a marked improvement, over conventional methods, when used for delineating watershed and stream networks.

7.1 INTRODUCTION

Topography is an important factor in water resource analysis, and digital elevation models (DEMs) provide hydrologists with a useful opportunity to process their spatial data on the computer. Many data sources are used to produce the digital elevation model of an area, including field surveys, topographic maps, aerial photographs and satellite images. However, the sampling patterns obtained from these data sources differ considerably, as they will have been assembled using dissimilar point distributions, as well as discontinuous contour or slope registration. Similarly, the spatial interpolation technique using to construct a DEM and its grid size often varies.

There are several geographic information systems (GIS) algorithms available to construct a DEM. For example, the CREATETIN function in the GIS program ARC/INFO allows the user to combine several topographic data sources to build a single DEM. However, the spatial accuracy of a DEM is necessarily variable and as DEM errors propagate through a hydrologic model, the accuracy of a simulated hydrograph, for example, is very dependent on the accuracy of the DEM used (Lagacherie *et al.*, 1996).

Essentially, a DEM is the basic (digital) data set needed to perform topography based hydrologic modeling, and several characteristics about the surface hydrology of a particular area can be determined using DEMs. Processing DEM data to extract hydrologic features is increasingly common as mentioned by [(Moris and Heerdegen, 1988), (Jones *et al.,* 1990), (Howard, 1990), (Fairchild and Leymarie, 1991), (Tarbatoon *et al.,* 1991), (Greg, 1994), (Nelsen *et al.,* 1994), (Garbrecht and Martz, 1996) (Guercia *et al.,* 1996)]. Jay and Chu (1996) stated that the users of DEM data, however, often perform their analysis without carefully considering the accuracy of the data and how this could affect the integrity of the extracted hydrologic features. This issue has been articulated in many other publications, including [(Mark, 1982) (Marks *et al.*, 1984), (Band, 1986), (Goodchild and Mark, 1987)].

Hutchinson (1989) developed a method of removing spurious pits (sinks) from elevation and streamline data. This method has been incorporated as a function, named TOPOGRID, into recent releases of the popular GIS program ARC/INFO. The TOPOGRID function eliminates spurious sinks while building a DEM by imposing rivers on it. The user has to define true closed catchment locations in order to avoid their filling.

The method discussed in this research paper takes a different approach to improving the accuracy of a DEM, by focusing on the role of surface clipping (boundary delineation) during the construction of the DEM. The proposed approach is achieved through a stricter definition of the BREAKLINE parameter in ARC/INFO's TIN (triangulated irregular network) module. In order to illustrate the advantages of the new method, the results of DEM building obtained by using the conventional TOPGRID function will be compared with those achieved with the proposed method.

Breaklines define the smoothness and continuity of surface interpolations during the construction of DEMs. As the name implies, breaklines are linear features which delineate the boundaries within which the contour height interpolations take place. Breaklines therefore change the behaviour of a surface model, as the depth coordinates (or z values) of the three dimensional data are clipped along a breakline.

The DEM breakline standards proposed by the developers of ARC/INFO, Environmental Systems Research Institute, are three fold (ESRI, 1996):

- "hard" define interruptions in surface smoothness such as rivers, shorelines or ridges;
- "soft" do not define interruptions in surface smoothness representing structures with a fixed elevation such as irrigation pipes or highway with fluctuating elevation;
- faults, representing abrupt hikes or falls such as geological faults.

However, this paper expounds the view that rivers and streams should be specified as soft breaklines, rather than hard breaklines, during the construction of a digital elevation model for hydrologic purposes.

7.2 DATA AND METHODS

Examining the spatial consequences of using soft or hard breaklines would not have been possible without assigning notional values to the river features used later to conduct the visualization tests. Using ARC/INFO to achieve this aim, the INTERSECT function was used first to compute the geometric intersection of two coverages (layers): one coverage contained the river outline; the other contained an unclipped digital elevation model of the study area. Only those features common to both data layers were extracted from both layers.

The next step involved using the LINEGRID function to convert the line feature just obtained into a lattice (raster) file with height values. This step is necessary to enable the use of hydrologic 'filtering' algorithms, such as stream flow and direction functions, which work with raster files. Finally the resulting lattice was used to create a point coverage needed to create the triangular irregular network (TIN) of the height values which would be used to construct a DEM of the study area.

An error free DEM (see chapter 6) was created using the ARC/INFO functions CREATETIN and TINLATTICE. The river vectors used in this research were overlaid onto the lattice data representing the original DEM, in order to segregate those cells in the lattice which contained rivers. All identified river cells then had their depth value reduced by 3 meters as an estimate to the river's surface height.

Two separate digital elevation models of the study area were created using rivers as soft and hard breaklines. It was interesting to note that when the rivers were defined as soft breaklines, the resulting DEM had a smooth appearance and preserved the map location of the river network. Figures 7.1 and 7.2 represent, respectively, the influence of hard and soft breakline clipping. For most hydrologic modeling purposes, it is important that the river should represent their true location in the catchment by maintaining their varying elevation during analysis.

The VIP function in ARC/INFO played an important role in this research by enabling the visualization of the effect of both hard and soft breaklines, as both types had to be evaluated to see which gave the best (visually correct) results for hydrologic modeling. Using a 3x3 'high-pass' filter, the VIP function assesses the significance of each point in the lattice. The change in the surface (height value) at each point is measured by comparing it with its eight neighbouring points. The points to be included in the resulting coverage are selected by the VIP function on the basis of their relative significance. The most significant points are selected first, less significant points are added on until a specified percentage of data is achieved. Higher percentages give the resulting data an odd structure, and the best results were achieved with the default value of 10% for all lattice points. Higher percentages would have given a river breakline a disproportionately higher value.

7.3 DISCUSSION

The developers of ARC/INFO, Environmental Systems Research Institute (ESRI), recommend rivers to be used as hard breaklines during DEM construction. However, as Figures 7.1 and 7.2 show, a DEM constructed with its rivers specified as hard breaklines results in discontinuous surfaces. The resulting simulated landscape in this case has a smooth appearance on either side of the rivers, but not for the river locations themselves. The abrupt columns in the simulated surfaces shown in Figure 7.1 are caused by the fact that contour vectors in the model split at the locations defined as hard breaklines, and a quintic spatial interpolator interrupts the normal (linear) interpolation process at these locations. During subsequent modeling, therefore, this uneven surface behaviour would propagate spatial errors and affect the outcome of such essential hydrologic processes as FLOW DIRECTION, FLOW LENGTH AND FLOW ACCUMULATION.

However, unlike rivers, lake and dam boundaries can be defined with hard breaklines, because the latter interpolate the same height for whole polygons where it is reasonable to represent a clipped surface as a flat area. Therefore, unlike the case of rivers, assigning heights to lakes, dams and reservoirs is not problematic, because of the uniform characteristics of their surfaces. The accuracy of a DEM is crucial for hydrologic modeling, and the partial integrity of the proposed DEM building method was checked by comparing the source data with the elevation values derived from DEM. As Table 7.1 shows, the quality of data achieved with the proposed method was not compromised by the processes used to build the new DEM. Original data supplied by Department Of Surveying and Land Information (DOSLI), New Zealand has a vertical accuracy of ± 10m. It can be seen from Table 7.1 that all the data is within the accuracy level of the original data, which shows the accuracy of the DEM built using the proposed method.

The TOPOGRID function of ARC/INFO has been widely used to clear the spurious sinks from a DEM. The process involves inferring drainage lines via the lowest saddle point in the drainage area surrounding each spurious sink. This function is useful to enforce a drainage pattern on the DEM. According to Hutchinson (1989), the output drainage cover resulting from the use of the TOPOGRID function would match closely the position of the original streams. However, experience indicates that Hutchinson's function gives good results for morphological studies of drainage patterns, but visualization of the resulting covers is compromised by the obscured location of the original streams.

The alternative method outlined in this chapter is especially useful in locating any change in the natural course of rivers, as a result of assigning river depths before employing watershed and river network delineation procedure. This will usually eliminate the need for the TOPOGRID function, as fewer (if any) sink locations are produced if the rivers are defined as soft breaklines during DEM construction. The proposed procedure also automatically detects closed catchments within the study area by defining their approximate area and depth, and fills only the sinks.

A watershed is the up slope area contributing flow to a given location. The watershed is also referred to as a basin, catchment, or contributing area. Watershed boundaries are a key requirement for all surface hydrologic modeling and can be delineated from a DEM using flow direction and accumulation grid as input. If false flow direction has been calculated as a result of an anomalous procedure of building a DEM then the delineation procedure will also be affected. River or stream networks can also be delineated from a DEM using the FLOW ACCUMULATION grid as an input in a GRID algebraic expression

Some 5000 cells were used to calibrate the delineation procedure proposed in this paper, and the results from the new method matched the original (digitized) river coverage very closely. However, as Figure 7.3 reveals, three locations (encircled in the diagrams) did not match well, as some catchment streams changed direction naturally at fairly sharp angles. By using the conventional method, however, the resulting river network deviated on average by 2 to 6 cells from its digitized course. With the aid of a global positioning system (GPS), all changes were subsequently checked in the field and confirmed. Watershed delineation using proposed and conventional method was also compared and showed false polygons at many locations by using conventional method in the catchment as shown in Figure 7.4.

7.4 CONCLUSION

Terrain characteristics are very important in hydrologic analysis, and digital elevation models (DEMs) are increasingly popular with hydrologists because many catchment features can be obtained from them. However, during DEM building, spatial errors tend to propagate through the hydrologic model. The findings of this study call for an reassessment of the basic steps involved in building digital elevation models, for the delineation of stream networks and watersheds. The method discussed in this research paper takes an alternative approach to improving the accuracy of a DEM, by focusing on the role of surface clipping (boundary delineation) in the construction of digital elevation models. In an ARC/INFO modeling environment, this approach is achievable through a strict definition of the breakline parameter during the construction of the DEM. Breaklines are linear features which delineate the boundaries within which the contour height interpolations take place. In geo-computational terms, a breakline is a clip feature which defines the continuity of surface interpolations during the construction of DEMs. This paper proposes that rivers or streams be used as soft breaklines (with notional height values) during DEM generation. When used for extracting hydrologic features, the new method gives more hydrologically appropriate results, compared to those obtained by other methods. The geometric distortions which beset conventional delineation procedures are often the result of false flow directions and accumulations, which are addressed directly in the proposed method.

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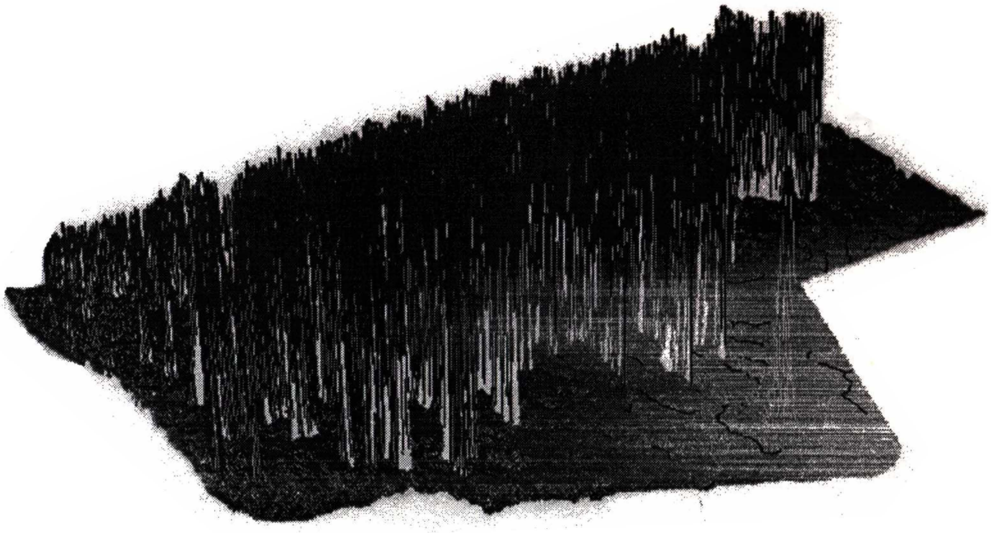

Figure 7.1 Surface description using rivers as hard breaklines (VIP function).

Figure 7.2 Surface description using rivers as soft breaklines.

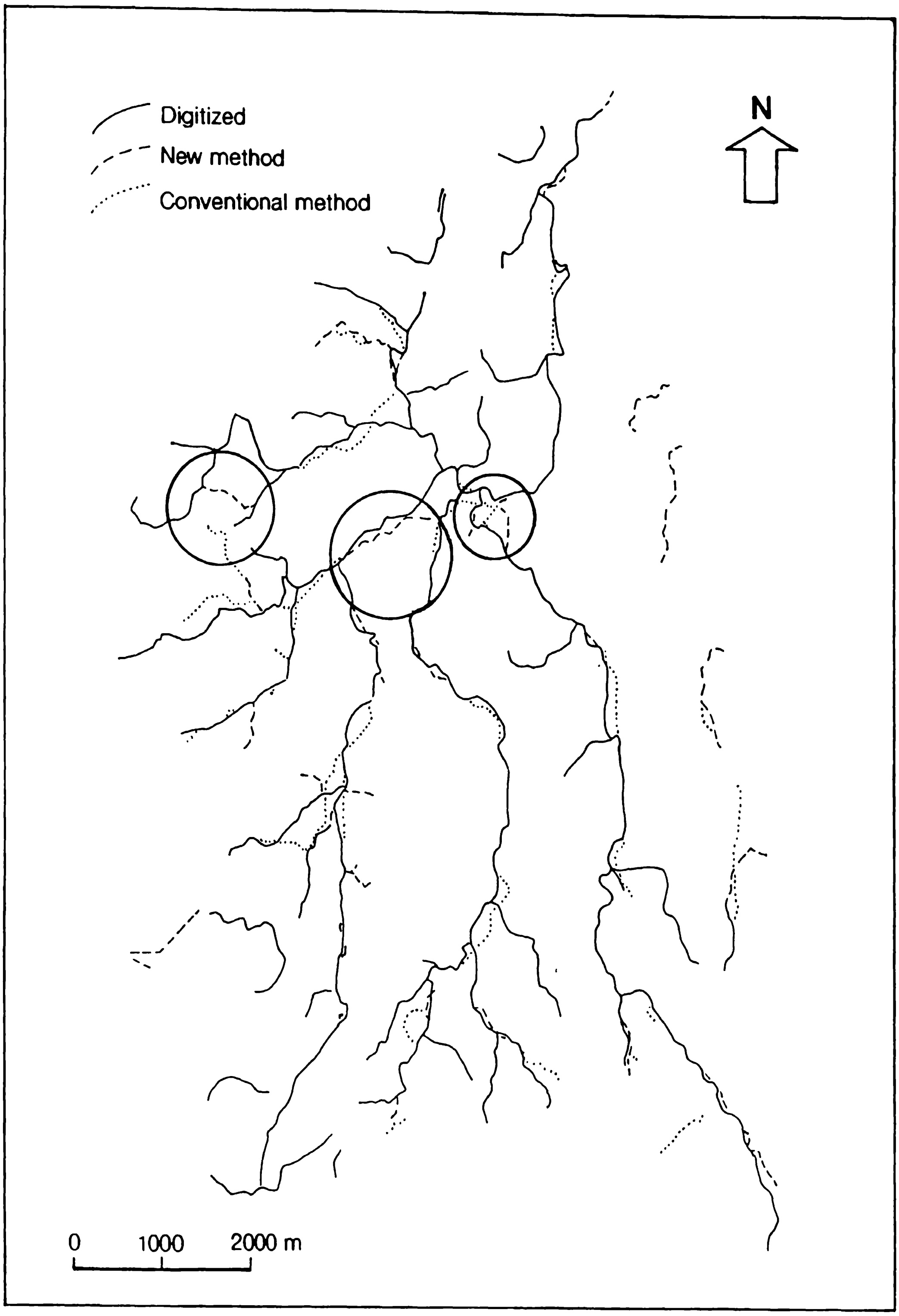

Figure 7.3 Comparison of different methods of stream network delineation.

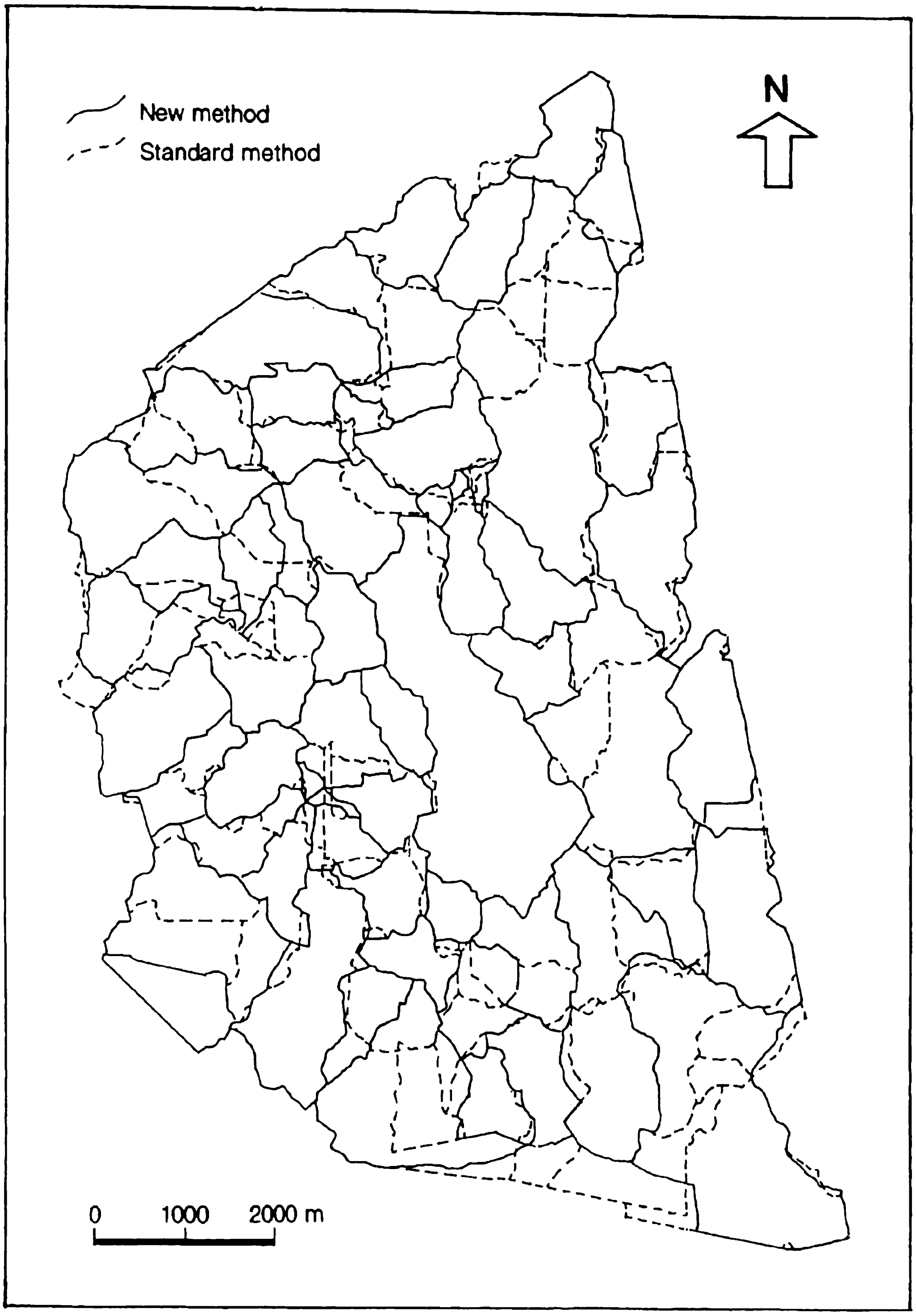

Figure 7.4 Comparison of conventional and new method of watershed delineation.

Easting	Northing	DEM Elevation (m)	Original elevation (m)	Absolute difference (m)
2779403	6353784	553.072	556	2.928
2777483	6354340	540	532	8
2772535	6371510	160	170	10
2773494	6377469	280	282	2
2788594	6374338	82.756	86	3.244
2784302	6364440	380	384	4
2786423	6356713	485	490	5
2772535	6362723	400	405	5
2784302	6372975	70.922	70	0.922
2779402	6353784	553.072	555	1.928
2779908	6370298	202.37	200	2.37
2770262	6370399	439.73	440	0.27

Table 7.1. Comparison of elevations derived from proposed method and original data.

CHAPTER 8

FAILURE OF THE CURVE NUMBER APPROACH FOR RUNOFF ESTIMATION

ABSTRACT: *The curve number approach is widely used as an embedded hydrological component in geographic information systems (GIS). This ready accessibility of a hydrological tool gives rise to the possibility of uncritical use because the curve number is not universally applicable as a means of predicting quickflow. In particular, the curve number approach is likely to fail for localities where there is a high infiltration rate coupled with deep percolation through joints and cracks. The land surface characteristics in such situations have little control over the nature of the runoff hydrograph, and surface-based classification systems such as the curve number method can offer little support toward predicting the quickflow hydrograph. A case study is presented here where the use of the curve number method failed to produce a realistic match to the observed hydrograph in the Opuiaki river catchment, New Zealand using ARC/INFO GIS software.*

8.1 INTRODUCTION

The curve number (CN) method of quickflow runoff prediction has been widely incorporated into GIS software because curve number values are derived from landuse and soil type information which can easily be derived in a GIS environment. The curve number value attempts to represent the amount of rainfall that runs off a watershed as quickflow, and the method proceeds via a table which derives the site curve number as a function of specified land surface characteristic: average antecedent moisture conditions, hydrologic soil group, cover type, treatment and hydrologic soil condition (USA Soil Conservation Service, 1972). Many studies using CN in GIS applications have been reported in the literature - see, for example, [(Hill *et al.*, 1987), (White, 1988), (Muzik, 1988), (Steube and Johnston, 1990), (Bhaskar *et al.*, 1991), (Chang and Muzik, 1991), (Drayton *et al.*, 1992), (Sharma and Singh, 1992), (Brilly *et al.*, 1993), (Smith, 1993), (Warwick and Haness, 1994), (Nearing *et al.*, 1996)].

A concern here is that the easy accessibility through GIS to the CN method as a hydrological tool gives rise to the possibility of uncritical use because the curve number is not universally applicable as a means of predicting quickflow volumes. In particular, the curve number approach is likely to fail for localities where there is a high infiltration rate coupled with deep percolation through joints and cracks. The subsurface geology rather than land surface characteristics will be the dominant factor here, so surface classification methods such as CN are likely to offer little support toward predicting quickflow volumes.

These limitations of the CN method are well known to hydrologists; but because of the increasing use of GIS in hydrological applications, it was felt that it would be helpful to emphasize the limitations of the CN method with a specific case study of a failed runoff prediction.

8.2 GIS DATABASE

The main data sets for this study are elevation contours, rain gauges and discharge recorders, soil types and landuse coverages. These coverages formed the basis of watershed and river network delineation, spatial rainfall and runoff over the area. Table 8.1 shows the coverages required as an input to the model. Contours data was obtained from the Department of Soil and Land Information, New Zealand and all other coverages were produced by using different functions and writing a script (AML). A DEM was created using CREATETIN and TINLATTICE functions which later was used to delineate the watershed and stream network and to estimate surface water FLOWDIRECTION, FLOWACCUMULATION, FLOWLENGTH, stream length, average watershed slope and curve numbers for the study area.

8.3 USE OF CURVE NUMBERS

Direct runoff volume was computed using the standard SCS runoff curve number technique (USDA-SCS, 1972):

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad (8.1)$$

Where Q = direct runoff (mm), P= Precipitation (mm), which was estimated using the spline method of spatial rainfall interpolation using ARC/INFO, I_a = Initial abstraction (mm) and S = potential maximum retention which can be written as:

$$S = \frac{25400}{CN} - 254 \qquad (8.2)$$

Where CN is the SCS runoff curve number, which is a function of soil classification, antecedent moisture conditions and landuse. The initial abstraction was estimated using the empirical relationship $I_a = 0.2S$ recommended by the SCS.

GIS was used to estimate the CN for each sub-watershed. Landuse categories and soil types were established in accordance with SCS methodology. It is important to note that these landuse categories do not typically correspond with the more detailed categorization of the study area. Two lookup tables for SOIL and LANDUSE were created using the "TABLES" program in ARC/INFO having unique identifiers, CN#1 and CN#2 for hydrologic soil group and landuse types respectively. The two coverages LANDUSE and SOIL were merged using the UNION function to create a series of soil group and landuse polygons. The resulting polygon had a unique pair of landuse and soil type identifiers. The RELATE function was used to obtain the item CN#1 and CN#2 from the SOIL and LANDUSE lookup tables, respectively. The CALCULATE command was employed to compute a new item CN#3, which is simply the sum of CN#1 and CN#2. A runoff curve number is then automatically assigned to each polygon based upon the lookup table defining CN as a function of CN#3. Table 8.2 shows the average sub-watershed CN values along with other hydrologic parameters of the study area.

8.4 QUICKFLOW RUNOFF HYDROGRAPH GENERATION

The unit hydrograph of a watershed is defined as the direct quickflow hydrograph that results from one unit of excess rainfall generated uniformly over the watershed at a uniform rate during a specific period of time. The unit hydrograph approach was used to translate the time distribution of excess rainfall into a runoff hydrograph (Chow, 1988). The equation for the storm hydrograph in discrete form is

$$Q_n = \sum_{i=1}^{n} P_i U_{n-i+1} \qquad (8.3)$$

Where Q_n = the storm hydrograph ordinate, P_i = excess rainfall and U_{n-i+1} is unit hydrograph ordinate.

The peak flow rate of SCS dimensionless unit hydrograph is given by

$$Q_p = \frac{0.208A}{t_p} \qquad (8.4)$$

Where Q_p is the peak flow rate (m^3/s), A= drainage area (km^2), t_p is the time to peak (hours) which is estimated using stream length and average watershed slope information.

8.5 ROUTING PROCESS

Flow routing is a procedure to determine the time and magnitude of flow (i.e. the flow hydrograph) at a point on watercourse from the known hydrograph at one or more points upstream (Chow *et al.*, 1988).

The Muskingum routing method was used in this study which models the storage volume of flooding in a channel by a combination of wedge and prism storages. This method consists of a spatially lumped form of the continuity equation.

$$\frac{dS}{dt} = I - O \qquad (8.5)$$

and a storage-discharge relation is expressed as

$$S = K[xI + (1-x)O] \qquad (8.6)$$

Where S = storage or volume of water with the reach, I = inflow rate and O= outflow rate, K= average travel time and x = dimensionless coefficient used to weigh the relative effects of inflow and outflow on reach storage.

The routing procedure uses the finite difference form of the continuity equation combined with the storage equation above.

$$S_2 - S_1 = K[x(I_2 - I_1) + (1-x)(O_2 - O_1)] \tag{8.7}$$

and

$$S_2 - S_1 = (\frac{I_1 + I_2}{2})\Delta t - (\frac{O_1 + O_2}{2})\Delta t \tag{8.8}$$

Combining (8.7) and (8.8) gives

$$(\frac{I_1 + I_2}{2})\Delta t - (\frac{O_1 + O_2}{2})\Delta t = K[x(I_2 + I_1) + (1-x)(O_2 + O_1)] \tag{8.9}$$

Where Δt is the routing period or discretization time interval. Equation (8.9) is re-arranged and solved for O_2 to produce the Muskingum routing equation as follows:

$$O_2 = C_o I_2 + C_1 I_1 + C_2 O_1 \tag{8.10}$$

Where:

$$C_o = \frac{-Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \tag{8.11}$$

$$C_1 = \frac{Kx + 0.5\Delta t}{K - Kx + 0.5\Delta t} \tag{8.12}$$

$$C_2 = \frac{K - Kx - 0.5\Delta t}{K - Kx + 0.5\Delta t} \tag{8.13}$$

Note that $C_o + C_1 + C_2 = 1$

K = average travel time and was evaluated through calibration and x = weighting factor which varies from 0 to 0.5 and a typical value for most natural streams 0.2 was used in this study. An analysis of the weighting factor (x) for this watershed indicated little to no sensitivity in varying x. Therefore $x = 0.2$ is used in this study. The methodology flow chart can be seen in Figure 8.1.

8.6 CURVE NUMBER EVALUATION

A surface runoff model for the Opuiaki river catchment, New Zealand was developed to evaluate the applicability of the widely used curve number method of excess rainfall estimation. The unit hydrograph approach was used to translate the time distribution of excess rainfall into runoff hydrographs for each subwatershed and routed through the network to the principal drainage lines using the Muskingum method. The topographic parameters for each cell were derived from a digital elevation model of the study area. The data required in this study was processed by the widely used geographic information system (GIS) software ARC/INFO due to its flexibility in combining many layers of data arithmetically and logically to provide the required information.

Two storm events (Table 8.3) were selected for the evaluation purposes. The results show the continuous under predictions of the both storm events when compared with the observed data (Figures 8.2 & 8.3). Different travel times (K), 15, 30, 45, 60, 90 and 120 minutes were used to check their effects on the predictions but no significant effect was detected. Figures 8.2 and 8.3 shows the comparison of observed and predicted hydrographs using travel time of 15 and 120 minutes. Table 8.3 explains the observed and predicted results at different travel times. It can be seen from Figure 8.2 & 8.3 and Table 8.3 that both storms have similar time to peak (t_p) as the observed hydrographs that show the accuracy of the methodology used, but the inability of the CN to produce comparable results. The CN is based on the average conditions of limited soil types, landuses and antecedent moisture conditions based on small agricultural experimental watersheds. No CN value could describe the study area well, which has a soil of high infiltration rate and landuse of native bush and *pinus radiata.*

The reason for the CN failure in this case may be the assumption reflected in the initial abstraction term used in the equation (which consists of interception, initial infiltration, surface depression storage, evapotranspiration and many other factors) that is generalized to a constant value. This assumption cannot be applied in areas with a high baseflow component and very little surface runoff like the Kaimai Hydropower catchment. The CN method was found limited in its approach of assigning just a single CN value to a grid or sub-watershed having more than one landuse and soil type. Hjelmfelt (1991) investigated the CN procedure and reported that although the standard CN tables provides helpful guidelines, the CN is not always constant and can vary from event to event. The variability in CN cannot be explained by three antecedent moisture conditions alone. The present study supports the conclusion of Hjelmfelt (1991) and further adds that CN can be used as a parameter to optimize, and the value of CN from the table can be used to get the initial estimate of the value. In this study, the results were very sensitive to any change in CN value, any increase or decrease affected the results positively or negatively. The analysis of the selection of CN for the study area was not investigated further as it was beyond the scope of this study.

A comment is made here as an aside, on the use of the correlation coefficient (r) as an index of goodness of fit between observed and predicted discharges. For example, a number of authors have cited high values of r (or r^2) as indicative of the suitability of the CN approach in their respective study areas [(White, 1988); (Sharma and Singh, 1992), (Nearing *et al.*, 1996). In fact, the correlation coefficient only gives a measurement of the linear association between the observed and predicted values, and does not measure of how well the predicted observations match the observed. This effect can be seen in Table 8.3 where average correlation coefficient value at different travel times was 0.73 and 0.755 for both the storms, but the observed and predicted values were very different (Figure 8.2 and 8.3).

8.7 CONCLUSION

It can be concluded from this study on the applicability of CN approach for estimating surface runoff that users should not use this approach solely because of its simplicity and easy incorporation with GIS functions. This method may give useful results in conditions similar to the original conditions of CN development but will give erroneous results in other areas like Opuiaki river catchment with a high baseflow component and little surface runoff. The CN can be used in other areas as an initial estimate of the value for optimization purposes but its use in its original form is not recommended. The hydrologic soil groups, landuse classifications and the antecedent moisture conditions provided with this method are not detailed enough to be used universally. The correlation coefficient between observed and predicted discharges should not be used to evaluate the applicability of the CN approach, and is recommended that the observed and predicted discharge hydrographs should be plotted when comparing the results. The CN approach in its original form is not recommended for the study area or any other area with different conditions than its developmental conditions. This research has successfully demonstrated the integrated approach of GIS use in surface hydrologic modeling by combining the vector and raster data structures and also shows the effective use of arc macro programming language of ARC/INFO GIS software.

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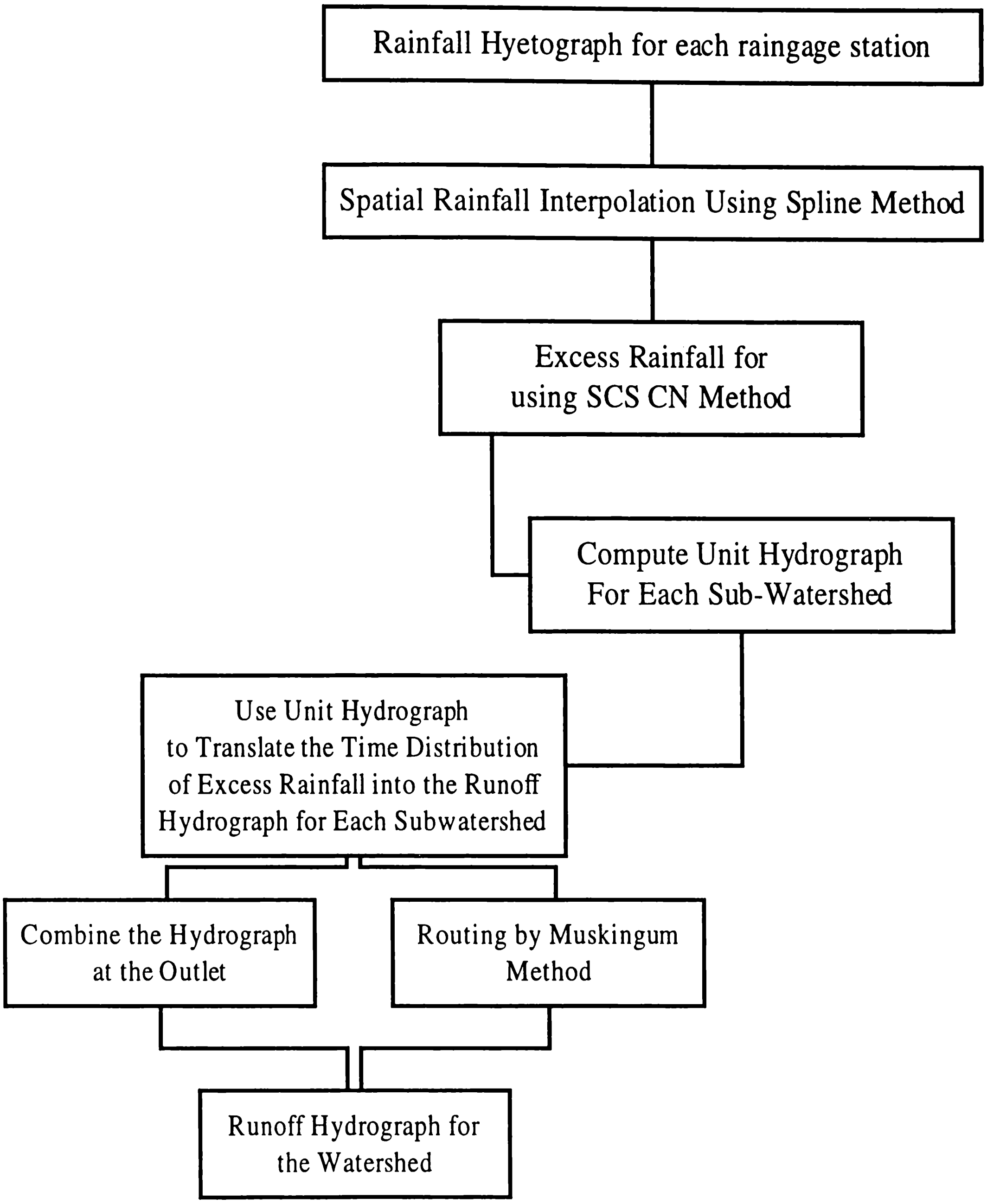

Figure 8.1 Methodology flow chart of surface runoff model

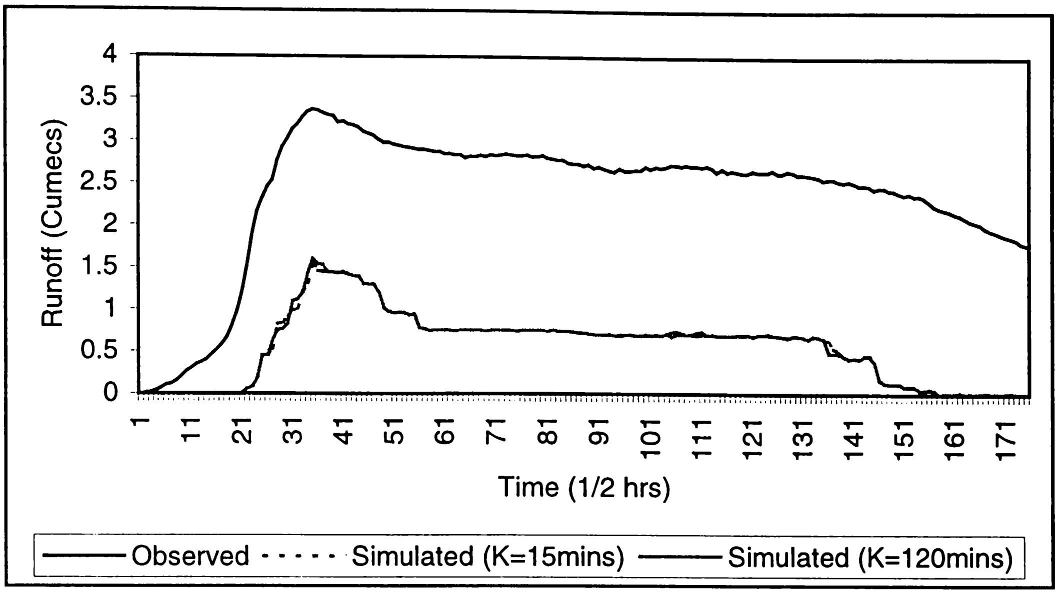

Figure 8.2 Observed and predicted runoff for the storm event of 20/8/96.

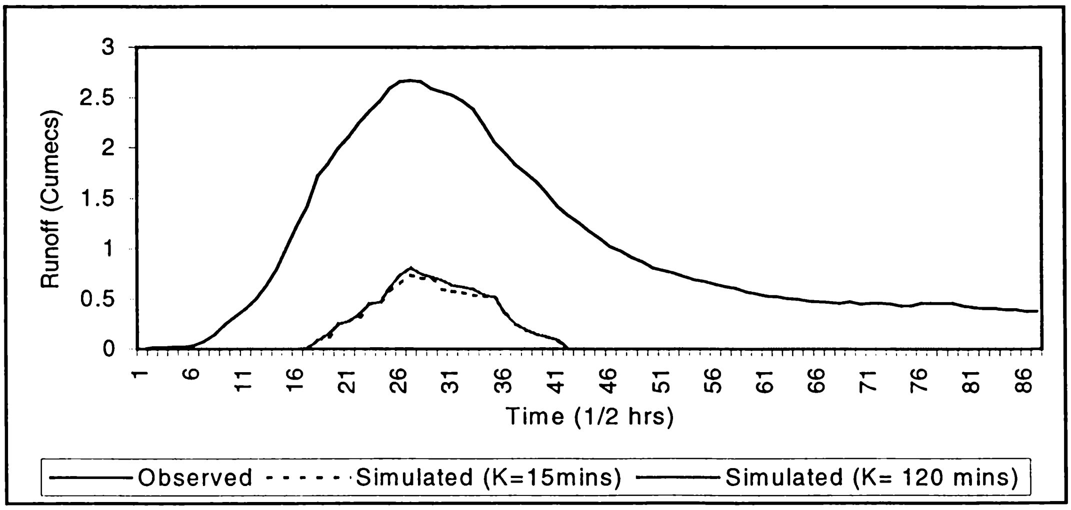

Figure 8.3 Observed and predicted runoff for the storm event of 1/10/96.

Coverage name	**Description**	**Coverage type**
CONTOUR	20 m contours map	Arc
RAIN GAUGES	Rain gauge locations	Point
BASINS	Delineated watersheds	Polygon
RIVER	Delineated river network	Arc
SOIL	Soil types	Polygon
LANDUSE	Catchment landuse	Polygon
CHANNEL	Surface runoff routes	Arc

Table 8.1 Principal ARC/INFO input coverages.

Sub-watershed#	Area (km^2)	Stream Length (km)	Average CN
1	19.2	9	42
2	18.7	4.25	48
3	19.4	5.15	39
4	14	1.01	37
5	16.7	3.01	41

Table 8.2 Hydrologic parameters of Opuiaki river catchment.

Date	Rainfall Duration (minutes)	Total Rainfall (mm)	Time to peak (min)		Travel Time (K) (minutes)	Peak Discharge (m^3/s)		Correl. Coeff.
			Observed	Predicted		Observed	Predicted	
20/8/96	585	74.2	1050	1050	15	3.369	1.53	0.76
			-	-	30	-	1.55	0.72
			-	-	45	-	1.54	0.71
			-	-	60	-	1.56	0.72
			-	-	90	-	1.58	0.75
			-	-	120	-	1.60	0.75
01/10/96	300	34	810	810	15	2.666	0.74	0.76
			-	-	30	-	0.74	0.75
			-	-	45	-	0.73	0.77
			-	-	60	-	0.75	0.73
			-	-	90	-	0.78	0.75
			-	-	120	-	0.81	0.755

Table 8.3 Storm characteristics at different travel times.

CHAPTER 9

SURFACE HYDROLOGIC MODELING: PERFORMANCE COMPARISON OF SPATIAL AND LUMPED APPROACHES

ABSTRACT: A map-based surface water flow simulation model which is based on Geographic Information Systems (GIS) and Object Oriented Programming (OOP) was evaluated for the Kaimai Hydropower catchment, Tauranga, New Zealand after modification in its original codes. The selection of this model was based on its strength in addressing the GIS and hydrologic modeling as an integrated field in the area of runoff prediction involving time series data. The map-based model overcomes the inability of ARC/INFO GIS in handling time series data. It gave a good match with both observed and black box predicted inflows. It proved to be a good strategic management tool for planning purposes but has limited use as an operational tool because of greater computational requirements involved. The map-based model is a useful addition in the field of integrated spatial hydrologic modeling using GIS. It also solves many of the basic problems such as feature oriented map operations, dynamic segmentation of an arc, spatial time series database development which previously were not possible in a GIS environment.

9.1. INTRODUCTION

Only a few years ago, GIS was a management tool merely used to analyse spatial data ranging from environmental and urban planning to agricultural studies. At this time, hydrologists were collecting their own data and storing in a format specific to the model they worked with. GIS was not analytical enough for their needs, and the model was not effective at data management or display. The integration of the technologies began slowly as GIS was used to perform overlays and aggregate information such as basin characteristics to pass to an external FORTRAN program or statistical package. These links evolved to more complex and robust implementations, where simple models were embedded in GIS or input/output (I/O) routines of the GIS were embedded into complex models. During this time the software industry graduated to multiple window systems and menus, and started to develop integrated applications. By the early 1990s, developers of GIS software began to include functionality of particular interest to hydrologists. As a result, connections between GIS and hydrologic models have grown steadily stronger (Kopp, 1996) and many researchers successfully developed or linked hydrologic models with GIS such as: [(HEC, 1983, 1985), (Debarry and Carrington, 1990), (Johnson *et al.*, 1988), (Muzik, 1988), (White, 1988), (Vieux *et al.*, 1988), (Ross *et al.*, 1990), (Curtis, 1994)].

Lumped runoff models are often used to simulate runoff processes in large basins. These models are often preferred to distributed runoff models, as the latter tend to be more complex and require much more computation for large watersheds. However, most lumped runoff models are abstract, and do not allow a close examination of the influence of a basin's topographic characteristics on runoff processes. Furthermore, a lumped runoff analysis seldom provides enough information about the water distribution in the basin. In order to overcome the shortcomings associated with both the distributed model and the lumped-parameter model, Ye (1996) developed a surface runoff model which took into account the distributed nature of state variables and topographic characteristics. This GIS-based hydrologic simulation model consists of three elements:

i) equations that govern the hydrologic processes;
ii) maps that define the study area;
iii) database tables that describe numerically the study region and model parameters;

When a model is constructed with its three elements separated, its portability and user-friendliness are usually limited because any modification of one component will not be reflected in the others. The purpose of this research is to evaluate the map-based flow simulation model with all three model components integrated. The selection of this model was based on its strength in addressing the GIS and hydrologic modeling as an integrated field in the area of runoff prediction involving time series data. The original model was developed (Ye, 1996) for Niger River basin, West Africa with a total drainage area of 119,532 km^2 and included many approximations and average conditions to apply on a continental scale using monthly time step. Considerable effort was put in this evaluation study to modify the codes to make it work for the study area at daily time steps . This research will also evaluate the techniques developed as part of the map-based model on other GIS related problems in the field of hydrologic modeling like feature oriented map operation, dynamic segmentation of an arc, time series data handling. The criterion adopted for the evaluation was to find out whether map-based model could be used for inflow prediction purposes and the level of its contribution in the field of spatial hydrologic modeling.

9.2. OVERVIEW OF THE MAP-BASED MODEL

More recently there is a trend towards OOP by many of the researchers and software developers and is often referred to as a new programming paradigm and provides the opportunity to build substantial applications based on the work of others. User interface can be developed more quickly in an object oriented development environment because the developer and ultimately the user begin with a palette of pre-existing objects. Objects created for one application can serve as building blocks for other applications. In an OOP system, the rule is, "Ask, don't touch". Complex data are treated as single objects managed automatically by the underlying operating environment and encapsulated procedures (i.e., complexity) are completely hidden from the requestor. The difference between procedural programming and OOP lie mainly on the organization of programs, calling of modules and how variables are stored and retrieved (Winblad *et al.*, 1990). Although in an OOP language state, behavior and interface are used jointly to define an object, they can each be defined independently from one another. This fact can be used to support the design of a generic GIS database management system. In the context of hydrologic analysis, the state of an object can be described by the attributes of a stream section or a river basin while the behavior can be viewed as the hydrologic processes occurring on a river section or a river basin. Since the state and behavior are independent, they can be treated separately with state variables be stored and managed in a GIS database and behaviors described by various models. The concept of state and behavior independence is essential to the design of a GIS database that can be shared by many external models. GIS database design of map-based surface flow simulation model is based on this concept (Ye, 1996). Model using similar approach have been developed by [(Shiba *et al.,* 1996), (Ackermann, 1996), (Costa *et al.*, 1996), (Fedra and Jamieson, 1996) in different hydrologic modeling areas.

As mentioned earlier, the map-based model is developed using the concepts of OOP and GIS. GIS was used to integrate the maps and databases while the OOP was used to integrate the data sets and programs. ARCVIEW as the host environment was used to develop a map centric surface flow simulation model because it provides both spatial database management and OOP (AVENUE) capabilities. The model consists of a set of pre-processor, processor and post-processor AVENUE programs. ARC/INFO GIS was used as a part of pre-processing procedures. This model designed data structures that can be imbedded in or connected to a GIS map to manage the spatially referenced time series data efficiently and effectively. The spatial operations applied to a given map feature that would involve the features of other map can also be carried out in this model.

The map-based model considers two types of models, one for the flow in river streams and other for the flow over a regular land surface. The conceptual design and equations used in this model are explained in Appendix 3. The pre-processors are used to create objects, construct model base maps, create time series data tables and process time series data. The processor is used to simulate water flow on river streams and sub-watersheds. The post-processors are used to analyse and display model results and can also be used to interpolate the flow at any user defined locations, to create dams and flow diversions on river network. The main methods used in this model are: i) inverse distance method for rainfall interpolation, ii) a simple bucket model for water surplus estimation [(Thornthwaite, 1948), (Willmott *et al.*, 1985), (Mintz and Serafini,1992)] iii) convolution procedure developed by Olivera and Maidment (1996), iv) In this map-based surface water flow simulation model, four flow routing modules are provided to simulate water movement between From-Node and To-Node. Which are (1) response function (2) two-step function (3) dam/reservoir-two-step function and (4) Muskingum-Cunge methods. All of these four modules are constructed based on the principle of continuity.

9.3 MODEL EVALUATION

As mentioned in the last section, the map-based model uses both lumped and distributed approaches of modeling. The map-based model is lumped for each subwatershed because only one averaged value is calibrated for each parameter within each subwatershed but for the whole basin model can be distributed or semi-lumped because the value for each parameter may vary between sub-watersheds depending on the availability of the data.

The map-based model requires point coverages of rainfall and runoff stations and associated time series data attached to them in a format, time in the first column and the rainfall or runoff data in the respective columns according to the field defined on the point coverages so the model can read time series data associated to each rainfall or runoff gauge. Three other important coverages are required as an input which are a line coverage representing the river network, polygon coverage representing the drainage area and watershed boundary line coverage. These maps or coverages were obtained by applying a delineation procedure developed by Choudhry *et al.* (1997) on the digital elevation model of the area using 50x50m grid size and threshold value of 15000 cells. Seven pre-processors were run in order to set up the base maps and to create necessary tables for holding time series data which will later be used for simulation purposes. Before using pre-processors, it is very important to dissolve single cell polygons, which are result of delineation procedure. Dissolving procedure can't be accomplished using programs within ARCVIEW, it requires the use of the "DISSOLVE" function of ARC/INFO as well. This procedure dissolved all the single cell polygons to its adjacent polygons with the same grid-code which share at least one boundary line. The program provided within the map-based model dissolved all the unwanted single cell polygons. This procedure was important to maintain the basic assumption of the model that each subwatershed contains one and only one river section. Pre-processor procedures created the attributes of a subwatershed polygon and river line object as mentioned in Table 9.1 and Table 9.2. Only attributes related to surface water flow simulation model were used in this study.

9.3.1 Model calibration

Once the maps of the study area have been set after building the topology, and time series tables related to the simulation model have been created using pre-processors, then the model was calibrated. Before calibration two important procedures were applied i) water surplus on the center of watershed polygons was computed from rainfall data ii) initial estimates of the parameters were filled in the attribute tables of river and watershed coverages that will later be used for optimization procedure. An ARC/INFO program was used to estimate the parameters like lag time, diffusion number, mean flow length and flowtime using the "FLOWLENGTH" and "ZONALSTAT" functions of the ARC/INFO. An initial estimate of all other parameters was set for optimization.

A sub-model was created associated with the T4 inflow station for calibration purposes. Figure 2.2 of chapter 2 shows an overlay of sub-watersheds, rivers, rainfall and runoff stations in the study area. Six months of daily rainfall and runoff data was used for the calibration purposes. Two optimization routines (interactive and directional set) are available in the model. The directional set method of optimization was used in this study because of its flexibility in handling multiple parameters and coverages. Table 9.3 explains the seven parameters of the simulation model, which were selected initially for model calibration. An optimization procedure was applied on the T4 sub-model using the parameters explained below. It was noted that parameters "Resk", "Tores" and "Togrd(2) had little or no impact on simulation. Therefore, ResK = 12 and Tores = 0.25 were maintained throughout the calibration but Togrd (2) was set to zero as only one of these parameters (Togrd(1), Togrd(2)) was required for calibration. Togrd(1) was retained and set equal to 0.1. Both river flow velocity and overland flow velocity affect flow distribution over a time domain, only one of them (river velocity) was retained for optimization purposes while the overland flow velocity "Vfact" was set equal to 0.035m/s through out the calibration. All these parameters were achieved by running the model many times under different model conditions. Finally, three parameters LossC, river velocity and Togrd were used for final run. The model gave a good match between observed and calibrated data. The model was validated using an independent set of data and the results are explained in Figure 9.1.

9.4. BLACK BOX TYPE INFLOW PREDICTION MODEL

The Rainfall-runoff models can assist in decision-making problems ranging from inflow prediction, on-line flood forecasting to landuse change evaluation and design of hydraulic structures. A black box rainfall-runoff model has been developed to compare its prediction ability with the map-based model for the Kaimai Hydropower scheme, New Zealand which consists of three parameters. The parameters were optimized using an optimization method of finding the greatest or least value of a function (Rosenbrock, 1960). The model was developed and validated using rainfall and discharge data and gives a good fit to the observed data. Figure 9.1 explains the results of the model.

The general form of the recursive prediction equation is as follows:

$$\hat{Q}_{t+1} = P(\hat{Q}_t + \beta R_{t+1}) + \gamma(1 - P) \qquad (9.1)$$

Where,

γ = Baseflow constant

t = daily interval

R_t = Daily rainfall forecast (mm)

$\hat{Q}_t$ = The most recent recorded inflow used for first calculation.

The recursive prediction equation for the Opuiaki river catchment is

$$\hat{Q}_{i+1} = 0.8128(\hat{Q}_i + 0.041 R_{i+1}) + 0.277 \qquad (9.2)$$

$$\hat{Q}_{i+1} = 0.8128 \hat{Q}_i + 0.033 R_{i+1} + 0.277 \qquad (9.3)$$

9.5. DISSCUSION

Figure 9.1 shows the performance of the black box and map-based models, compared to the observed data. Both models display a good match with the observed data. The main advantage of the black box model is that results are readily available “at the click of a button”. This outcome can further be used as an input to real-time power scheduling software in the case of hydropower operation. However, the black box approach has limited applicability, in terms of strategic planning and management. Such abstract models cannot take into account the spatial variability within the catchment, because of the lumped nature of the parameters. By contrast, map-based models give users the opportunity to change the model's assumptions (or equations), by adjusting the parameters of the inherited object as stated earlier. Users can define the parameters for each sub-watershed or river section depending on the availability of the data, which would make map-based models very useful for planning purposes.

In a map-based algorithm, water movement takes place at three levels:

i) watershed to river movement, defined on a watershed polygon;

ii) water movement on a river/stream section contained in a sub-watershed polygon;

iii) inter-section river movement.

Algorithm (i) and (ii) in the model are problem-specific, which makes map-based models easy to modify in order to simulate other flow related phenomena, such as non-point source pollution (as long as the module for polygon flow is properly modified). The model can also be used to see the effect of dams and flow diversions, or to interpolate the flow rate at any point on a river arc; and will also give users the opportunity to plot the flow distribution. Options are available for plotting flow distributions along a selected stream or flow time series (Fflow, Tflow, and Pflow), at a specified location. These options also make this model superior than the black box model as black box model cannot give results at any part of the catchment.

As discussed in the introduction, the hydrologic simulation achieved through the map-based model has combined three elements (equations, maps and database tables). By incorporating these elements into a spatial data structure, the model was able to overcome the limited ability of most current GIS software to handle time-series data which are very important to hydrologic phenomena. Furthermore, maps built for surface flow simulations can also be used for sub-surface flow models; and map-based models are interactive and menu driven, which make them easier to work with. Despite the many advantages highlighted above, however, there are several limitations associated with map-based modeling. Object oriented environments require that both the input and output tables have the same number of records. Any change in one table will necessitate the pre-processing procedures to run again. Also, optimization routines cannot be run for a whole basin at once. For calibration purposes, the model requires the construction of sub-models associated with each runoff station.

More specifically, the current map-based model has encountered some limitations relating to the type of software used. An ARCVIEW driven map-based model cannot be used independently, as it would require frequent interactions with the ARC/INFO superset. This renders the model rather expensive to operate. In additions, ARCVIEW cannot handle more than 200 data points for plotting purposes, which may limit the model user in visualizing the results interactively. The model's low speed has also presented a limitation, especially when 1200 or so points, more than two coverages and four parameters were used, during the calibration process, to optimize more the model's parameters. These limitations concede the shortcomings of the proposed map-based model as an operational tool, in the field of inflow prediction, for hydropower operation. Nevertheless, the model is expounded here as a contribution towards integrated hydrologic modeling, using aspects of modern GIS technology.

9.6 CONCLUSION

The map-based model is a map-centric and it allows all the regular model procedures such as construction, simulations, modifications, and result processing to be activated directly from the model maps. Based on this 'map-centric' and object-oriented concept, a map-based water flow simulation model is evaluated and successfully applied to simulate surface flow on the Kaimai Hydropower river basin, Tauranga, New Zealand.

It proved to be a good strategic management tool for watershed planning purposes but showed its inability as an inflow prediction tool when compared with the black box model results. However, its spatially distributed nature allows user to find information for any part of the catchment, which makes it superior from black box model. The map-based model can be used for other environmental studies such as non-point source pollution with little modifications. It provides a significant contribution towards integrated hydrologic modeling using GIS and has successfully designed the spatial database for handling time-series data. This model has also addressed successfully many other inherited problems of GIS like, feature oriented map operations, dynamic segmentation of an arc. It can be applied to any area where a digital elevation model is available with minor modification in the codes. In short, map-based model is a step forward in the field of integrated spatial hydrologic modeling using GIS.

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	State	**Function (What the attribute represents)**
1	Shape	Pointer pointing to the map location of a polygon object
2	Area	Area of a watershed polygon (m^2)
3	Perimeter	Perimeter of a watershed polygon (m)
4	Cover_	Polygon ID, based on which pointers to time-series vectors (PFlowVt,sprVt, rchVt, headVt, dhVt, dvolVt, etc.) associated with the polygon are constructed.
5	Cover_id	User assigned polygon id
6	Grid_Code	Key field linking a subwatershed polygon with the river line section it contains
7	Pisdone	0 indicates the polygon has NOT been simulated, non-zero, otherwise, and the value equals the number of polygons between this polygon and the outlet
8	PFlow	Local flow contribution, for unsteady state, it gives the average flow rate over the models simulation period (m^3/s).
9	FlowTime	Average time it takes for flow starting from an element (a grid cell) on a subwatershed to reach the outlet point of the subwatershed (s)
10	DiffNum	Diffusion number of PFlow indicating the extend of the PFlow spread-out
11	V	Overland flow velocity (m/s)
12	ThmRslt	For thematic plotting of a selected attribute at a given time step
13	Hasgrd	0 indicates no groundwater flow model exists underneath, 1, otherwise
14	ToGrd	The percentage of flow recharging to the groundwater system
15	MFL	Mean flow length of a subwatershed (m)
16	Msurp	Soil moisture surplus (m^3/s) (subwatershed river flow contribution)
17	ToRes	The fraction of the subwatershed water surplus that goes to subsurface reservoir
18	ResK	Mean residential time of water in a subsurface reservoir [T]

Table 9.1 The attributes of a subwatershed polygon object [Source: (Ye, 1996)].

	State	**Function (What the attribute represents)**
1	Shape	Pointer pointing to the map location of an object
2	FNode_	Node ID of the starting point of a river line section
3	TNode_	Node ID of the ending point of a river line section
4	Lpoly_	Left polygon machine-assigned ID (ID of the polygon to the left of the line)
5	Rpoly_	Right polygon machine-assigned ID (ID of the polygon to the right of the line)
6	Length	The length of a river line section (m)
7	Cover_	Machine assigned river line ID
8	Cover_id	User assigned river line ID
9	Grid_code	Key code linking subwatershed polygon with the river line section it contains
10	LIsDone	0 indicates a river line has NOT been simulated, non-zero value, otherwise, and the value equals the number of joints between this river line and the basin outlet
11	IsHead	1 indicates a river line is a head section (section with no upstream river lines)
12	IsOutlet	1 indicates a river line is a outlet section (last section on a stream network)
13	FFLOW	The flow rate at the FNode of a river line (m^3/s)
14	TFLOW	The flow rate at the TNode of a river line (m^3/s)
15	DFlow	The water withdraw on a river line (diversion flow rate) (m^3/s)
16	Velocity	Flow velocity on a river line (m/s)
17	LossC	Loss coefficient related to a river line (1/m)
18	Timelag	Flow time to the TNode of a river line along its longest upstream flow path (s)
19	MELE	Mean elevation of a river line (m)
20	HasDam	0 indicates there is no dam in the river line, non-zero indicates otherwise, and the value is the dam-id of the first dam on the river line
21	Hasresp	0 indicates no response function is available, non-zero value indicates otherwise, and the value equals the number of the elements in the response function
22	Hasgrd	0 indicates no groundwater flow model exists underneath, 1 indicates otherwise
23	togrd	The percentage of river flow that goes to groundwater recharge

Table 9.2 The attributes of a river line object [Source: (Ye, 1996)].

No	**Parameter**	**Definition of attribute or parameter**
1	LossC	Loss coefficient related to a river line (1/m)
2	ResK	Mean residential time of water in a subsurface reservoir [T]
3	ToRes	The fraction of a subwatershed water surplus that goes to the subsurface reservoir
4	VFact	Overland flow velocity (m/s)
5	Velocity	Flow velocity on a river line (m/s)
6	Togrd(1)*	Percentage of river flow that goes to groundwater recharge
7	Togrd(2)*	Percentage of subwatershed flow recharging to groundwater system.

(Symbol (1)* and (2)* is used to distinguish between river and watershed parameters)

Table 9.3 Model parameter to be calibrated.

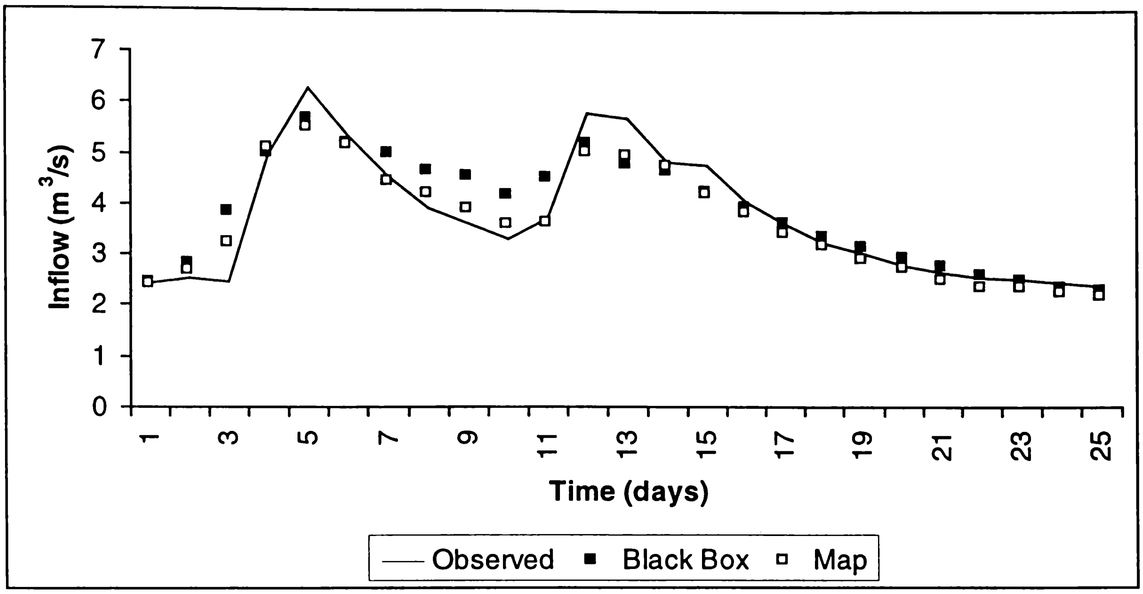

Figure 9.1 Comparison between observed, black box and map-based model results.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

This study has shown the effective use of black box and distributed (GIS) modeling approaches by applying both approaches in the study area. The importance of GIS data quality for hydrologic applications has been demonstrated by studying different types of GIS errors and developing techniques to handle them. The objectives mentioned in Chapter 1 were achieved as follows:

1. A black box inflow prediction model for the Kaimai Hydropower catchment was developed as a requirement for the power scheduling software "HYMAX". The model was tested as a predictive tool by including rainfall forecasts from New Zealand Meteorological Services and gave good prediction when compared with the observed data. The inflow prediction model was used as an input to the HYMAX software in order to evaluate the performance of the Kaimai Hydropower scheme.

   The data analysis for the evaluation of HYMAX concluded that there is clear evidence of improvement in the operation of the Kaimai Hydropower scheme by using the power scheduling optimization software (HYMAX). The winter season data analysis showed a significant improvement in the income of the Kaimai Hydropower scheme by 7.0%, apparently achieved by instructing the operators about HYMAXs decisions. This improvement may be a little less in the summer season. More data is required to quantify the actual increase in the income for the summer season provided HYMAX is being used in decision making. HYMAX always showed a significant improvement over the control room operation for the analysis period. The software has demonstrated the benefit of optimizing the storage-constrained schemes like the Kaimai Hydropower scheme in a competitive power-marketing environment. It is worth noting that all these improvements in the operation of the hydropower scheme are by instructing the operators about the HYMAXs decisions, but the real power of HYMAX is its ability as a real-time prediction tool. The data analysis results indicated there is still a possibility of improvement in the operation of the Kaimai Hydropower scheme by using HYMAX as an independent real-time prediction tool.

2. The Kaimai Hydropower catchment has undergone landuse change from native forest to *pinus radiata* in different parts of the catchment since 1982. There was no detectable reduction in annual or seasonal water yield, on the basis of analysis of electrical power output as a proxy for catchment water yield. The minimal impact is attributed in part to the fact that fully developed *pinus radiata* and the native forest vegetation appear to have similar water loss characteristics. Also, the incremental nature of the landuse change meant that at any one time only a small proportion of the catchment was in a clear-felled state, causing a small water yield increase after landuse change for winter and spring seasons. It is recommended, where appropriate that incremental catchment landuse change is a more desirable landuse modification option.

3. The use of GIS in the field of hydrologic modeling has increased significantly over the last decade. A review was conducted in the following areas: i) past efforts and current trends in using GIS to perform hydrologic analysis. ii) errors involved in using digital data and their effects in hydrologic modeling results. iii) limitations of GIS use in hydrologic modeling. The review concluded that despite concerns about GIS use in hydrology at present, spatial aspects of hydrology are likely to become integrated into a GIS framework in the future.

4. A study was conducted of the effects of different types of GIS errors such as generalization of the data, vector to raster conversion, and sink artifacts. The conclusion of the data analysis was three folds:

i) as the level of generalization increases, the information loss also increases which can be significant for surface hydrologic modeling applications. A manual procedure of avoiding generalization error is proposed.

ii) the conversion of data from vector to raster format clearly indicates that as the grid size increases the area displacement also increases, which can introduce false parameters in the hydrologic model. A model for the study area was developed which shows the relationship between the grid size and area displaced.

iii) a method that distinguishes between DEM processing errors and natural true closed catchments is also developed and proposed for hydrologic studies.

5. Digital elevation models (DEMs) are widely used to delineate (the topographic characteristics of) hydrologic features. However, during the building of DEMs, spatial errors often propagate through the hydrologic model. Therefore, the accuracy of any DEM-based hydrologic model depends on the accuracy of the DEM used. The role of 'breaklines' (which define and control surface behavior in terms of smoothness and continuity) was examined in building DEMs for surface hydrologic modeling, and a new methodology is proposed which used soft breaklines to improve the quality of these models. The new technique has showed a marked improvement over conventional methods for delineating watershed and stream networks.

6. A surface runoff model for the Opuiaki river catchment, New Zealand was developed to evaluate the applicability of the widely used curve number (CN) method of excess rainfall estimation. The unit hydrograph approach was used to translate the time distribution of excess rainfall into a runoff hydrograph for each subwatershed, which was then routed through the network to the principal drainage lines using the Muskingum method. The CN method failed in the Opuiaki river catchment, New Zealand because the hydrologic conditions required by this method could not accurately describe the geology of the study area which has a high infiltration rate coupled with deep percolation through joints and cracks.

   The land surface characteristics in such situations have little control over the nature of the runoff hydrograph and surface-based classification systems such as the CN method could offer little support toward predicting the quickflow hydrograph. It was noted that the correlation coefficient between observed and predicted discharges should not be used to evaluate the applicability of the CN approach, or as an index of goodness of fit in general. The CN approach, in its original form, is not recommended for the study area or any other area with similar hydrologic, soils and landuse conditions. This study successfully demonstrated an integrated use of GIS in surface hydrologic modeling by combining the vector and raster data structures and also explained the effective use of The Arc Macro programming language (AML) of ARC/INFO GIS software.

7. A map-based model is map-centric and it allows all the regular model procedures such as construction, simulations, modifications, and result processing to be activated directly from the model maps. Based on this 'map-centric' and object-oriented concept, a map-based water flow simulation model was evaluated and successfully applied to simulate surface flow on the Kaimai Hydropower river basin, Tauranga, New Zealand. The selection of this model was based on its strength in addressing GIS and hydrologic modeling as integrated field in the area of runoff prediction involving time series data. The map-based model overcomes the inability of ARC/INFO GIS in handling time series data and has given a good match when compared with the observed and black box predicted inflows. The model proved to be a good strategic management tool for planning purposes but has limited use at present as an operational tool because of the great computational requirements involved. The map-based model should be a useful addition in the field of integrated spatial hydrologic modeling using GIS. It also solves many basic problems such as feature oriented map operations, the dynamic segmentation of an arc, and spatial time series database development which previously were not possible in a GIS environment.

10.2 RECOMMENDATIONS

The results from this study suggest the following research and study needs:

- The black box inflow prediction model should be modified for rainfall forecasting as well.

- The impact of other GIS errors (like resampling and digitizing errors) on hydrologic modeling should be evaluated.
- Techniques should be developed to replace the raster based digital elevation model (DEM) with the triangular irregular network (TIN) in doing hydrologic data analysis involving GIS. The TIN data structure represents more accurately the original grid data and boundaries of the triangulation can conform to any desired shape.
- An automated methodology should be developed to generate data (such as landuse and soil types) using remote sensing technology and directly link these data to the GIS.
- The appropriate CN should be developed for the study area using the optimization technique.
- The map-based model should be evaluated as an integrated model (surface and sub-surface components) for the study area.

APPENDIX 1

A1.1 DATA COLLECTION

Prior to this study, there was no recorded detailed rainfall and streamflow data available in the catchment. In order to develop an inflow prediction model, rainfall and stream flow data sets were required in a half-hour interval. Field surveys were conducted to find the suitable locations for the rainfall and stream flow gauges. The location of the rainfall and streamflow stations can be seen in Figure 2.2 of Chapter 2.

A 1.1.1 Rain gauge

The selection of rain gauge type was constrained with the budget available. Three Davis 0.2mm rain gauges with data loggers were selected for the study area as shown in Figure A1.1. These gauges have the capability to be used as real time recording gauges, which is required for the inflow prediction for the hydro scheme. Rain gauges were tested following the instructions available in the user manual before being installed in the field. The locations of the rain gauges were selected using the following criteria reported in (Fenwick, 1994) by making sure:

- That the surface is level which was achieved using the T-shaped leveling trough in the base.
- That there is an unobstructed path for water runoff.
- That the rain gauge is away from any object which attracts a magnet as it contains a magnet operated switch.
- That the selected location is accessible for normal cleaning and is distant from trees or other sources of heavy pollen or debris.
- That no objects are within a 30-45° arc from the orifice.

A1.1.2 Streamflow recorder

Two starflow ultrasonic doppler instruments were selected for stream flow gauging in the catchment. This instrument also measures water velocity, temperature and depth. The starflow instrument can be set at different scan rates and log intervals and can also be used for real-time recording. The doppler instrument was adjusted to a 60-second scan rate and the average value of flow for the half-hour was obtained. Figure A1.2 explains different parts of the starflow dopller instrument. According to the users manual, starflow measures velocity to an accuracy of ±2% of measured velocity and depth to ±0.25% of the calibrated range. This instrument was found sensitive to high water pressures.

A1.1.3 Selection of the site for starflow gauge

Due to budget constraints only two starflow doppler instruments were purchased. Initially, it was intended to install the starflow doppler instruments at the outlets of T5 and T3 tunnels as the sum of the flow from these two tunnels constitute the total inflow for the lake Mangaonui, with the exception of flow from Mangaonui and Waitaia streams. These two streams were gauged using a Pygmy meter and their inflow was found as 0.057 and 0.03 m^3/s respectively. It was practically not possible to install the doppler instrument at the T5 outlet because of the K5 submersible turbine at that location, so, the doppler instrument was installed at the T5 inlet. Unfortunately, the doppler instrument at the T3 outlet location did not work because of high water pressure at that particular location. The location of T3 inlet was not accessible and the other tunnels such as T2 and T1 were not of much use as the purpose was to estimate the value of natural inflow going into the Lake Mangaonui. The other starflow doppler instrument was installed at the T4 outlet. Locations of T1, T2, T3, T4 and T5 tunnels can be seen in Figure 2.2 of chapter2.

A1.2. LAKE INFLOWS

The purpose of all the stream gauging in the catchment was to obtain an accurate value of the natural inflow to all three lakes. These inflow measurements were necessary for the construction of an inflow prediction model. The only available stream flow data was at T4 and T5 locations. In order to establish a relationship between tunnel discharges and the lake inflows, the natural inflows for the lakes were required. Natural inflows to the lakes were synthesized by finding the time when no power was being generated at upstream and downstream locations of any particular hydro station. The relationships were established between tunnel flows and the synthesized natural inflows for the Lake Mangaonui, Lake Matariki and Lake Mclaren. Lake Mclaren data was adjusted for the Mangakarengorengo River contribution, which was gauged as 1.1 m^3/s under normal conditions. The Mangapapa River was also gauged, its contribution to the Lake Matariki after its flow was diverted to Lake Mangaonui, was found to be 0.18 m^3/s under normal conditions. The data analysis showed that T5 flows were closely related to those of Lake Mangaonui and Matariki and T4 flow was closely related to Lake Mclaren. The reason T4 flows are closely related to Lake Mclaren is that under normal and flood conditions, all the flow from upper catchment (after diverting through tunnel T5) including spillage goes directly to Lake Mclaren by-passing both the upstream lakes. The Lake Mangaonui and Matariki inflows were obtained by multiplying the T5 inflow by a factor of 2.6 and 0.33 respectively, and Lake Mclaren inflows were estimated by multiplying the T4 inflow by 2.62. These constants are the slopes of the cumulative relationships between tunnel inflows and synthesized lake inflows.

A1.3 REAL-TIME DATA ACQUSITION

Real-time rainfall and streamflow data is important for operational purposes especially in this study where the inflow prediction model needs both variables as inputs. The Kaimai Hydropower scheme has a system control and data acquisition system (SCADA) in place for their everyday operation. Tunnel inflows and rainfall gauges were telemetered to the SCADA system to obtain the real-time rainfall and streamflow data for inflow prediction purposes.

A1.4 REFERENCES

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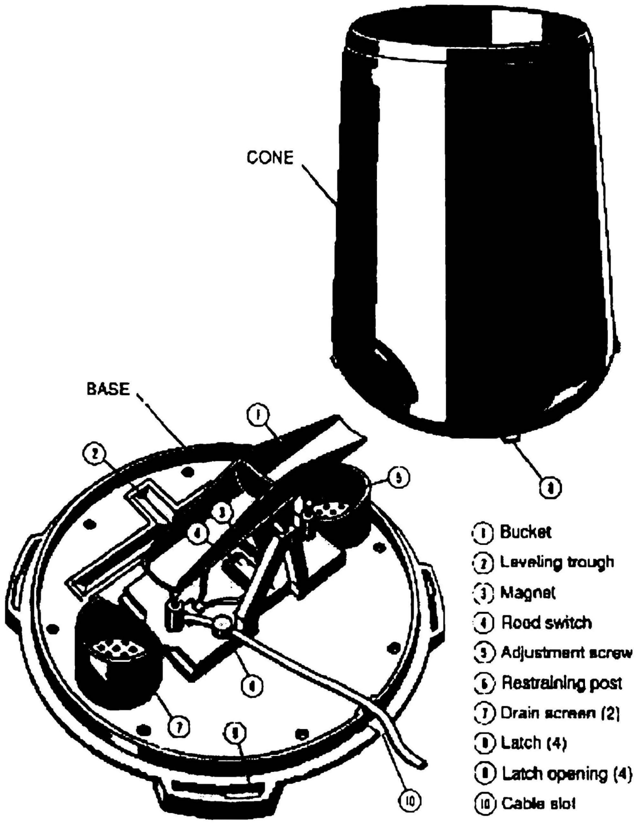


Figure A1.1 Davis rain gauge used for the Kaimai Hydropower catchment (Source: Unidata corporation, 1996).

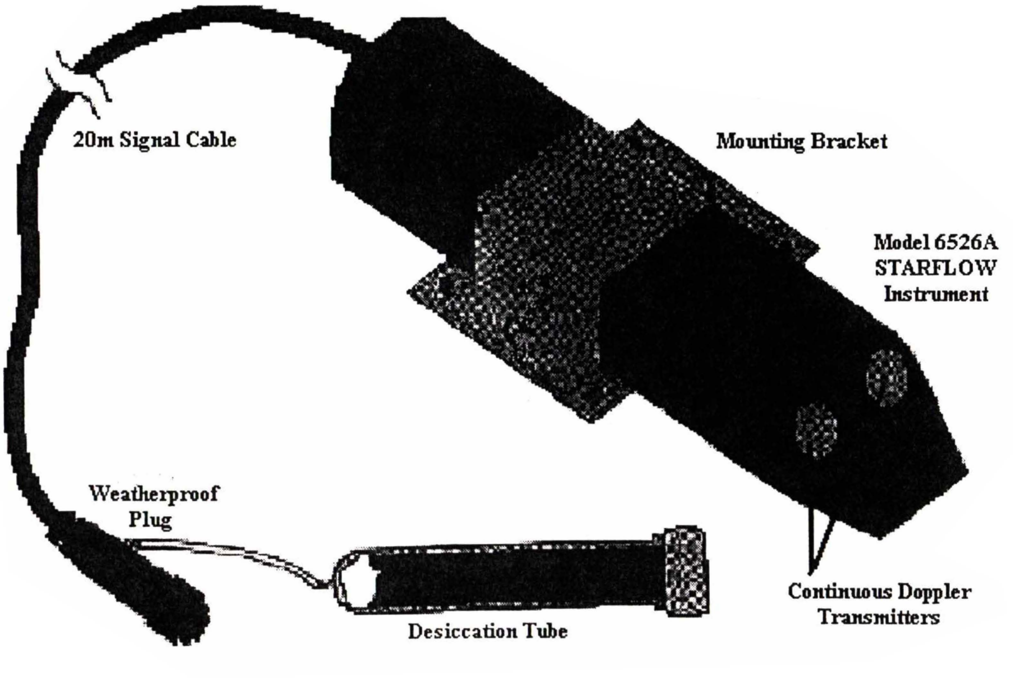


Figure A1.2 Starflow doppler instrument used for the tunnel discharges (Source: Davis instruments, 1993).

APPENDIX 2

A2.1 SENSITIVITY ANALYSIS

A sensitivity analysis was carried out on the parameters of T4 and T5 model equations. The sensitivity analysis results of the T4 model only are presented in Table A2.1, as both equations were sensitive to the same parameters.

In this study, three parameters (Table A2.1) were chosen to evaluate how the model performs and these terms were allowed to vary from their estimated optimal values. This was accomplished by varying one parameter at a time with other parameters fixed for a calibrated set. The change of parameter values was based on increasing and decreasing the certain parameter a small amount. Table A2.1 shows the original calibrated values and also the values increased and decreased at a 5% level with a maximum of 10%. Visual graphs and quantitative measures such as mean absolute difference and mean sum of square error of the change of the hydrologic responses were examined to see the sensitivity of these parameters.

All the three parameters, proportion lost "P" (which is the proportional rate at which water lost in the system), "γ' baseflow constant and "β" scale factor were very sensitive. Any change in these parameters can significantly effect the model results, so, the numerical estimates are well defined in this particular case.

Parameters	P	γ	β	Abs. diff	Mean sum of squares
Calibrated	0.9951	2.14	0.041	0.229	0.0.125
P	1.045 (+5%) 1.095 (+10%) 0.945 (-5%) 0.896 (-10%)	-	-	$3.79*10^{19}$ $1.46*10^{42}$ 1.497 1.57	$3.6*10^{40}$ $1.1*10^{86}$ 3.28 3.664
γ	-	2.247 (+5%) 2.354 (+10%) 2.033 (-5%) 1.926 (-10%)	-	0.2607 0.324 0.274 0.335	0.135 0.168 0.138 0.174
β	-	-	0.043 (+5%) 0.045 (+10%) 0.039 (-5%) 0.037 (-10%)	0.245 0.282 0.243 0.28	0.135 0.163 0.134 0.164

Table A2.1 Sensitivity analysis of the T4 model parameters

APPENDIX 3

This appendix is a part of the map-based surface water flow simulation model and is taken from Ye (1996) to explain the concepts of the map-based model.

A3.1 CONCEPTUAL DESIGN OF A MAP-BASED HYDROLOGIC MODEL

In this section, the concepts of object-oriented programming as stated by Goldberg (1983) and Razavi (1996) were applied to the conceptual design of a map-based surface flow simulation model. The classes of polygon and line objects are of essential importance to this model because river basins can be regarded as polygon objects while river streams, as line objects. The equation, Object=State+Behavior was used to define these two classes of objects.

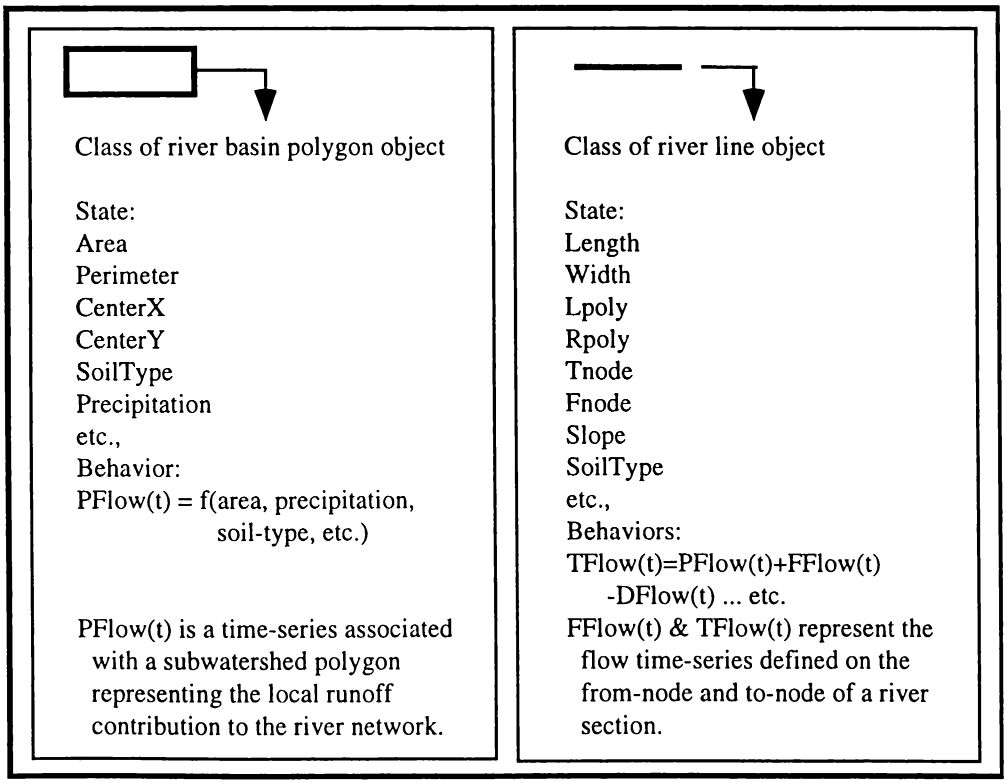
- ***River basin and polygon classes***

For a given object in the polygon object class, its state can be described by area, perimeter, and shape, etc. Its behaviors are drawing-itself, coloring-itself, get-dimension, return-center etc. Get-dimension, return-center, and drawing-itself are the names of element functions (methods) of the objects that perform the tasks of getting the dimension sizes, returning the center point of the polygon object and drawing, and coloring the object. Element functions are the functions that are defined by a class to be associated with an object of the class.

River basin polygons can be viewed as a subclass derived from the polygon object class. Therefore, for a given river basin object, its state can be described by the properties it inherits from the polygon object class plus its own unique state properties, such as soil type, rainfall depth, slope, streams it contains, its adjacent basins, and hydraulic conductivity K_x and K_y, etc. For the same reason, the behavior of a river basin object can also be described by the behavior properties that it inherits from polygon object classes plus the behaviors of all kinds of hydrologic and hydraulic processes, which can be described by different hydrologic and hydraulic models.

• *River stream section and line classes*

For a given object in the line object class, its state can be described by its length, To-Node (Tnode), From-Node (Fnode), Left-Polygon (Lpoly), Right-Polygon (Rpoly), and shape, etc. (In an ARC/INFO's arc coverage, Fnode and Tnode are used to denote starting point and ending point IDs while Lpoly and Rpoly are used to denote the IDs of polygons to the left and to the right of a line.). Its class behaviors may be drawing itself, coloring itself, "get-dimension", "return-center", get-end-point, and get-start-point, etc. Again, get-dimension, return-center, etc., are the names of the element functions of an object that perform the tasks of getting the dimension sizes, returning the center point of the line, drawing and coloring the line object. A river stream object belongs to the line object class. Therefore, for a given river stream object, its state can be described jointly by the properties that it inherits from line object class plus the behaviors of all kinds of hydrologic or hydraulic processes which can be in turn, described by different hydrologic and hydraulic models. Figure A3.1 show the examples of classes and objects



Class of river basin polygon object

State:
Area
Perimeter
CenterX
CenterY
SoilType
Precipitation
etc.,
Behavior:
PFlow(t) = f(area, precipitation,
soil-type, etc.)

PFlow(t) is a time-series associated with a subwatershed polygon representing the local runoff contribution to the river network.

Class of river line object

State:
Length
Width
Lpoly
Rpoly
Tnode
Fnode
Slope
SoilType
etc.,
Behaviors:
TFlow(t)=PFlow(t)+FFlow(t)
-DFlow(t) ... etc.

FFlow(t) & TFlow(t) represent the flow time-series defined on the from-node and to-node of a river section.

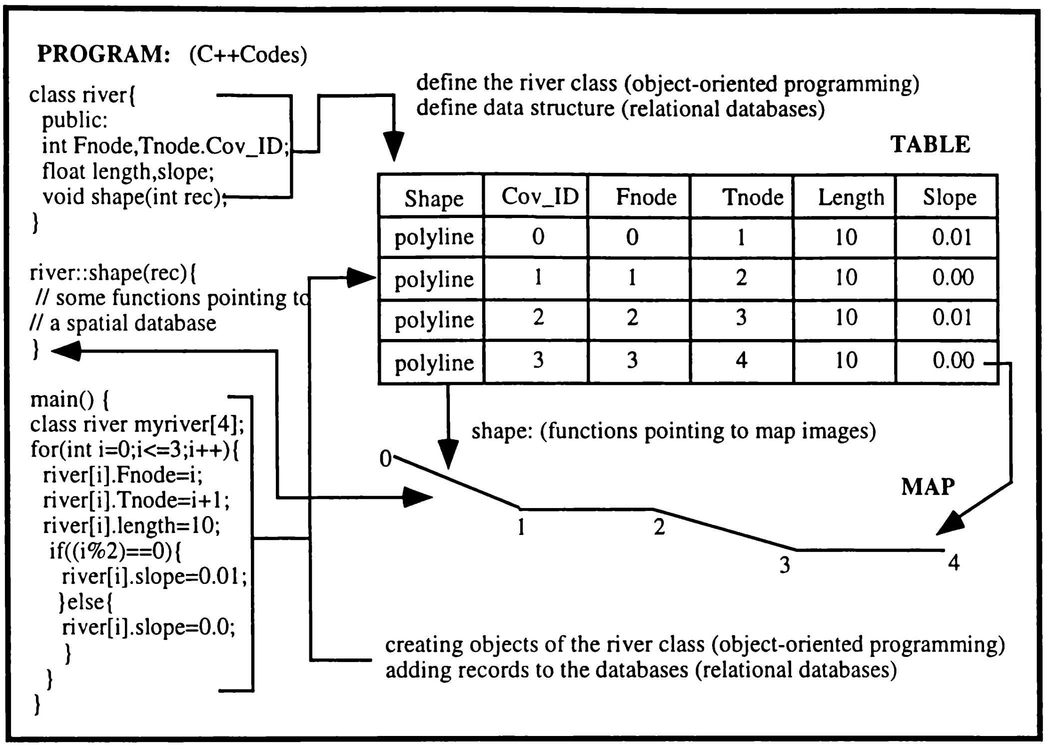
Figure A3.1 State and behavior defined on an object

A3.2 RELATIONSHIPS BETWEEN MAPS, DATABASES AND PROGRAMS

It is important to understand the relations between the maps, relational databases and programs in order to understand the design of the map-based model. Figure A3.2 shows how an object is defined and referenced in an object-oriented programming language, in a relational database, and on a map. C++ is used here to illustrate how an object is defined in an object-oriented programming language.

As stated above, an object is defined by the equation: object = state + behavior. The behavior of an object is governed by some equations. Equations are usually translated into element functions. In the same way, states of an object are defined as variables of a class. The program section in Figure A3.2 illustrates how a class is defined and objects generated in C++. In this example program, objects are created in two steps. First, a class is defined and functions declared, and then the instances (objects) of the class are generated. From the aspect of a database management system, these two steps are equivalent to the actions of creating a database structure (template) and adding records to the database.

When a GIS map is constructed, a relational database is also created to store the spatially referenced data sets. Such databases appear as feature attribute tables (FTAB) in the digital elevation model program. In the database of a GIS map, one field is used to hold the pointers to the geographical features on the map. In a class, states (variables) and behaviors (element functions) can be defined as either private or public. A "private" variable/function is accessible only by other elements of the same object while a public variable/functions can be called by other objects. The distinction of "private" and "public" types of functions and variables provides a mechanism for programs to control the messages (requests) exchanged between objects, whose importance can be seen below in the process of simulation model constructions.



PROGRAM: (C++Codes)

```
class river{
 public:
 int Fnode,Tnode.Cov_ID;
 float length,slope;
 void shape(int rec);
}

river::shape(rec){
 // some functions pointing to
 // a spatial database
}

main() {
class river myriver[4];
for(int i=0;i<=3;i++){
 river[i].Fnode=i;
 river[i].Tnode=i+1;
 river[i].length=10;
  if((i%2)==0){
   river[i].slope=0.01;
  }else{
   river[i].slope=0.0;
  }
 }
}
```

define the river class (object-oriented programming)
define data structure (relational databases)

TABLE

Shape	Cov_ID	Fnode	Tnode	Length	Slope
polyline	0	0	1	10	0.01
polyline	1	1	2	10	0.00
polyline	2	2	3	10	0.01
polyline	3	3	4	10	0.00

shape: (functions pointing to map images)

MAP

creating objects of the river class (object-oriented programming)
adding records to the databases (relational databases)

Figure A3.2 Presentation of objects in a program, database and map

A3.3 GOVERNING EQUATIONS FOR SURFACE WATER FLOWS

Given a numerical simulation model, there are always two components, (1) mathematical equations governing the process and (2) attribute data (extracted from maps and other sources) supporting the equations. In the context of object-oriented programming, a mathematical equation describes the behavior while a set of attribute data gives the states of an object. The following section reviews the equations governing surface water movements that were used for the map-based simulation model design.

A3.3.1 Equations related to the surface water flow simulation

Two types of models are considered for surface water flow simulation: one for the flow in river streams and one for the flow over a regular land surface. Figure A3.3 shows the data flow path on the map-based surface water flow simulation model. As can be seen from Figure A3.3, the map-based flow simulation model uses six procedures to process and convert the rainfall data sets to produce a flow time series defined on the river section nodes.

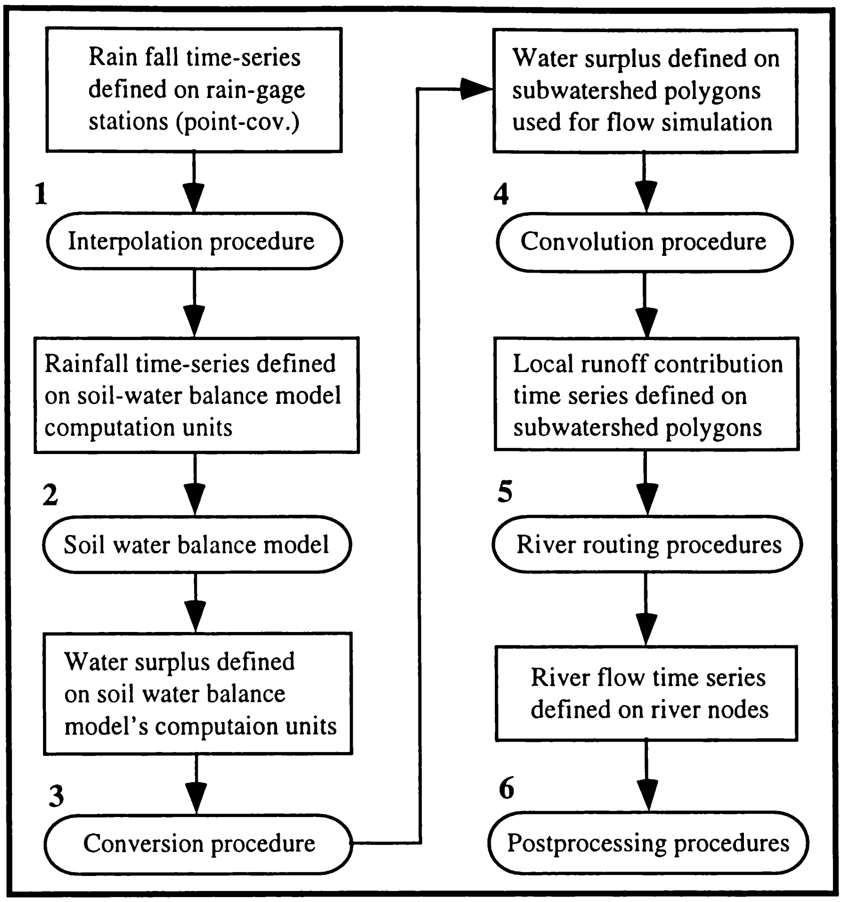


Figure A3.3 Data flow path in the map-based surface water flow simulation model

The input data for this map-based surface water flow simulation model are a set of rainfall time-series defined on the rain-gauge stations on the study area. These rainfall time-series are interpolated using some spatial interpolation methods (procedure 1) to each of the computation units of a soil-water balance model. The interpolated rainfall time series are used by the soil-water balance model (procedure 2) to produce soil-water surplus time-series defined on the computation units of the soil-water balance model.

If subwatershed polygons of the study area are used as the computation units of the soil-water balance model, the water-surplus time series can be used directly by the convolution procedure to be described below (procedure 4) to produce the local runoff contributions. Otherwise, a conversion procedure (procedure 3) has to be applied to convert the water-surplus from a set of time series defined on the computation units of the soil-water balance model to another set of time series defined on the subwatershed polygons before the convolution procedure can be applied. The converted water surplus is used as the input to convolute with the response function of a subwatershed to produce a flow time-series representing the runoff contribution of subwatershed (procedure 4). The river routing procedures (procedure 5) together with the river network analysis procedure are then applied to generate a flow time-series defined at the starting and ending points of each river line section in the river stream network.

In the following sections, the equations governing the soil-water balance computation, water surplus to runoff conversion, river flow routing and the methods of converting time-series data between different spatial features are discussed.

A3.3.1.1 The soil -water balance model

The purpose of applying soil-water balance model is to estimate soil-water surplus given the precipitation time series, temperature, net-radiation and soil-water holding capacity. The surplus is defined as water which does not evaporate or remain in soil storage and is available to generate surface and subsurface runoff. The surplus can be estimated using a simple bucket model (Thornthwaite, 1848, Willmott et al., 1985, Mintz and Walker, 1993). For the simple bucket model, the basic equations for calculating surplus are:

$$
\begin{aligned}
&\frac{w(t)}{\Delta t} = \frac{w(t-1)}{\Delta t} + P(t) - E(t) \\
&S(t) = \frac{(w(t) - w^*)}{\Delta t};\ w(t) = w^* \quad \text{if } w(t) > w^* \qquad\qquad (A3.1)\\
&S(t) = 0;\ w(t) = w(t) \qquad\quad \text{if } w(t) \le w^*
\end{aligned}
$$

where, $S(t)$ = surplus $[LT^{-1}]$,

$P(t)$ = precipitation $[LT^{-1}]$,

$E(t)$ = evaporation $[LT^{-1}]$,

$w(t)$ = soil moisture storage of the computation unit at time step t [L],

w^* = soil-water holding capacity [L],

Δt = computation time step [T].

- ***Constructing a precipitation surface from rainfall data***

The precipitation data are usually available in the form of time-series data associated to a point coverage representing the locations of rain-gauge stations.

These rainfall time-series need to be spatially interpolated to the cells on which equation A3.1 will be applied. There are many algorithms available to perform such spatial interpolation, such as the methods of triangulated irregular network (TIN), Kriging, Thiessen polygons, two-dimensional spline, and inverse-distance. The procedures for applying these methods for interpolation can be found in numerous publications, e.g. the series of ARC/INFO User's Guide, (ESRI, 1992). When the TIN method is used for the interpolation, a TIN is first constructed from the point coverage of the rain-gauge stations. The ARC/INFO function TINLATTIC can then be used to interpolate the rainfall values to the centers of soil-water balance computation units.

• *Computing the evaporation*

Three types of equations are available for evaporation estimations and they are listed below.

(1) Energy method:

$$E_r = \frac{R_n}{l_v \cdot \rho_w} \qquad \text{(A3.2a)}$$

where, E_r= the estimated evaporation rate[mm],

R_n = net radiation flux {200 W/M^2}={200 J/SM^2},

l_v = latent heat of water vaporization{2441 KJ/Kg},

ρ_w= water density{997 Kg/M^3}.

The numbers listed in { } are used to provide a sense of the parameter's normal value range.

(2) Aerodynamic method:

$$E_a = B(e_{as} - e) \qquad \text{(A3.2b)}$$

where, E_a= the estimated evaporation rate[mm],

e_{as} = vapor pressure at water surface {3167 Pa at 25°C},

e = vapor pressure of the air,

$$B = \frac{0.622k^2\rho_a u_2}{p\rho_w[2\ln(z_2/z_o)]}$$

k = Von Karman's constant, k = 0.4,

ρ_a= air density, { $\rho_a = 1.19\ kg/m^3$ at 25°C},

p = ambient air pressure, {p = 101.3 kPa at25°C},

u_2 = air velocity at elevation Z_2,

Z_0 = reference height of boundary.

(3) Combined aerodynamic and energy method:

$$E = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma} E_a \qquad \text{(A3.3)}$$

where, $\Delta = \frac{de_s}{dT} = \frac{4098 e_s}{(237.3 + T)^2}$ is vapor pressure gradient with temperature,

γ = psychometric constant.

- ***Setting the model's initial conditions***

As can be seen from equation A3.1, computation of soil-moisture surplus is an iterative procedure, and the initial soil moisture storage w(t=0) is needed before the computation can start. Since the initial soil moisture storage is typically unknown the following water balancing procedure is applied to force the net change in soil moisture from the beginning to the end of a specified balancing period to zero, i.e., $w(0) - w(n+1) < \xi$, where n is the number of time steps of the computation period, and ξ is a user specified tolerance. Starting with the initial soil moisture being set to the water-holding capacity and budget, calculations are made to until the t=n+1. w(0) is then set to w(n+1) to start another budget calculation circle until the condition $w(0) - w(n+1) < \xi$ is satisfied.

A3.3.1.2 Converting time-series between different spatial features

The soil-water balance model produces time-series of water surplus defined on the model's computation units. Because the units used for soil-water balance are usually different from the subwatershed polygons used for surface water flow simulation, the time-series of water surplus need to be converted so that they are defined on the subwatershed. This section describes the procedure for the conversion of a data set defined on one type of spatial features to those defined on another set of spatial features.

To illustrate the procedure, assume P is a set of data defined on In-Coverage and is to be converted so that it is defined on Out-Coverage. The first step of the data converting procedure is to use the INTERSECT function provided by the ARC/INFO to establish the spatial relationships between In_Coverage and Out_Coverage. The INTERSECT operation produces a new Intersect-Coverage. As shown in Figure A3.4, nine components of P on the In-Coverage will become four components defined on Out-Coverage after the conversion. Assume the area on each feature on the In-Coverage to be A_1, A_2, ...A_9, and the areas of map units on the Intersect-Coverage to be I_{ij}, with i representing the In-Coverage ID and j representing the Out-Coverage ID. Let OP and IP represent the components of P defined on the Out-Coverage and defined on the In-Coverage, respectively. The equations used for OP_1 can then be written as:

$$OP_1 = \frac{IP_1 \cdot I_{11} + IP_2 \cdot I_{21} + IP_4 \cdot I_{41} + IP_5 \cdot I_{51}}{I_{11} + I_{21} + I_{41} + I_{51}} \qquad \text{(A3.4a)}$$

If P is an intensive property, and

$$OP_1 = IP_1 \cdot \frac{I_{11}}{A_1} + IP_2 \cdot \frac{I_{21}}{A_2} + IP_4 \cdot \frac{I_{42}}{A_4} + IP_5 \frac{I_{51}}{A_5} \qquad \text{(A3.4b)}$$

If P is an extensive property.

In general, the conversion equations can be written as:

$$OP_j = \sum_i IP_i \cdot I_{ij} \qquad \text{(A3.5a)}$$

If P is an intensive property, and

$$OP_j = \sum_i IP_i \cdot \frac{I_{ij}}{A_i} \qquad \text{(A3.5b)}$$

If P is an extensive property, where,

OP_j = property P defined on unit j at the Out-Coverage,

IP_i = property P defined on unit i at the In-Coverage,

I_{ij} = the area of unit i on the In-Coverage that intersects with unit j on the Out-Coverage,

A_i = the area of unit i on the In-Coverage.

To convert time-series data, equation A3.5 needs to be applied to the data at each time step.

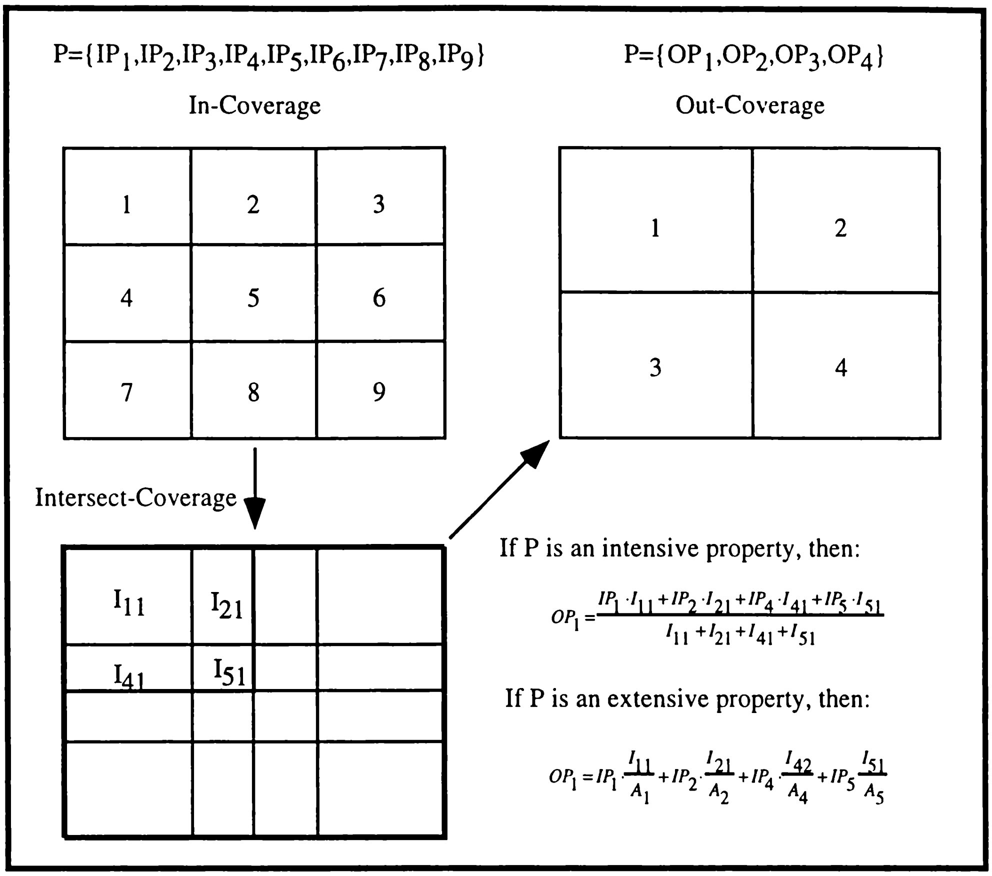


Figure A3.4 Converting data sets between different spatial features

A3.3.1.3. Convolution procedure used to compute local runoff

The time series (PFlow(t)) representing the local runoff of a subwatershed to the river stream network can be calculated from the time series of water-surplus (SurpF(t)) defined on the subwatershed. In the following text, when referring to a time-series in general, for example, PFLOW, the notation PFlow(t) will be used and when referring the same time-series related to a specific spatial feature, the notation $PFlow_i^t$ will be used; a subscript indicates the spatial feature index, and a superscript indicates the time index. Because the water surplus can reach a river section through either overland flow or through subsurface flow, the portion of surplus flow that reaches a river section through overland flow will be referred to as SFlow(t) and the portion that goes into subsurface flow before it reaches the river section will be termed as OFlow(t) (Figure A3.5). Based on this assumption, we have:

$$PFlow(t) = SFlow(t) + OFlow(t) \qquad \text{(A3.6)}$$

The overland flow portion (SFlow(t)) can be computed from SurpF(t) using equation (Olivera, 1996):

$$SFlow_i^t = \sum_{k=0}^{\min(t,N)} SurpF_i^{t-k}(1-\alpha_i)\cdot U_i^k \qquad \text{(A3.7)}$$

where, $SFlow_i^t$= local flow contribution (m^3/s), (through surface) of subwatershed i at time step t,

$SurpF_i^{t-k}$ = soil moisture surplus (m^3/s) of subwatershed i at time step t-k,

U_i^k = k-th component of the response function of $PFlow_i^t$ on $SurpF_i^t$,

α_i = the fraction of surplus that goes to subsurface, $(0 \le \alpha_i \le 1)$,

N = total number of components in the response function U_i^k.

The response function of $PFlow_i^t$ on $SurpF_i^t$ used in this study is given below:

$$U_i^k = \frac{1}{2k\sqrt{\pi D_i \frac{kv_i}{T_i}}}\exp\left(-\frac{\left(1-\frac{kv_i}{T_i}\right)^2}{4D_i\frac{kv_i}{T_i}}\right) \quad k=1,2,3....N \qquad \text{(A3.8)}$$

Where, k =1,2,3...N, the index of components in the response function,

D_i= dispersion coefficient for subwatershed i, Dispersion coefficient is used to measure the degree of the spread-out of overland water flow over time.

V_i = average overland flow velocity for subwatershed i (m/s),

T_i = average overland flow time for subwatershed i (s).

Figure A3.4 is constructed to illustrate how the parameters of Equation A3.8 can be estimated. In Figure A3.5, subwatershed P_i is composed of a number of cells (elements) and for a given element e, its flow length l_e can be calculated using the GRID module in ARC/INFO. The flow time of water from element e to the outlet of the subwatershed can be estimated by dividing the flow length l_e by the average flow velocity v_e, which could estimated from the topology and land cover information of the subwatershed. The average overland flow time for subwatershed P_i is then computed using:

$$T_i = \sum_{e=1}^{N_e} t_e \cdot \frac{A_e}{A_i} \qquad \text{(A3.9)}$$

Where: A_e and A_i are the areas of element e and subwatershed i, respectively.

When all the elements forming the subwatershed have the same size, which is the case when the GRID module is used, Equation A3.9 becomes:

$$T_i = \frac{1}{N_e}\sum_{e=1}^{N_e} t_e \qquad \text{(A3.9a)}$$

Where, N_e = the number of elements in the subwatershed.

Using the ZonalStat function provided by the GRID module in ARC/INFO, the average overland flow length l_i and standard deviation σ_i of the subwatershed P_i can also be calculated. With these two parameters being calculated, the dispersion coefficient for the subwatershed P_i can be computed using:

$$D_i = \frac{\sigma_i^2}{2(l_i^2)} \qquad \text{(A3.10)}$$

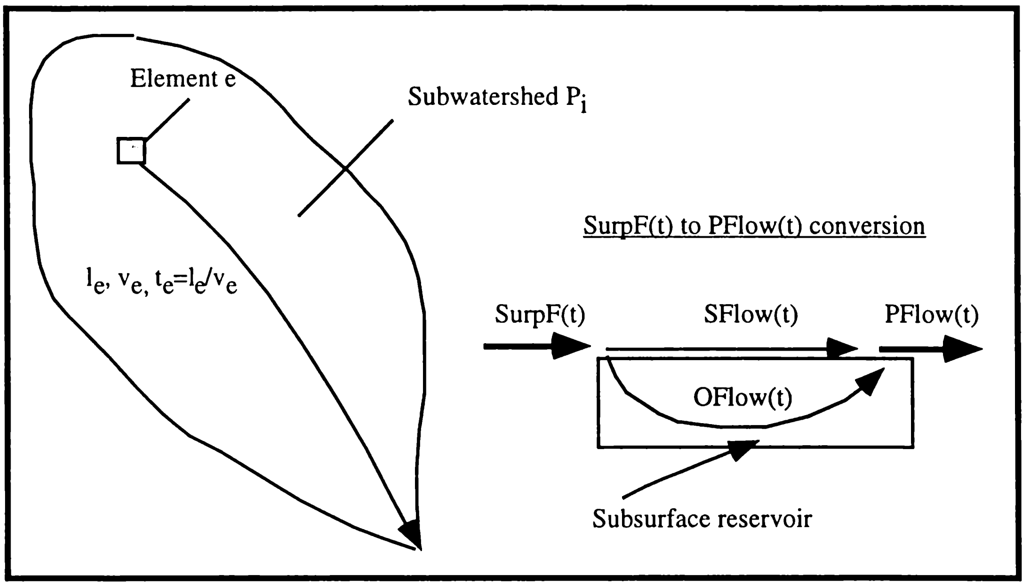


Figure A3.5 Converting SurpF(t) to PFlow(t)

The subsurface water flow component of PFlow(t) is considered to be going through an imaginary under-ground-reservoir whose flow can be simulated using a linear-reservoir-model (Equations A3.11 and A3.12):

$$OFlow_i^t = S_i^{t-1} / K_i \qquad (t = 1,2,3,....) \qquad \text{(A3.11)}$$

$$S_i^t = S_i^{t-1} + (SurpF_i^t \cdot \alpha_i - OFlow_i^t) \cdot \Delta t \qquad \text{(A3.12)}$$

where,

$OFlow_i^t$ =PFlow's subsurface component at time step t, on polygon i $[L^3T^{-1}]$,

S_i^t = storage of the underground reservoir at time step t, on polygon i $[L^3]$,

K_i = the linear reservoir constant [T].

After the components simulating surface and subsurface water flows are computed, the local flow contribution of subwatershed i at time step t is computed using equation A3.6.

A3.3.1.4 Flow routing on a river section

The flow in a river section shown in Figure A3.6 can be simulated using the Muskingum or Muskingum-Cunge method (McCarthy, 1938, Cunge,1969, Chow, 1987). The Muskingum method is based on the principle of continuity and a relationship between discharge and the temporary storage of excess volumes of water in a river section during the simulating period. The principle can be expressed as:

$$\frac{dS}{dt} = I(t) - Q(t) \qquad \text{(A3.13)}$$

where, S = the volume of water in storage in a river section,

$I(t)$ = water inflow time-series (hydrograph) of the river section $[L^3T^{-1}]$,

$Q(t)$ = water outflow time-series of the river section $[L^3T^{-1}]$.

In deriving the flow routing formula for the Muskingum method, it is assumed that the storage volume in a river section (Figure A3.6) is composed of two portions of storage: a wedge storage and a prism storage. It is further assumed that the cross-sectional area of the water flow is directly proportional to discharge into the section, the volume of prism storage is K•TFlow(t) and the volume of wedge storage is K•X•(FFlow(t)-TFlow(t)), where K is a proportionality coefficient and X is a weighting factor showing the relative importance of FFlow(t) and TFlow(t). With these assumptions, the total storage of the section can be written as:

$$S(t) = K \cdot TFlow(t) + K \cdot X \cdot (FFlow(t) - TFlow(t)) \qquad \text{(A3.14)}$$

The formula of Muskingum routing method is derived by expressing the storage change of the section between time step t and t-1 in terms of FFlow(t) and TFlow(t) using Equation A3.14. The Muskingum-Cunge method is derived based on the Muskingum method taking into consideration the lateral flow (PFlow(t)). Detailed descriptions of Muskingum-Cunge flow routing method can be found in Applied Hydrology (Chow, 1988).

The Muskingum-Cunge flow routing method is described below in equation A3.15:

$$TFlow(t) = C_1 \cdot FFlow(t) + C_2 \cdot FFlow(t-1) + C_3 \cdot TFlow(t-1) + C_4 \qquad \text{(A3.15)}$$

Where,

TFlow(t) = flow time-series at the To-Node of a river line,

FFlow(t) = flow time-series at the From-Node of a river line,

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X) + \Delta t} \qquad \text{(A3.16a)}$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X) + \Delta t} \qquad \text{(A3.16b)}$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X) + \Delta t} \qquad \text{(A3.16c)}$$

$$C_4 = \frac{PFlow_i^t - DFlow_i^t - Loss_i^t}{2K(1-X) + \Delta t}, \; (C_4 \text{ accounts for lateral flows}). \qquad \text{(A3.16d)}$$

$$K = \frac{\Delta x}{\bar{c}}, \text{ K is a storage constant [T],} \qquad \text{(A3.16e)}$$

$$X = \frac{1}{2} - \frac{Avg(TFlow, FFlow)}{2\bar{c}\bar{B}S_e\Delta X} \qquad \text{(A3.16f)}$$

X = a weighting factor showing the relative importance that FFlow and TFlow have on the river section's storage,

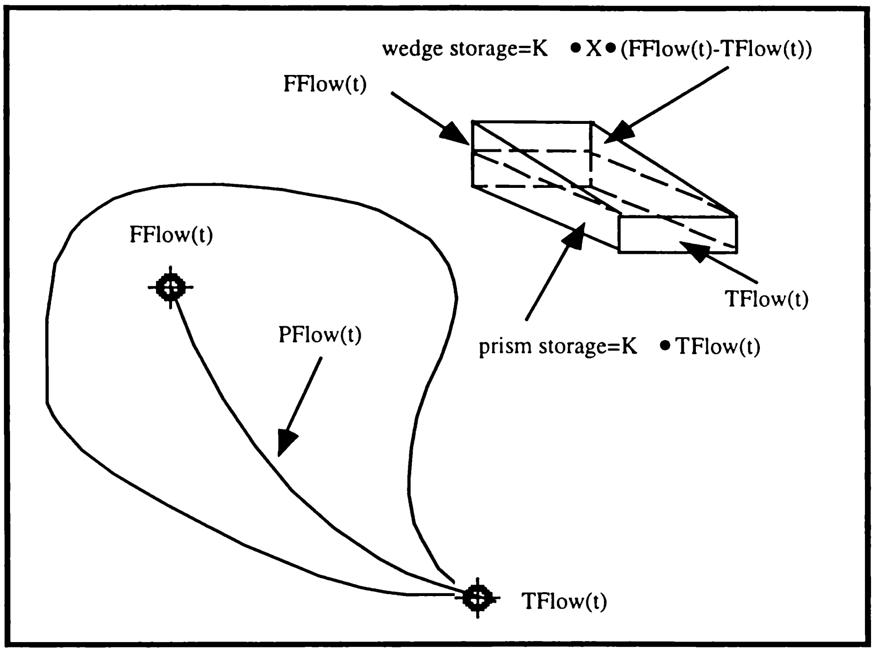
Δx = the length of the river section, [L]

$\bar{c}$ = kinematic wave velocity [LT^{-1}],

$\bar{B}$ = cross-sectional top width associated with average of TFlow and FFlow,

S_e = the energy slope, and ΔX = length of a river section.

To ensure the stability of the flow routing C_3 needs to be non-negative. From equation A3.16c, it can be seen that in order for $C_3 \geq 0$, we need to have: $\Delta t \leq 2K(1-X)$.



FigureA3.6 Flow routing on a river section

A3.4 MAP-BASED SURFACE FLOW SIMULATION MODEL

The map-based surface water flow simulation model was used for the water resources assessment and management of a Kaimai Hydropower river basin. The model can be applied to any area where a digital elevation model (DEM) is available or to a region whose river basin polygons and river stream lines are available. Listed below are the tasks that this model can accomplish:

- Simulate the river stream flow time-series based on the precipitation defined on a polygon or water surplus on the soils. After applying the simulation model to a river basin, the flow rates are available at the From-Node and To-Node (termed FFlow and TFlow respectively in the model) of each river stream line. From-Node and To-Node represent the starting and ending points of a river section line. The post-processor of the simulation model can also interpolate flow rates to any user defined points along the river section.
- Estimate the flow contribution of each subwatershed (termed PFlow in the model).
- Allow reservoir objects to be added to a river section to simulate the effects.
- Allow diversion points to be set on a river section to simulate the effects of the diversion facilities on downstream river flows.
- Plot longitudinal flow profile along a user specified river stream.

- Plot river flow time-series (FFlow(t) and TFlow(t)) of a river section or flow contribution time-series of a subwatershed.
- Allow a user to clip out part of a river basin to create a sub-model so that more detailed study of the selected subregion can be performed.
- Provide an optimization model to facilitate the calibration of the simulation model.
- Allow a user to modify the modeling conditions directly from the model base maps.

Three classes of objects are essential for this map-based surface water flow simulation model. They are i) a line class created to represent river stream sections, ii) a polygon class created to represent the subwatersheds associated with the river sections, and iii) a point class created to represent reservoirs or diversion points within any river section. Each river section is an instance (object) of the line class, with its states being stored in a line value attribute table and its behavior described by some flow routing equations. As each record is added to the line attribute table, a new river section object is created. The same thing can be said for the river basin polygon and reservoir point classes.

Based on their functions, the programs in the map-based surface water flow simulation model can be grouped to form three modules: pre-processor, processor and post-processor. The pre-processor is used to create the model objects, construct model base maps, create time-series data tables and process time-series data. The processor is used simulate water flow on the river streams and subwatersheds. The post-processor is used to analyze and display model results. The post-processor also contains utility programs that can be used to modify model maps and modeling conditions, and to perform map operation and database management tasks. Figure A3.7. shows the components of the map-based surface water flow simulation model and its construction procedure

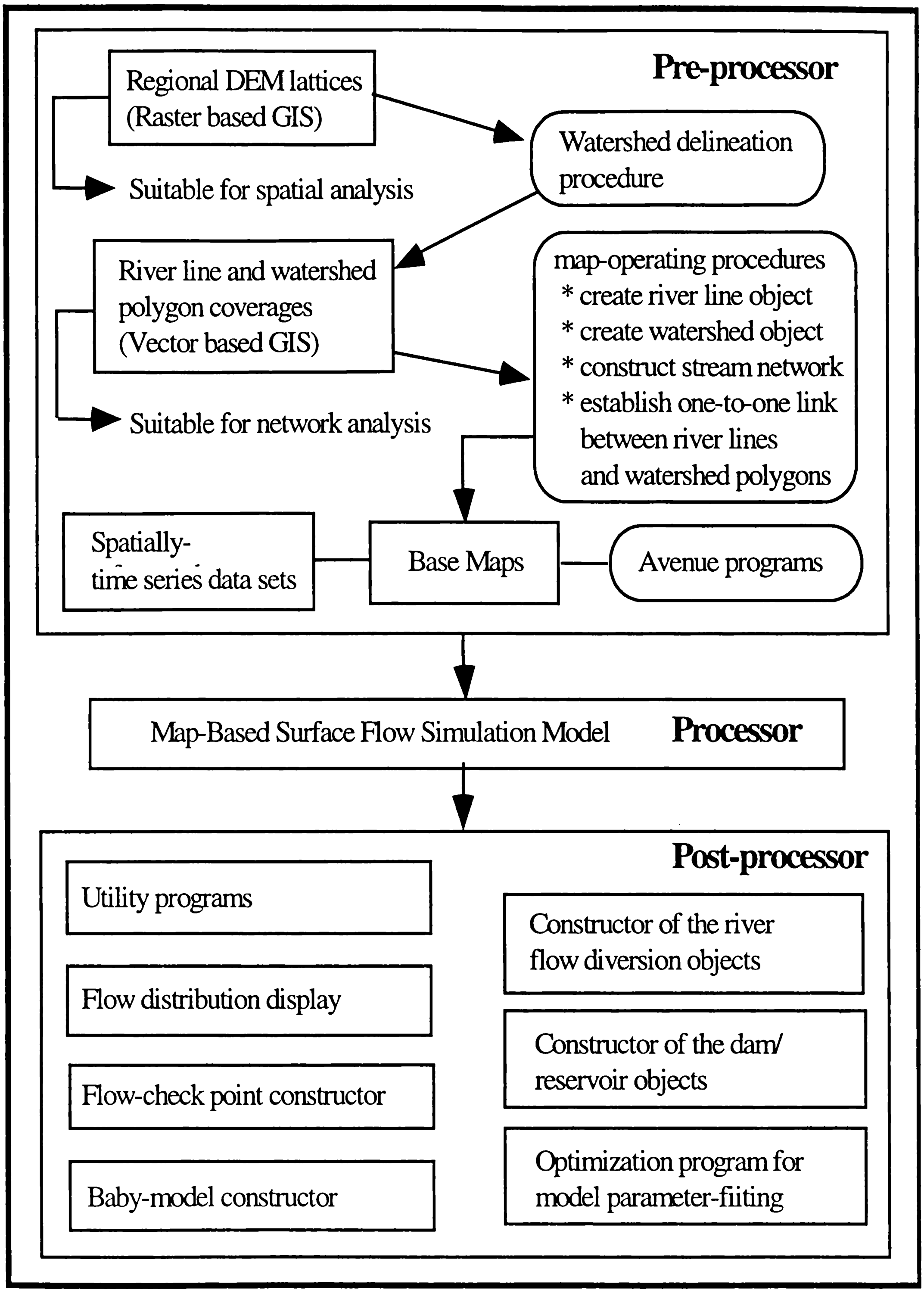


Figure A3.7 Components of the map-based surface flow simulation model.

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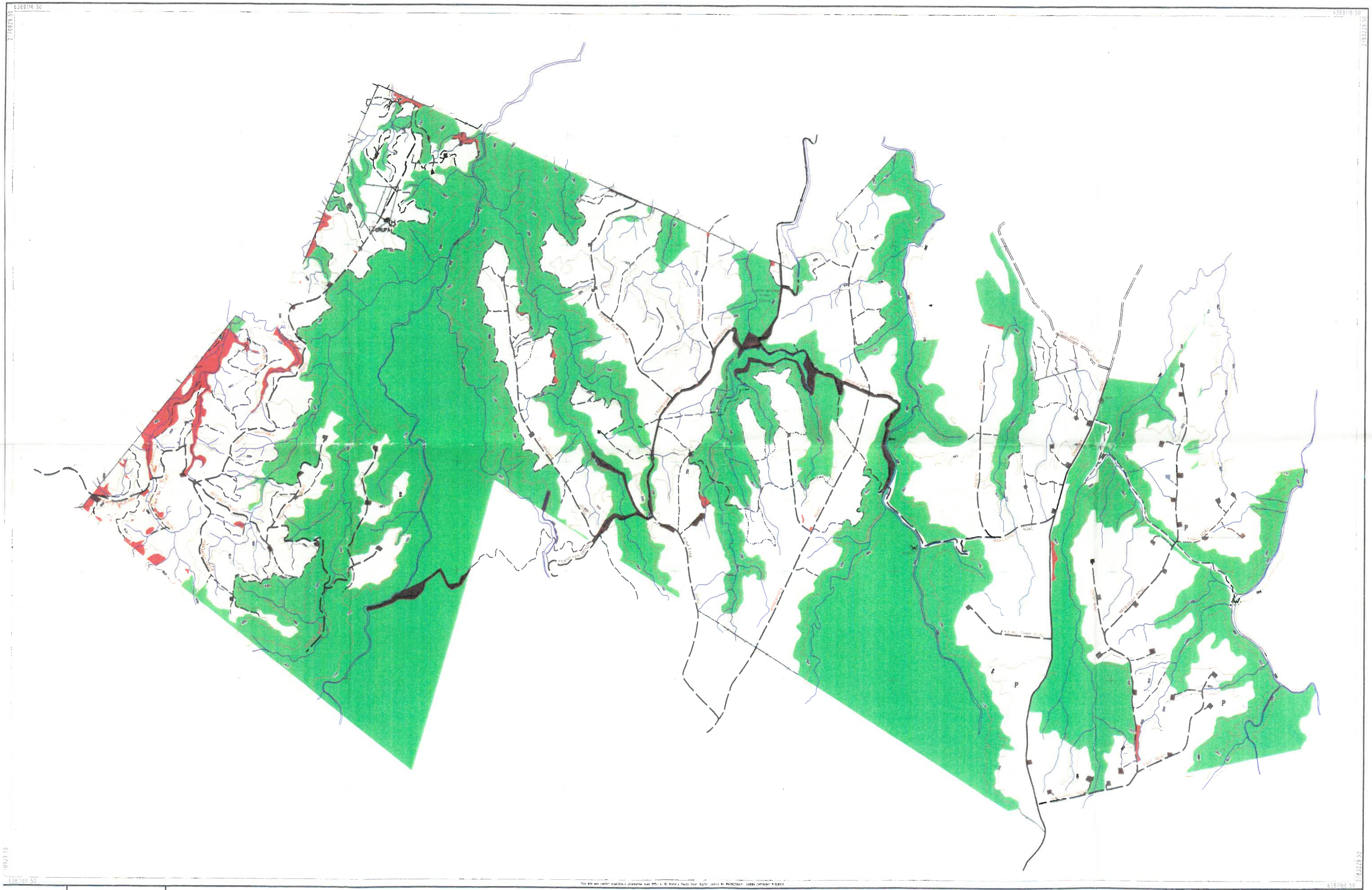

Contour Interval 10M
NZMG U1521
7-NOV-1996

Appendix 4 Catchment landuse and contour map of the study area