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Spatiotemporal Hydrological Modelling with GIS for the Upper Mahaweli Catchment, Sri Lanka

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Department of Natural Resources Management

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ABSTRACT

Sustainability of water resources is imperative for the continued prosperity of Sri Lanka where the economy is dependent upon agriculture. The Mahaweli river is the longest in Sri Lanka, with the upper catchment covering an area of 3124 sq.km.. The Mahaweli Development programme, a major undertaking in the upper catchment has been implemented with the aims of providing Mahaweli water to the dry zone of the country through a massive diversion scheme and also for generating hydropower. Under this programme, seven large reservoirs have been constructed across the river and large scale land use changes in the catchment have occurred during the last two decades.

Critics now say that the hydrological regime has been adversely affected due to indiscriminate land use changes and, as a result, river flows have diminished during the last two decades, thus jeopardising the expectations of this massive development programme. Reforestation programmes have been recommended because of the benefits of forest in resource conservation and also the water derived from fog interception. Selection of the best sites for these forest plantations for maximum benefits, especially in terms of water yield from fog interception has the utmost importance. This created the need for a comprehensive model to represent the hydrology and to simulate the hydrological dynamics of the catchment.

In conceptual terms, GIS is well suited for modelling with large and complex databases associated with hydrological parameters. However, hydrological modelling efforts in GIS are constrained by the limitations in the representation of time in its spatial data structures. The SPANS GIS software used in this study provided the capability of linking spatially distributed numerical parameters with corresponding tabulated data through mathematical and statistical expressions while implicitly representing temporality through iterative procedures.

The spatial distribution of land use was identified through the supervised classification of IRS-1A LISS II imagery. Daily rainfall data for a 30 year period and corresponding gauging locations derived from GPS were managed and retrieved through a Lotus 1-2-3 database. The fog interception component was estimated based on elevation and the monsoon season. Hydrological processes such as interception and evapotranspiration were derived from individual sub models and finally combined within the overall hydrological model structure. The model was run with daily time steps on numerical values of each quad cell of the thematic coverage. The information on flow derived from the model was depicted as a series of thematic maps in addition to the time series of numerical values at subcatchment and catchment outlets. The results confirmed that the model is capable of simulating catchment response of the UMCA successfully.

The time dimension was accommodated through a series of non-interactive REXX programmes in developing the customised version of the model. It is concluded that the software architecture of SPANS GIS is capable of accommodating spatiotemporal modelling implicitly in its spatial data structures although changes in the model structure may necessitate considerable reprogramming.

Sensitivity of the model for different spatial interpolation techniques was evaluated. Further, sensitivity of the model for the defined hydrological parameters, spatial resolution and land use was also assessed. The model is sensitive to land use changes in the catchment and it shows 15-35% annual increase of runoff when forests are converted to grassland. Further studies are required to develop a more detailed set of hydrological parameters for the model.

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Chapter 1

1. INTRODUCTION

1.1 Modelling Approaches in Hydrology

Hydrological modelling is concerned with the accurate prediction of the partitioning of water among the various pathways of the hydrological cycle (Dooge, 1992). Hydrological models provide a framework for conceptualising and investigating complex relationships that exist in hydrological processes in order to have assessments of the hydrological environment, mostly as a function of the catchment response in terms of river flow rates or flood peaks. The modelling approach has been proven to be successful and efficient in dealing with hydrological data at different temporal scales and in producing modelling results at varying temporal resolutions. Most of the hydrological models are numerical and computer based, and assume some form of spatial averaging process for parameter definitions. The lack of recognition of spatial diversity in hydrology at the catchment scale has been a serious constraint hampering the simulation, validation and practical application of the hydrological modelling results.

1.2 Role of Geographical Information Systems in Spatial Modelling

Geographical Information Systems (GIS) are effective and efficient tools for storing, analysing and visualising spatial information. Most GIS provide analytical and semantic modelling capabilities to represent spatially varying phenomena through spatial references based on mathematical and statistical functionality. In hydrological modelling efforts, the contribution of GIS begins with spatial discretization of catchment geometry and extends up to the computation of hydrological response simulations. However, current GIS software architecture is deprived of functional algorithms to deal with temporal attributes and temporal variability which are compulsory for successful hydrological modelling.

1.3 Spatiotemporal Hydrological Modelling in GIS

The hydrological processes in the real world are typically three dimensional and time dependent. Computer based, mathematical models that simulate spatially distributed, time dependent hydrological processes in nature are increasingly recognised as a fundamental requirement (Steyaert, 1993) in water resources management issues.

GIS and hydrological modelling are found to be complementary. GIS could benefit from the temporal modelling capabilities of hydrological models and hydrological models could benefit from spatial modelling capabilities of GIS functionality (Walsh, 1993). Further, the immense progress in computing technology has literally diminished the barriers for effective coupling and integration of these two disciplines. Within this conceptual framework, this study was focused on developing a spatiotemporal hydrological model in a GIS environment to investigate the hydrological dynamics and behaviour of Upper Mahaweli Catchment Area (UMCA) in Sri Lanka.

1.4 Background of the Study

1.4.1 UP/ OFI Link Project

The University of Peradeniya, Sri Lanka and the Oxford Forestry Institute, UK Link (UP/ OFI Link) Project was proposed immediately after the symposium on "Reforestation with Pinus (*Pinus caribaea*) in Sri Lanka" which was organised by the University of Peradeniya and sponsored by the UK Overseas Development Administration (ODA) in 1987. The UP/ OFI Link Project identified four main research themes namely: (i) natural forest ecology and management, (ii) forest genetic resource conservation and management, (iii) agroforestry and (iv) hydrology of forest and grassland. The Institute of Hydrology, UK was subcontracted to carry out the fourth component (UP/ OFI Final Report, 1997) and the local counterpart was the Department of Agricultural Engineering, University of Peradeniya, Sri Lanka. This study was undertaken on the recommendation of the hydrology sub component of the UP/ OFI Link Project.

1.4.2 Mahaweli Development Programme

The Mahaweli Development Programme is the largest development programme ever implemented in Sri Lanka. The initial time schedule for the project was slashed considerably due to economical and political reasons through the implementation of the accelerated phase. Under this massive development programme, a series of large reservoirs were constructed across the main water course at Kotmale (Morape), Polgolla, Victoria, Randenigala and Rantembe within the boundary of UMCA (MASL, 1986). The construction of these reservoirs inundated a considerable agricultural land area (5400 ha.; White et al., 1993) and the accompanied developments were responsible for the displacement of several settlements (14,000 families; White et al., 1993). These reservoirs were constructed with the aims of providing continuous water supply for the dry zone of the country through diversion schemes and generating electricity through hydro-electric power to meet the ever increasing local demand.

1.4.3 Problem Identification

There have been massive changes in the structure and composition of the land use in UMCA associated with the Mahaweli Development Programme. These changes have been very prominent due to both the short time in which they occurred and the high magnitude of the impact on the catchment environment. The development programme along with the revised government policies towards a free market economy has also led to considerable changes in agricultural land use in the UMCA. Steep slopes were put under cultivation without proper soil conservation practices. Indiscriminate clearing of tree crops and natural forests also triggered soil erosion at alarmingly high rates. Most of the land changes being geared towards achieving short run benefits, have yielded adverse impacts on the sustainability of the land and water resources in the catchment, and undoubtedly pose a serious threat to the expected benefits from the development efforts. A large amount of national wealth has been spent on the Mahaweli Development Programme and the success of this endeavour is basically dependent upon the hydrological stability of the catchment.

1.4.4 Present Problem and Future Crisis

A criticism is often raised by the environmental concern groups that the hydrological regime of the UMCA has been adversely affected by the activities and outcomes of the development programme. Productivity of the agricultural land has been diminishing due to severe land degradation. Loss of productivity has directly affected the income status of the farmers thus creating social problems. Further, reservoir siltation and eutrophication demand considerable maintenance expenses. Frequent land slides have threatened human life and infrastructure. If the present problems are not properly resolved, a future crisis is inevitable and that will jeopardise the expectations of the Mahaweli Development Programme.

1.4.5 Mitigation Efforts

Large scale afforestation and agroforestry schemes have been introduced considering the environmental benefits of the forest cover in terms of the hydrological stability and sustainability of the catchment resources. These have also been viewed as a solution to ever increasing demand for timber and fuelwood in Sri Lanka. Forestry planning strategies have mostly been focused on the physical land capability and sociological considerations. Whenever the potential physical impacts of forests are considered, the emphasis has been confined to localised site investigations rather than catchment-wide assessments. However, the hydrological consequences of afforestation and the other related land resource conservation measures could lead to high water losses from the catchment system in the forms of interception and evaporation losses and thereby diminishing the water yield.

1.4.6 Water Yield and Cloud Deposition

Research findings elsewhere in the world have confirmed the reduction of river flows associated with land use conversions into forest (Hatton & Dawes, 1992; Fahey & Watson, 1991; Burch et al., 1989). Conversely, it has also been reported that forests in high altitudes, known as cloud forests, can contribute significantly to river flow through the process of fog interception (Ingraham & Matthews, 1988; Oyenbande, 1988; Juvik & Ekern, 1978).

Hence, it is important to find the strategic locations for afforestation in order to ensure a positive contribution to the catchment water budget, while providing extensive benefits for catchment conservation. This requires a comprehensive understanding of the spatial and temporal dynamics of catchment behaviour. Spatially distributed, process-based hydrological modelling can provide the insight and background for such planning and management efforts involving catchment resource conservation.

1.5 Guidelines for the Study

1.5.1 Overall Aim

The overall aim of the study was to develop a spatially distributed and temporally oriented hydrological model to simulate catchment dynamics and behaviour so that an effective conservation planning methodology can be formulated, implemented and monitored to ensure the long term sustainability of the land and water resources of UMCA.

1.5.2 Objectives

The basic objectives of the study are to explore the possibilities of developing a methodology for time series hydrological modelling in GIS and to employ such a methodology for a case study in Sri Lanka. The specific objectives could be summarised as follows:

(a) To identify the hydrological behaviour of the catchment and to determine the influence of changes in the structure and composition of land use upon the stationarity of the rainfall regime of UMCA during the last 2-3 decades.

(b) To develop a hydrological model to simulate the catchment response to hydrological inputs in UMCA.

(c) To identify the existing land use through the application of digital classification techniques to satellite imagery.

(d) To develop a customised application for spatiotemporal hydrological modelling in GIS.

(e) To validate the hydrological model by determining the success of modelling results in comparison to the actual field observations through statistical and regression techniques.

(f) To simulate the hydrological dynamics of the catchment in a GIS environment to answer 'what if' questions with exact spatial and temporal reference.

1.5.3 Layout of the Thesis

Chapter 1 introduces the concepts of hydrological modelling and spatial data analysis. The importance of hydrological modelling in GIS is highlighted. Further, a general background of the study, problem identification and definitions of objectives are also included in this chapter. The layout of the thesis is also presented.

Chapter 2 deals with the analysis of rainfall regime in UMCA. Issues related to availability and quality of rainfall data are discussed. Spatial and temporal distribution status of rainfall data is analysed in detail.

Chapter 3 presents the analyses of hydrological time series including rainfall and derived drought related statistics. Linear and non-linear trends, shifts (jumps) in the time series and hydrological variability are the key issues discussed in this chapter.

Chapter 4 describes the individual hydrological processes in the UMCA hydrological model. Compilation and evaluation of the hydrological model are included. Issues related to river flow data and data quality are discussed. The influence of land use changes on catchment hydrology are also documented.

Chapter 5 includes the procedure adopted to identify the land use of the catchment based on analysis of digital multi-spectral satellite data. Accuracy of the classification is assessed and land use is reclassified to define the spatial diversity of hydrological parameters for hydrological modelling.

Chapter 6 looks at the key issues related to spatiotemporal hydrological modelling in GIS. Data representation formats and interpolation techniques are discussed. Modelling related GIS functionality is summarised and a generic description of the model structure in GIS is presented.

Chapter 7 evaluates the results of modelling in GIS. Model sensitivity for parameter definitions and calibration is determined. The effects of temporal and spatial resolution on modelling results are enumerated. An overview of errors in GIS is presented and the issue of error propagation in quadtrees is discussed.

Chapter 8 summarises the overall status of the study. Conclusions drawn from the evaluation of modelling results are presented. Recommendations are made and the guidelines for complementary future research programmes are proposed.

In addition to the main chapters, the thesis is further supported by a comprehensive list of references and several appendices.

1.6 Study Area

1.6.1 Mahaweli River

The Mahaweli river is the longest in Sri Lanka and its total length exceeds 335 km.. It originates from the central highlands of the country, passes through the mid country and finally reaches the sea on the South East coast. Starting from Hatton mountains, Mahaweli first flows in North-Westerly direction. It changes its course to North-Northeast at Ginigathena. About 10 km upstream of Gampola, is the confluence with the Kotamle oya. The river takes its turn to East-Southeast near Kandy and after Victoria, its flow direction is mainly East until it reaches the lower boundary of UMCA. The last stretch of the river in upper catchment is joined by several small tributaries. Between Randenigala and Rantembe, Uma oya, Badulu oya and Amban ganga, the major tributaries of Mahaweli join the main water course.

1.6.2 Location and General Description of UMCA

The total catchment area of the Mahaweli river is about 10,400 sq. km.. The catchment of the Mahaweli river upstream of Rantembe covers an area of 3120 sq. km. of the central and hill country, and is called Upper Mahaweli Catchment Area (UMCA). The UMCA is located between longitude 80^0 25' to 81^0 01' E and latitude 6^0 45' to $7^0$30' N and encompasses areas in Central, Uva and Sabaragamuwa provinces. The location of UMCA is shown in Plate 1.1. The demarcation of the upper catchment is based on the elevation above 150 m from the mean sea level. The Southern boundary of UMCA is formed by the mountains between Haputale, Horton Plains and Adams Peak. The Eastern boundary lies along the line between Bandarawela and Mahiyangana while the Western part is on the line between Adams peak and Kandy. The hills Northwest of Kandy form the Northern limit of the UMCA.

1.6.3 Physical Characteristics of UMCA

The average annual rainfall in the UMCA varies remarkably from 5500 mm in the Southwest to 1700 mm in the Southeast (White et al., 1993). Elevation ranges from 2717 m at Pidurutalagala (Gibbon, 1990) which is the highest summit in the country, to 150 m at Rantembe. The study area includes four main agro-ecological regions, namely up country wet zone (WU), mid country wet zone (WM), up country intermediate zone (IU) and mid country intermediate zone (IM) (Wickramasinghe, 1986; Department of Agriculture, 1979).

The predominant lithology of the UMCA is charnockite and charnockite gneisses underlying a series of planation levels (Gibbon, 1989). The terrain can be described as mountainous, steeply dissected, hilly and rolling. Soils are typically red-yellow podzolic, reddish brown latasols and immature brown loams (Gibbon, 1990; Kalpage, 1967).

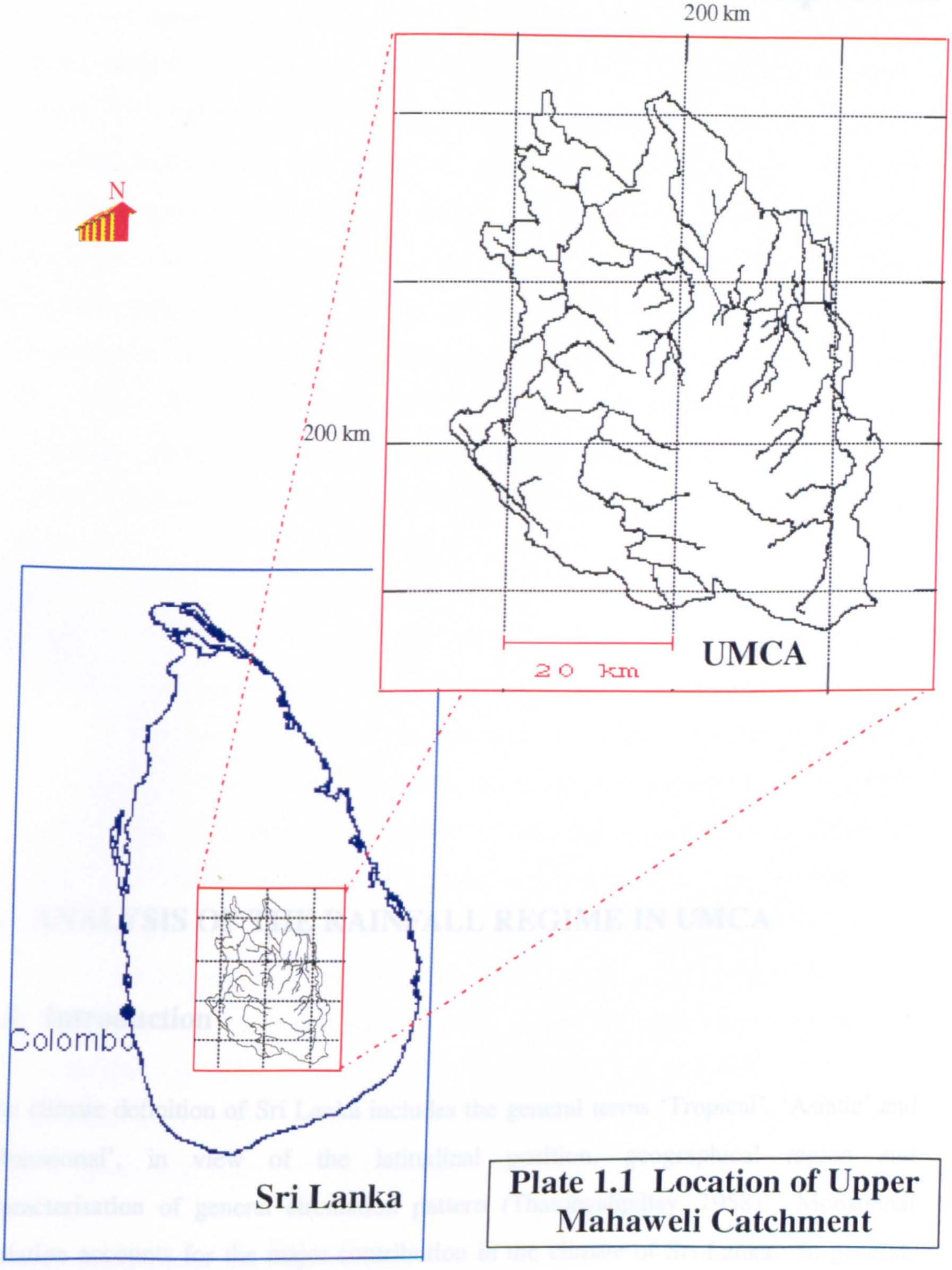


Plate 1.1 Location of Upper Mahaweli Catchment

Chapter 2

2. ANALYSIS OF THE RAINFALL REGIME IN UMCA

2.1 Introduction

The climate definition of Sri Lanka includes the general terms 'Tropical', 'Asiatic' and 'Monsoonal', in view of the latitudinal position, geographical region and characterisation of general circulation pattern (Thambyahpillay, 1958). Monsoonal variation accounts for the major contribution in the climate of Sri Lanka. In general, the rainfall distribution in Sri Lanka is subject to spatial and temporal variation leading to distinct patterns of regionality, seasonality and inter-annual variability in the climate (Sirinanda, 1983).

Despite the small extent of the country, rainfall varies remarkably, amounting to 1000 mm in the driest parts and to about 5000 mm in the wettest parts (Nomoto et al., 1983). The highest annual average (1964-1993) for Sri Lanka records 5207 mm (Kenilworth gauging station in UMCA), the lowest is around 931 mm (Hambantota gauging station). The regionality in the rainfall distribution in Sri Lanka has traditionally been generalised in terms of a wet zone in the Southwest region including the central hill country and a predominant dry zone covering the rest of the country. These macro regions have, in turn, been divided into smaller zones or regions, known as Agro-ecological regions according to the altitude, degree of dryness or transitional characteristics, mostly related to the rainfall parameters (Domros, 1974; Jayamaha, 1973; Alles, 1970). Even within these smaller zones, variations in the rainfall distribution, effectiveness, and reliability characteristics are mostly prominent. The situation is further complicated by the presence of highly varying terrain conditions in UMCA.

An accurate identification of temporal and spatial distribution of rainfall regions is important in hydrological modelling (Beven & Hornberger, 1982), especially when it is required to evaluate the essential characteristics of rainfall for the generation of associated statistics, derivation of rainfall indices, appraising interpolation algorithms and generalisation of hydrological information. The development of methodology for hydrological modelling and other subsequent assessment of modelling results were based on the information derived from the analysis of rainfall regime in UMCA. The spatial distributions and temporal variations of the rainfall characteristics are also of particular emphasis in terms of planning, development and management of the land and water resources of UMCA. In this chapter, a comprehensive effort was made to visualise and explain the spatial and temporal pattern of rainfall and its inter-relationships in order to understand the hydrological dynamics of UMCA.

2.2 Rain Gauging Network in UMCA

A dense network of rain gauging stations is required in order to investigate the exact distribution of rainfall in the highly varying terrain in UMCA. According to Walker (1962) some 620 stations reported daily rainfall data to the Department of

Meteorology. However, the number of available rain gauges has reduced drastically during the last 2 -3 decades. Further, the quality of the collected data at some gauging stations was also not acceptable. In the plantation sector, most of the estates privately manage standard rain gauges where rainfall is measured only once a day. The maintenance and the available skill exercised for the measurements are highly varying from place to place and time to time. The Department of Meteorology is short of the required resources to maintain the quality standards of the data collected at the estate sector locations. However, the stations which are directly managed by the Department of Meteorology and in particular, agricultural research stations were found to be maintaining a reliable and precise data collection service. Nevertheless, the collected data were subjected to considerable scrutiny in order to assess their reliability for a true generalised distribution of the temporal and spatial diversity, and the variation of rainfall.

2.2.1 Use of Global Positioning Systems

The distributed hydrological modelling discussed in the subsequent chapters required that all the rain gauging locations were accurately located in terms of the geographical reference according to a specified co-ordinate or projection system. The spatial locations recorded in the meteorological archives were not good enough for this purpose as some of the stations do not exist now and others have been moved to different locations.

A Trimble GPS (Geoexplorer Model) was used to find the location of the rain gauges. GPS was also used for the ground survey work in supervised classification of satellite imagery as discussed in chapter 5. The Trimble hand-held GPS unit was fitted with an external antenna which was mounted on the field vehicle provide continuous update of location data in the field. A brief description of GPS working principles, procedure adopted to collect the location data and the subsequent calculation of rain gauging locations are listed in Appendix A-1.

2.2.2 Accuracy of GPS Data

The location information derived through the computer processing of files downloaded from the GPS was in agreement with those derived from the contour maps. The discrepancies in the GPS derived data estimated between two successive observation periods were always within a deviation of 30 m. The expected highest resolution for the modelling is 32 m and thus, the GPS data were acceptable for gauging point locations in hydrological modelling.

2.2.3 Elevation Data for Gauging Locations

The process of differential correction required to derive accurate elevation data from GPS was not possible due to non-availability of two rover units. The elevation data already documented were found to be at a close range to the estimated elevation values from 1:63360 contour maps (Survey Department, 1978; 1977) at the locations shown by GPS. Hence, it was decided to use the original elevation values documented by the Department of Meteorology except for the cases of location change. The accuracy of elevation data provided by the Department of Meteorology is reasonably high, probably due to recent update of the records or due to a coincidence of obtaining the data from the same source paper maps.

2.2.4 Period of Rainfall Data and Sources

Most of the rainfall maps published by the Department of Meteorology have been prepared for 30 year periods suggesting that a historical climate cycle was considered to be pronounced more or less in a thirty year time span (Mel, 1971). Although this suggestion was not expected to be statistically tested in this study, it was decided to collect the daily data for a thirty year period starting from 1964 to 1993 in order to have the time series of a sufficient length.

Daily data were available for the specified time span only at 64 rain gauging locations in UMCA or at its close proximity. Of these, seven (7) stations were meteorological stations operated by the Department of Meteorology with continuous recording rain gauges, mostly of the tipping bucket type. The measurements of these stations are highly reliable as skilled observers are employed for these stations by the Department of Meteorology.

Rainfall data for this study, were recorded as monthly data sheets from the archives of the Department of Meteorology and subsequently fed into Lotus 1-2-3 Rel 5.0 worksheets. All the rainfall data were converted into metric units (mm) because the historical records before 1974 were in imperial units. The rainfall data were organised into a time sequential format making a data file for each month (eg. RF196401.WK4..... RF199312.WK, from January 1964 to December 1993) for all the gauging stations. For individual gauging stations, separate files were created to include the entire historical data set of that station. In addition, monthly rainfall totals were separately listed in annual files (RFMON64.WK4.... RFMON93.WK4) for all the stations and also in separate files for the individual stations. Finally, a summary file was created including annual data for all the stations in UMCA. The entire database is maintained via a series of non-interactive macro programmes.

2.3 Estimation of Missing Data

In almost all the rain gauging stations, the rainfall time series were not continuous to cover the exact 30 year period. There were missing values for individual days and in most of the cases they extend up to a month or a few months. The total amount of missing data is about 1.5% of the total data set.

The classical techniques of estimating missing rainfall at a point include the Normal Ratio method and Inverse Distance Squared method (Linsley et al., 1975). Advanced methodologies for missing data estimation have also been discussed in literature (Tabios & Salas, 1985; Chua & Bras, 1982). The most popular technique is the use of kriging for estimating the values of a variable at unmeasured points from nearby measurements (Bastin et al., 1984; Chua & Bras, 1982; Delfiner & Delhomme, 1975). In this analysis, the classical Normal Ratio method and Areal precipitation Ratioing method were employed for estimation of missing data in view of the easy approach, computational efficiency and the universal applicability of these methods.

2.3.1 Normal Ratio (NR) Method

In this method, the calculation of missing value is determined by a combination of the rainfall of the missing day at the surrounding stations and the proportions of the long term averages of the missing station and the surrounding stations. It takes into account the spatial distribution of rainfall by taking several surrounding regions and estimates the direction of storm origin and the function of decay rate. Also, it uses a proportionate value of the long term average rainfall of the stations and it indirectly accounts for a probable historical recurrence. The Equation 2.1 gives the formula used for the Normal Ratio estimation.

$$P_m = \left(\frac{N_m}{N_a}.P_a + \frac{N_m}{N_b}.P_b + \ldots\ldots\ldots\ldots \frac{N_m}{N_n}.P_n \right) \qquad \text{(Eq. 2.1)}$$

where P_m is the estimated daily value for the missing station,

N_m is the mean monthly rainfall for the missing station,

N_a, N_b....N_n are the mean monthly rainfall for the surrounding stations,

P_a, P_b....P_n are the rainfall of the surrounding stations for the missing day.

2.3.2 Areal Precipitation Ratioing (APR) Method

This method was developed to make use of the advantage of spatial uniformity of rainfall within short distances. It weighs the rainfall distribution in terms of the spatial proximity but contains no account of the historical recurrence. It can be considered to be a surrogate to Inverse Distance Squared Weighting method in the context that the dimensions of area estimates are similar to squared distance.

In the Areal Precipitation Ratioing, at least 4 surrounding gauging locations were selected. The criteria for the selection was not necessarily the surrounding station being located within the same sub catchment of the missing station but the representation of all directions in the spatial demarcation of the surrounding stations so that these stations cover both North-east and South-west monsoon paths. In the process of demarcating overall spatial coverage for calculations, the areal extents of surrounding stations were restricted using the digitised corresponding sub catchment boundaries. The estimation of areas covered by each station was carried out in SPANS GIS in the context of being missing data station included and excluded in each of the two calculations.

The calculation of missing daily data was based on the premise that the ratio of areal segregation due to inclusion and exclusion of the missing data station provides the proportionate criteria for the spatial rainfall weighting factor.

$$P_m = \frac{1}{A_m}.\left((A_{11} - A_1)*P_1 + (A_{22} - A_2)*P_2 + ...(A_{nn} - A_n)*P_n\right) \qquad \text{(Eq..2.2)}$$

where P_m is the estimated daily value for the missing station,

A_m is the area for the missing station according to nearest neighbour criteria determined from Thiessen polygons,

$A_1, A_2 ......A_n$ are the areas when missing station is included in nearest neighbour criteria,

$A_{11}, A_{22} ..... A_{nn}$ are the areas when missing station is excluded,

$P_1, P_2, ... P_n$ are the daily precipitation of the surrounding stations.

2.3.3 Comparison of NR & APR Methods

Both methods were used to estimate the missing data for a known period of one month in each of the four seasons and for 10 individual stations representing the agro-ecological zones of the UMCA. In the NR method, it assumes that the missing value always follows the average proportion of the long term time series distribution of the adjacent stations directly. It does not account for the distance to each rain gauge as a separate criteria. However, in the APR method, it measures the comparative spatial distance directly in terms of the nearest neighbour criteria and also assigns higher weights for relatively closely located stations. The Figure 2.1 shows the distribution of percentage error in both these methods. The percentage error was calculated using the monthly values due to the high degree of random variation found in the daily rainfall series.

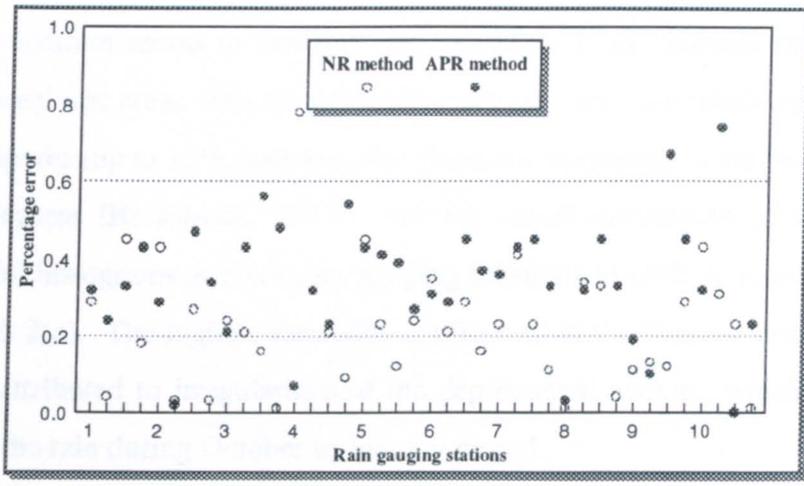


Figure 2.1 Comparison of Error Distribution of Rainfall Estimations in NR and APR Methods for UMCA Rain Gauging Stations

Although both methods derived realistic results, NR method estimates were found to be more acceptable. The percentage root mean square error for NR estimates is 0.276 and for APR estimates, it is 0.375. These results suggest that the rainfall distribution is more related to a pre-defined historical pattern at a particular location rather than a generalised measure of proximity. This behaviour can be due to the influence of relatively permanent factors such as orographic barriers and terrain irregularities distributed in the UMCA. Subsequently, all the missing data were estimated using NR method. The format of the Normal ratio method calculation is shown in Appendix A-2.

2.4 Temporal Distribution of Rainfall

2.4.1 Annual Variation of Rainfall

The average variability of annual rainfall in Sri Lanka ranges from just less than 8% in the Southwest region to over 20% in the Northern and Eastern extremes (Sirinanda, 1983). This pattern seems to conform the conditions in the tropical zone in general, where relatively wet areas with no appreciable dry seasons have relatively lower annual variability figures (up to 15%) whereas elsewhere, the variability could increase with the degree of dryness (Beckinsale, 1975). For the visual comparison of variability, the annual rainfall histograms at three rain gauging locations in UMCA is shown in Figure 2(a) through 2(c). The highest variability is observed in the Eastern strip of coast and that can be attributed to irregularities of the depressional activity, which accounts for the much of the rain during October to January period.

In UMCA, the highest mean annual rainfall for the study period (1964-1993) has been recorded at Kenilworth gauging station amounting to 5707 mm. Further, in the wettest year during this period (1985), the average has been exceeded by 2087 mm yielding 7295 mm of rain. In contrast, the driest year in the three decades (1983), has shown a deviation of 2612 mm from the mean value shedding only 2591 mm of rain for the entire year. In addition to this remarkable inter-annual variability of the rainfall, within two consecutive years, it has shown a difference reaching as high as 3215 mm between the years 1975 and 1976. The lowest mean annual rainfall has been recorded in UMCA for Welimada where the recorded lowest and highest annual rainfall figures are 929 mm and 1558 mm respectively.

In the context of temporal hydrological modelling, it is interesting to note the temporal distribution of annual rainfall in order to understand the extent of inter-annual variability. The temporal distribution of the deviations from mean annual rainfall in these two extreme cases is shown for the same period in Figures 2.3(a) and 2.3(b).

(a)

(b)

(c)

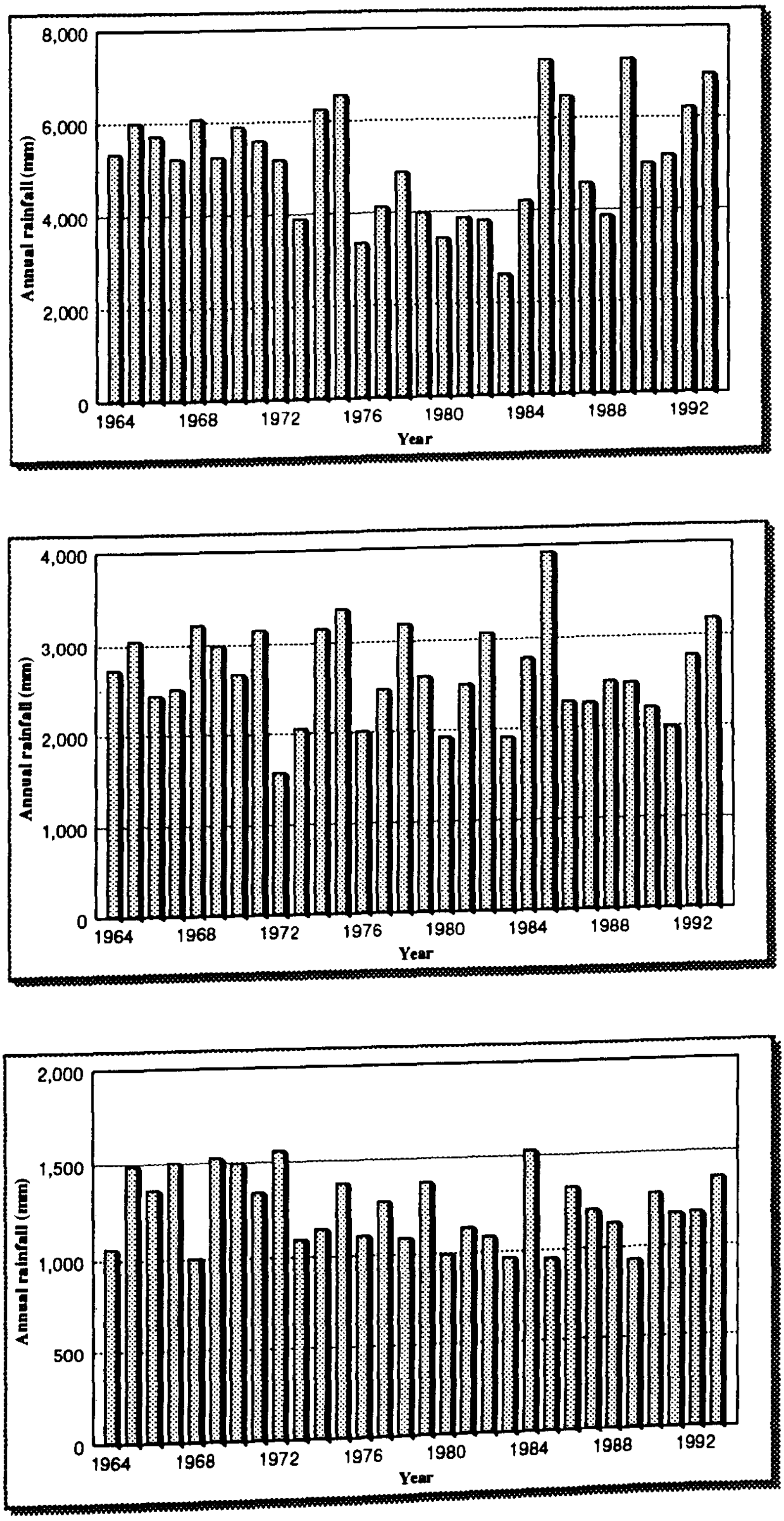


Figure 2.2 (a) - (c) Distribution of Annual Rainfall at Three Selected Gauging Stations (a) Kenilworth (b) Maskeliya (c) Welimada

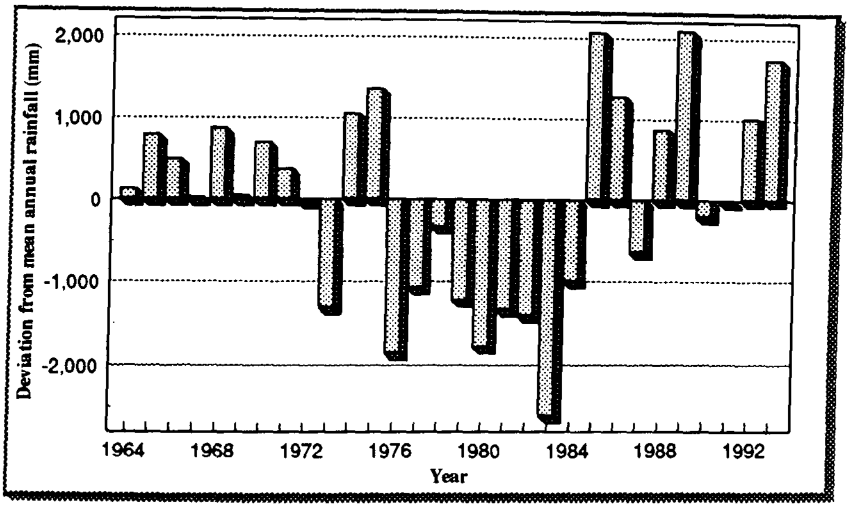


Figure 2.3(a) Deviations of Annual Rainfall from Mean Annual Rainfall at Kenilworth

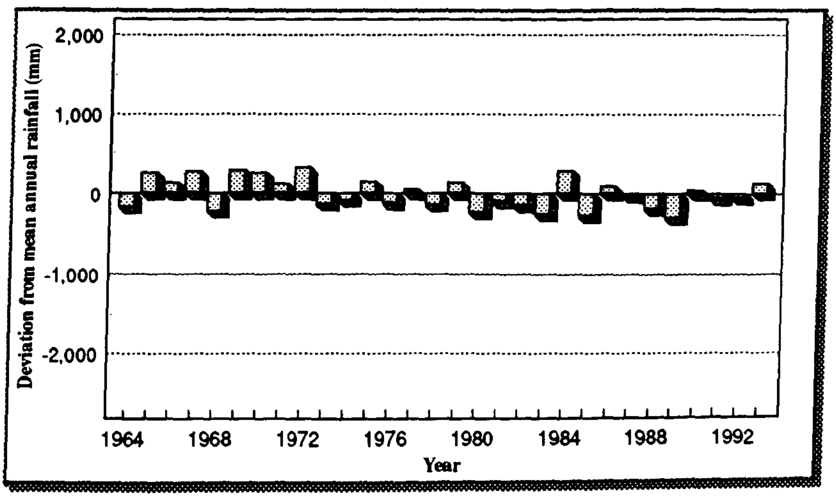


Figure 2.3 (b) Deviations of Annual Rainfall from Mean Annual Rainfall at Welimada

Although the period of records shown in Figures 2.3(a) and 2.3(b) is not sufficient to comment on the exact annual repeat cycles, it is obvious that the lag-01 serial correlation of the annual time series is quite high (0.55) in the data from Kenilworth station whereas in Welimada it is low and negative (-0.1). This could be attributed to the differences in location of individual gauging station with respect to that of orographic barriers in the catchment.

2.4.2 Seasonal Distribution of Rainfall

According to the general atmospheric circulation pattern in Sri Lanka, there is an unequivocal division of the year into four seasons (Domros, 1974). The rainfall year is customarily considered to be starting in March and ending in February (Jayamaha, 1985). This identification of seasonal distribution of rainfall is based on the relative dominance of causative factors in each season (Table 2.1).

Table 2.1 Seasonal Distribution of Rain Types

Season	Period	Dominant Type of Rain
First intermonsoonal season	March - April	Convectional
Southwest monsoon season	May - September	Orographic (monsoonal)
Second intermonsoonal season	October - November	Convectional, cyclonic, depressoional.
Northeast monsoon season	December - February	Orographic (monsoonal), depressional

The nature of seasonality, the time of on-set and termination of, and the duration of the seasons are not uniform even over any single major rainfall zone so much so that the seasonality is identified as a regional phenomenon (Sirinanda, 1983). However, the definitions of Agro-ecological regions which characterise the climate in the regions according to 75% probability expectancy of monthly and annual rainfall, monthly 75% probability expectancy of dryness, and latitudinal differences, identify areas where the variation is quite insignificant in view of the overall differences observed within the island.

In order to investigate the seasonal distribution of rainfall in a year at different locations and the temporal recurrence of seasonal distribution, correlation coefficients comparing rainfall of each season with that of the other seasons were calculated using representative data of all the agro-ecological regions using Spearman's non parametric correlation statistics.

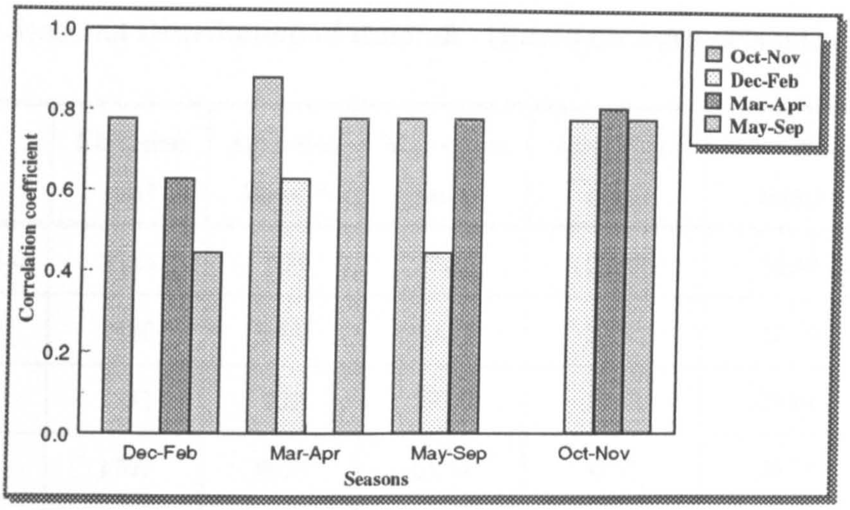


Figure 2.4 Spearman's Correlation Coefficient Statistics for the Comparison of Seasonal Rainfall (1964-1993)

The graphical representation of correlation coefficients between different seasons (Figure 2.4) clearly depicts the similarity of rainfall distribution in the four seasons with a slight deviation between the major monsoon season starting from May to September and inter-monsoon between December to February. However, it still provides a correlation close to 0.5. Further, there may be some added effects on the associations due to the probable non-stationarity of the underlying 30 year time series used for the analysis. The use of boundaries demarcated by the Agro-ecological zone definitions is particularly useful within the region of central highlands where drastic changes in climate within local environments are constantly evident. The relative concentration of rainfall as a percentage for each of the four seasons at key geographical locations in different Agro-ecological regions is set out in Table 2.2.

Table 2.2 Seasonal Distribution of Rainfall - (Based on Agro-ecological Regions)

Station	Elevation (m)*	Agro-Eco. Zone**	Mar - Apr. (mm)	May -Sep.. (mm)	Oct -Nov. (mm)	Dec. -Feb. (mm)
1. Bandaraeliya	1784	IU3	22.16	23.96	31.48	22.40
2. Dunsinane	1480	WU2	10.11	56.46	22.79	10.64
3. Dyraba	1353	IU2	19.00	29.13	26.84	25.03
4. Hakgala	1707	WU3	13.51	32.75	26.51	27.21
5. Hatton	1250	WU1	13.56	58.81	19.45	8.18
6. Kirimetiya	940	WM2	12.66	39.98	27.60	19.76
7. Liddesdale	1569	IU1	15.04	18.72	26.79	39.45
8. Nawalapitiya	580	WM1	12.44	58.37	21.00	8.19
9. Peradeniya	480	WM3	15.17	40.14	30.91	13.78
10. Woodside	820	IM2	12.73	23.14	32.44	31.69

* Source : Department of Meteorology

** Source : Department of Agriculture (1979)

However, the highly variable nature of the occurrence and the duration of the each season in a year make it difficult to categorically identify the exact dates to be grouped into an individual season. It is also observed that the existence of the four seasons does not exactly follow the annual calendar.

2.4.3 Distribution of Rainfall Within a Day

Rainfall distribution in a day could be considered only for the intermonsoonal seasons where convective rains make up the dominant rainfall type (Alles, 1970). Convective rains are characterised by high intensity, short duration, localised and highly spatially varying storms. Convective rainfalls also are by and large, a function of the distribution of the topographic profile in the central highlands (Domros, 1974). In general, the influence of the topographical features on the spatial variability of rainfall has been a major focus in several local research efforts (Suppiah, 1988; Nomoto et al., 1983; Sirinanda, 1983; Domros, 1974).

Further, there can be different types of rainfall occurring within a brief period of time, thus making the distribution of rainfall within a day highly stochastic and making predictions on the daily rainfall impossible.

2.4.4 Rainfall Reliability

In the context of the complexity of the rainfall process due to inherent variability which is difficult to represent in a basic model structure, the prediction of rainfall or rainfall reliability poses a serious dilemma not only at the daily intervals but also at the monthly and seasonal scales. However, several attempts have been made locally, to predict the likelihood or probability of receiving a pre-defined amount of rainfall as well as the pattern of the rainfall distribution within a specified degree of confidence (Suppiah, 1988; Sirinanda, 1983; Department of Agriculture, 1979; Alles, 1969; Jayamaha, 1955).

All these efforts have been based either on the extension of the historical records or on the generation of synthetic parameters to simulate the hydrological dynamics from the parametric or non-parametric estimations upon the past data. A serious complication arises with regard to the reliability of the predictions of rainfall for the future because of the inherent weakness of the assumption made to the effect that the underlying time series to be stationary. The validity of this assumption is extensively tested in chapter 3.

2.5 Spatial Distribution of Rainfall

2.5.1 Spatial Variability

The spatial variation of rainfall in the central highlands is a highly complex phenomenon compared to that which exists in less complex topography elsewhere in the country. The central part of the Southern half of the island is mountainous, rising to over 2700 m. The core region of the central highlands which encompasses the UMCA comprises many complex topographical features such as ridges, peaks, plateaux, basins, valleys and escarpments (Suppiah, 1988). The highest peaks (Pidurutalagala 2717 m, Kirigalpotta 2390 m, Totapola 2358 m) in the central ridge are surrounded by high plateaux, Hatton on the west and Welimada on the east (Nomoto et al., 1983). These topographical features strongly affect the spatial pattern and the variability of the seasonal rainfall, winds, relative humidity and temperature.

Domros (1974) concluded that the Coefficient of Variability (CoV) to be the best expression of spatial and temporal rainfall variability. It is also referred as Normalised Standard Deviation. It provides in percentages, the deviation of the individual annual rainfall values from the long term average of the annual rainfall for the observation period for different locations. A detailed analysis of CoV and the relevant literature are summarised in Appendix A-3.

2.5.2 Elevation and Rainfall Distribution

The importance of the rainfall distribution becomes critical for mountainous catchments where the weather systems interact with the topography resulting in highly non-uniform rainfall over the area (Loukas & Quick, 1996). In general, for the mid-altitude areas, it is assumed that the rainfall increases with elevation, and it is highest at the highest elevation (Barry, 1992). However, there are indications that the precipitation distribution does not always increase with the rise of the topographical profile (Loukas, 1991 as quoted by Loukas & Quick, 1996; Henderson, 1993; Loukas & Quick, 1993; Rasmusson & Tangborn, 1976). Wheater et al. (1991) showed the existence of a strong association between seasonality of catchment rain-day occurrence and elevation.

The spatial distribution of rainfall with respect to the elevation profile was investigated because of the influence of central highlands as an orographic barrier. During the monsoon seasons, in addition to the water shedding effect of the mountains, it establishes regional differentiation of highlands into windward and leeward areas where there are marked differences in the hydrological regimes. Furthermore, during the dry period, fog interception is increased especially, when covered with natural dense vegetation at high elevations. The mountain range influences the convectional and depressional storm events (Nomoto, 1983) and this suggests the need for investigating the effect of elevation on seasonal rainfall events though it is beyond the scope of the present study.

For comparison of altitude variations, the rain gauging station at the lowest altitudinal plane was considered as the reference and all the elevations beyond were calculated as departures from the reference. The rainfall values for each station were derived as a ratio of that of the reference station. This ratioing provides an enhanced effect in the visualisation of the relational behaviour of rainfall in the catchment. The relationship between the spatial distribution of rainfall and the elevation with respect to the reference station and for each season is shown in Figures 2.5(a) and 2.5(b).

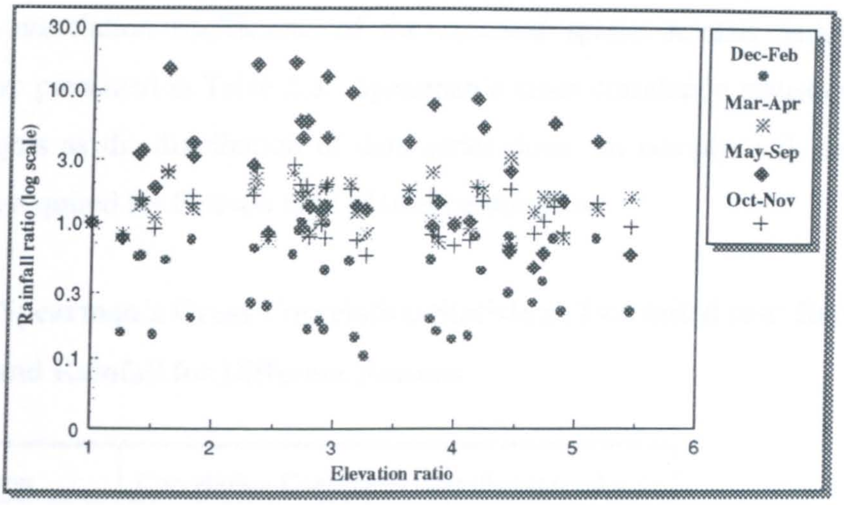


Figure 2.5(a) Elevation Ratio vs. Rainfall Ratio at Windward Stations for Southwest Monsoon (compared with reference station)

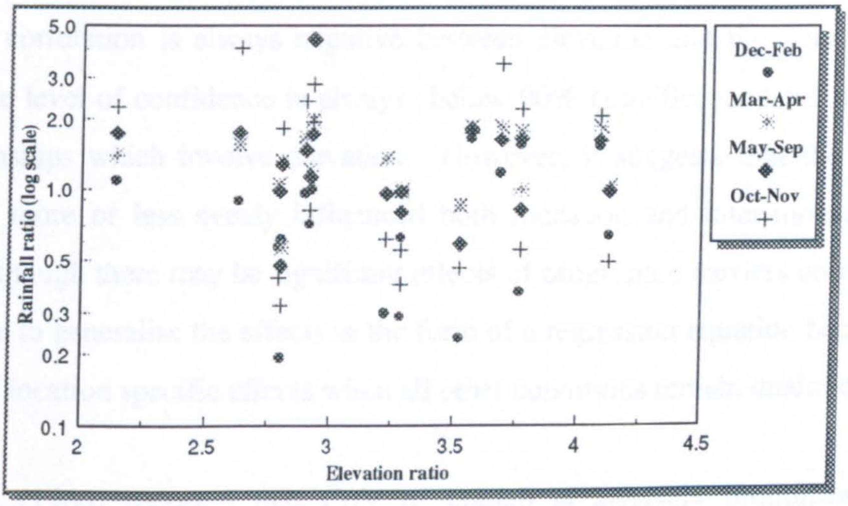


Figure 2.5(b) Elevation Ratio vs. Rainfall Ratio at Windward Stations for Northeast Monsoon (compared with reference station)

It is clear from the Figures 2.5(a) and 2.5(b) that the assumption of statistically significant cross correlation between the seasonal rainfall and elevation is not acceptable. However, it suggests very strong cross correlation among the seasonal data series for almost all stations. The topographic variation in UMCA is not consistent and the orographic effects are not caused by an aligned mountain series but by the presence of a few haphazardly located summits. This can be the reason for poor correlation with elevation.

The cross correlation coefficients of the seasonal spatial rainfall data series with elevation are presented in Table 2.3. Spearman's cross correlation statistics were used in the analysis as the distribution of data series does not comply with the normality assumption required for Pearson type of linear association.

Table 2.3 Spearman's Cross Correlation Statistics (Two tailed test) Between Elevation and Rainfall for Different Seasons

Season	Correlation Coefficient (significant level = α)
Dec - Feb	-0.0393 (α = .772)
May - Sep	-0.2186 (α = .102)
Mar - Apr	-0.0232 (α = .864)
Oct - Nov	-0.2235 (α = .195)

The cross correlation is always negative between elevation and the seasonal rainfall. Further, the level of confidence is always below 90% (significance level $\alpha > 0.1$) for the relationships which involve elevation. However, it suggests that the orographic effects are more or less evenly influenced both monsoon and inter-monsoon rainfall events. Although there may be significant effects of orographic barriers on rainfall, it is not possible to generalise the effects in the form of a regression equation because of the presence of location specific effects when all other conditions remain unaltered.

Chebotarev (1966) reported that CoV of rainfall is inversely proportional to the elevation above mean sea level. Accordingly, an attempt was made to compare the distribution of CoV and elevation of the gauging stations in UMCA. The correlation between CoV and elevation was found to be very poor (-0.089).

2.5.3 Rainfall Correlation with Distance

Detailed studies have been carried out to identify the spatial variations of rainfall correlation coefficients at point gauging locations (Wheater et al., 1991; Berndtsson & Niemczynowicz, 1986; Beven & Hornburger, 1982). Loukas & Quick (1996) showed that precipitation series at two different stations, measured by correlation coefficient as a measure of spatial variability, decreases exponentially with the increasing distance between two gauges.

It was attempted to develop the spatial correlation of rainfall as a function of distance. The distance was measured from a point at South-western edge of the catchment for Southwest monsoon and from a point at North-eastern edge for Northeast monsoon. For each monsoonal season, stations located on leeward side and windward side were considered. Intermonsoonal periods were also considered separately. According to Loukas & Quick (1996), spatial correlation of rainfall with respect to distance generally takes a exponential regression function. In this particular case, the relationships such as linear, logarithmic, inverse, power, quadratic and cubic were tried out and found to be not significant in explaining the inherent variation in the data series.

Further, an attempt was made to investigate the correlation between inter-station distance and rainfall based on five selected gauging stations on Northeast and Southwest slopes separately. The results which confirm the negative are summarised in Appendix A-4. However, these results clearly show that there is a very high correlation of the rainfall on the Southwest slope for all the monsoon and inter-monsoon periods and on the Northeast slope only for Northeast monsoon period (Appendix A-4).

2.6 Interpolation Between Adjacent Stations

Since it was not possible to find a generalised relationship between rainfall and distance, an attempt was made to investigate the correlation between adjacent stations with relatively short distances. Four pairs of adjacent stations were selected representing windward sides for both monsoons. The correlation coefficients derived for different temporal scales of data of adjacent stations are shown in Figures 2.6(a) through 2.6(d).

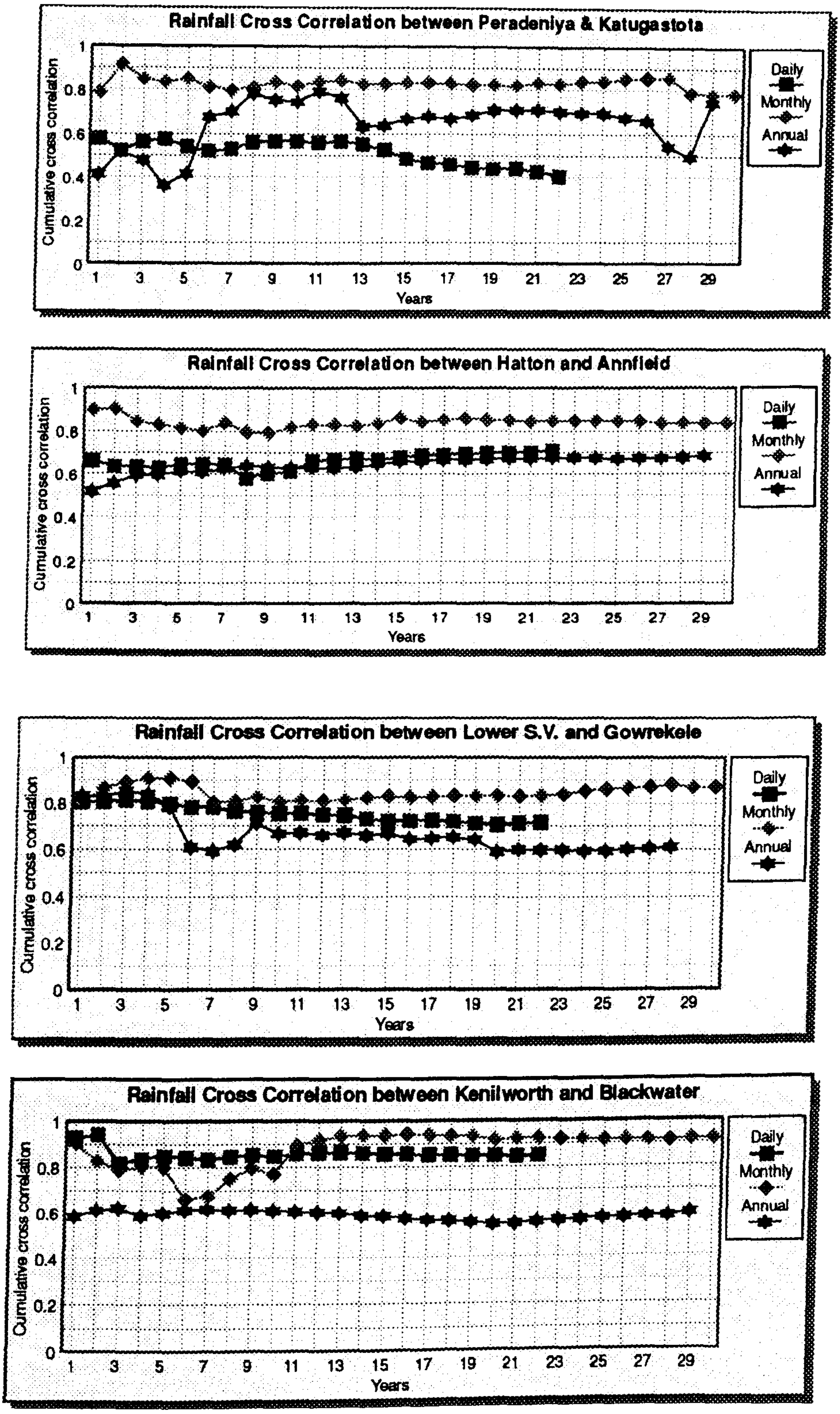


Figure 2.6 (a) - (d) Cumulative Annual Correlation Coefficient of Rainfall in Adjacent Stations for Daily, Monthly and Annual Time Series

In general, in all three temporal scales viz. daily, monthly and annual, it shows very high correlation in all the pairs of adjacent stations tested for correlation. All the stations selected for each pair were within 10 km of areal distance to each other. This suggests the possibility of employing a linear interpolation algorithm for point rainfall measurements between adjacent stations. However, according to the results in Section 2.5.3, the acceptability of linear interpolation is questionable when the distance exceeds 10 km.

2.7 Seasonal Rainfall Profile

The high correlation statistics shown in section 2.6 between adjacent stations provided the rationale for linear interpolation of seasonal rainfall in UMCA. A cross section of the interpolated seasonal catchment rainfall along the 200 km N line from the projection origin was considered, and seasonal rainfall and elevation values were recorded at every 2 km over 57 km distance along the cross section. The distribution of seasonal rainfall and the elevation are plotted on Figures 2.7(a) through 2.7(d) for the four seasons.

During the inter-monsoon period, the entire cross section received the most evenly distributed rainfall and particularly so for the March to April period. In contrast, Southwest monsoon presents by comparison, a great spatial differentiation of rainfall.

In comparison with elevation profile, a trend of increasing rainfall is characterised with the increasing altitude in the lower parts of the catchment. In the middle and upper parts of the catchment, increasing altitude shows a decrease in rainfall totals probably due to rain shadow effects and the availability of relatively dry air masses for condensation. The plots in Figure 2.6 show that the occurrence of the maximum belt of rainfall is on the lower Western slopes while the Eastern lower slopes receive comparably less rainfall.

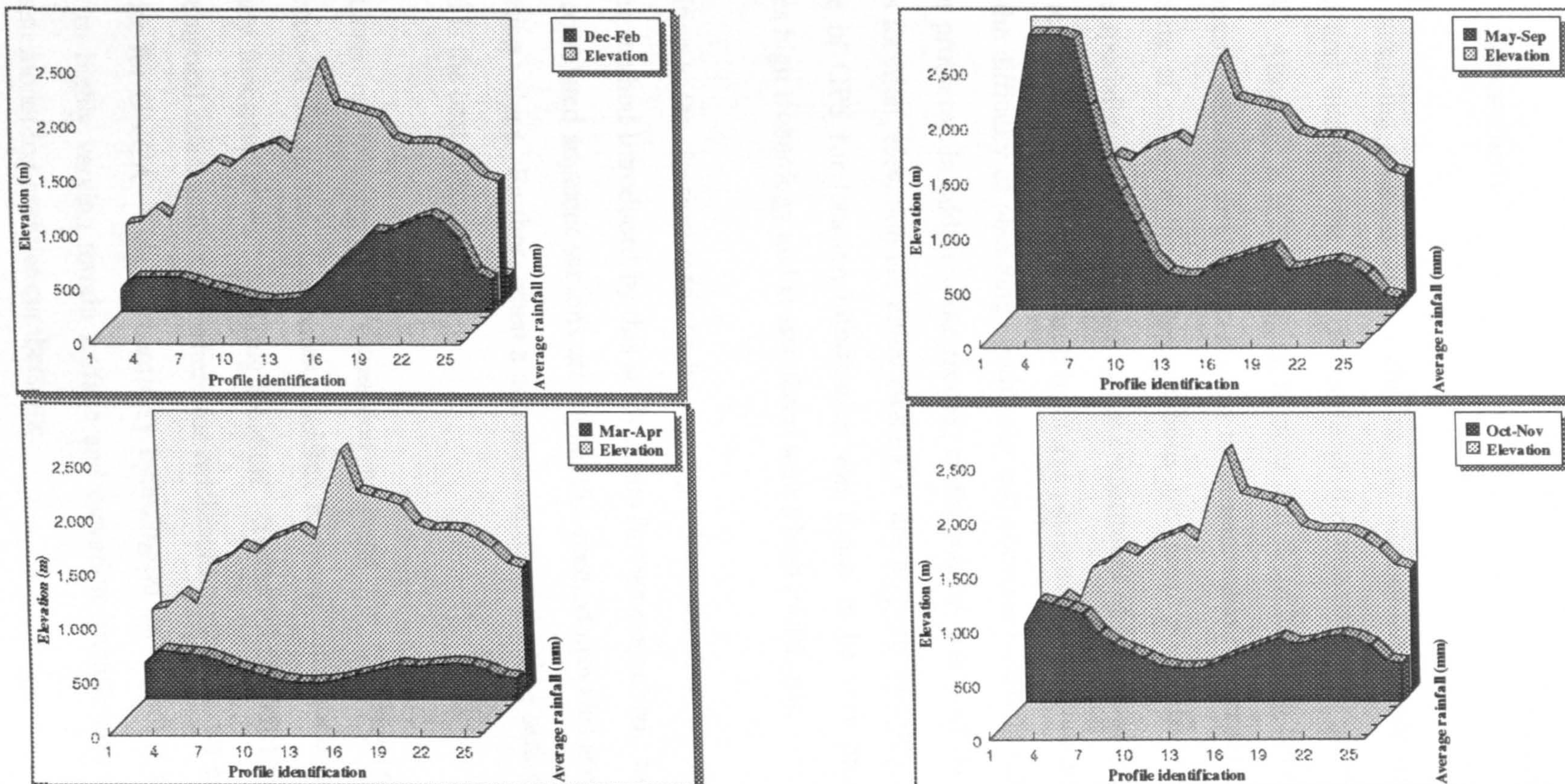


Figure 2.7 (a) - (d) West to East Catchment Cross Section (170-227 x 10^3 TM Co-ordinates) for Seasonal Rainfall and Elevation

2.8 Concluding Remarks

2.8.1 Discussion

In the foregoing sections of this chapter, an attempt was made to collect, format, analyse and interpret the data to evaluate the characteristics of rainfall regime in UMCA. Although it is encouraging to note that there has been a massive network of rain gauging stations in UMCA, it is so unfortunate that the general maintenance and the quality of some of the gauging stations are rather poor. However, some of the stations specially those maintained by the Department of Meteorology, the Department of Agriculture and various research institutes perform a commendable service. In this study, the difficulty of obtaining continuous and accurate historical rainfall records was a major problem. In addition, the records of the related details of the gauging stations such as location, elevation are either lacking or not properly updated. In this situation, the use of GPS for location information was found to be very promising though it involves high technology and is associated with a high initial cost.

In addition to the classical methods for missing value estimation, the Areal Precipitation Ratioing method introduced by this study needs further evaluation. In situations where highly correlated adjacent stations are found, this method provides accurate estimations for missing values. Further, when a non-stationarity of the time series is obvious, APR method is the best alternative.

The efforts on missing value estimation revealed the tendency for the historical recurrence of the rainfall distribution yielding temporal correlation rather than spatial proximity functions at each gauging location. It was found that most of the proven spatiotemporal relationships elsewhere for catchment hydrology are either not valid or imprecise for UMCA. This extraordinary hydrological behaviour of the UMCA could be due to highly varying terrain surface and elevation irregularities and it makes the catchment modelling exercise cumbersome.

The results of the analysis of temporal distribution of rainfall in UMCA poses doubts on the validity of some of the conclusions drawn in the previous studies. These discrepancies are mainly due to the application of generalised national information to UMCA where the catchment geometry is entirely different to the situation elsewhere in the island.

Although the extent of the variation of seasonal rainfall distribution differs from station to station, two fundamentally different types of annual rainfall regimes are marked by monsoons and the two inter-monsoon seasons are characterised by spatially more or less uniform rainfall conditions.

In terms of the spatial distribution of hydrological phenomena, it was found that the correlation are valid only within short distances irrespective of the elevation. This made the task impossible to derive any generalised relationship for the catchment between rainfall and other variables such as elevation and distance. However, high correlation at close proximity allows a better degree of reliance on the linear interpolation function in comparison to Thiessen polygon type of spatial demarcation. Nevertheless, it is understood that the accuracy of modelling could be vastly improved when it is possible to analyse individual storm events with exact identification of the geographical locations of storm origin and the associated spatial decay rates.

2.8.2 Conclusions

1. There is an urgent need to introduce an efficient meteorological data collection and reporting procedure specially for the estate managed rain gauging network. The available data from these stations require undergoing a rigorous processing procedure in order to verify the consistency.

2. The GPS performs satisfactorily even in the highly mountainous and varying terrain conditions and was found to be the most convenient way of field navigation.

3. Normal Ratio method proves to be producing better estimates compared with the Areal Precipitation Ratioing method for the missing data. However, in view of the

applicability for non-stationarity situations, APR method has better practical reliance. Accordingly, further studies are required to validate the APR estimations.

4. It is not possible to derive a generalised relationship in terms of spatial or temporal correlation in the catchment. The observed rainfall data in the catchment are highly specific to the individual locations. However, within short distances (less than 10 km), there is an acceptable level of correlation proving that linear interpolation of rainfall is not much deviated from the reality.

5. In a given location, there is a very high inter-seasonal correlation thus making it possible to predict seasonal rainfall with a reasonable accuracy.

6. The relationship of rainfall with the elevation is highly complex and deriving a generalised correlation is not possible. However, it may be possible to derive indices for seasonal and regional characteristics rather than catchment-wide assessments.

Chapter 3

3. ANALYSIS OF HYDROLOGICAL TIME SERIES

3.1 Introduction

Time series analysis has become a major tool in Engineering Hydrology. It could be used for building mathematical models to generate synthetic hydrological records or to forecast the occurrences of hydrological events ahead of time. The other uses of time series analysis include detection and modelling of trends, and shifts (jumps) that may be apparent in hydrological records, the filling in of missing data and extension of records (Salas & Ormijana, 1992).

In this chapter, the objective of time series analysis was to examine whether there was any significant development of trend, shift or variability in the rainfall regime of the catchment due to the changes made on the composition of land use. It has been questioned whether rainfall has reduced considerably during the last 2-3 decades and is the reason for diminishing river flow. If these questions are left unanswered and the hydrological variability is not properly assessed, it is not possible to rely on the historical hydrological records for water resources research and management in UMCA. Therefore, it is imperative to study the temporal distribution of hydrological data obtained from historical records in order to verify the reliability and applicability of past data for the existing conditions.

3.2 Distribution of Time series

3.2.1 Consistency of Hydrological Data

It was obvious that historical long term records of rainfall were not complete and consistent for the considered 30 year time lap. It was, therefore, necessary to determine the consistency of the data before any numerical analysis was carried out. Systematic errors that affect consistency may be present due to changes in the instrumentation, its location and the observers. Double Mass Curve technique was adopted to access the consistency of rainfall data and also to generate an unified consistent data sequence by comparing the locally integrated data from a selected station with the spatially integrated data from the adjacent stations.

3.2.2 Trend and Periodicity in the Rainfall Fluctuations

Previous studies on the rainfall fluctuations in Sri Lanka by the ordinary moving averages and the residual mass curves have revealed long period (20 years) cycles (Thambyahpillay, 1958). Power spectrum analysis has been used to identify the periodicity in the time series (Suppiah, 1986). However, there is an inherent weakness in this analysis that it discards trends present in the time series. Identification of rainfall time fluctuation regions has been attempted by Suppiah & Yoshine (1984) using

Empirical Orthogonal Function (EOF) analysis. However, seasonal variations have been estimated considering the island as a single unit.

3.2.3 Trends, Shifts and Variability of Rainfall Time Series

A trend in a time series is identified as the continuous increasing or decreasing order of the values with time, making it not possible to calculate one long term average with narrow confidence limits (Salas & Ormijana , 1992). Trends may be due to gradual changes which occur in one particular direction over a period of time. In contrast, jumps or shifts of a time series can result due to instantaneous changes occurred at any given instance of time. Variability of the time series can be due to the inherent stochasticity in the process or the local variations at the time of occurrence.

3.2.4 Selection of Rainfall Data Sequences for Analysis

Although it is generally accepted that the changes made in the UMCA in terms of land use and land cover have been gradual as may be the case for any catchment in general, large scale drastic changes were evident only during the Accelerated Mahaweli Development Programme. Accordingly, the period prior to 1977 can be considered as a relatively change free period. In the statistical analysis of the time series, it was, therefore, decided to divide the thirty year rainfall series into two unequal time series representing the periods prior to 1977 and after 1977. Because of the stochastic nature and inherent variability evident in the daily time series, monthly data were considered for the analysis. The analysis was extended to represent at least one rain gauging station in each of the 10 Agro-ecological zones found in UMCA.

3.3 Drought Related Properties

Droughts have been variously defined and have been studied from several points of view (Sirinanda, 1976). Drought definition includes scarcity of water for drinking and other household activities or lack of water for agricultural practices. In the UMCA, there is no specific period which can be defined as a drought. Further, almost all the area covered by the catchment is in the so-called wet zone of the country, although comparatively dry areas exist in Northwest and Southeast plateau. However, the assessment of the drought related properties in this study was based on the argument that the occurrence of prolonged dry spells were more frequent and number of rainy days in a year have diminished probably due to the changes in the rainfall regime in the UMCA.

In the evaluation of drought related properties, a threshold rainfall limit was assigned to categorise dry days in a given month based on evaporation demand. It has been estimated that the average evapotranspiration in the UMCA is around 4 mm/day (Kayne & Nakagawa, 1983). Since isolated storm events evaporate back to the atmosphere without penetrating into the soil, the concept of "Basic Effective Rainfall" (BER) was introduced in the definition of the existence of drought.

$$BER = (Rainfall - 4\ mm) \quad \text{if } Rainfall > 4\ mm.,\ \text{else } BER = 0 \qquad \text{(Eq. 3.1)}$$

Drought statistics were derived for the 10 gauging stations detailed in chapter 2 representing all the Agro-ecological zones. The time series analysis discussed in this chapter was based on the rainfall and drought statistics derived for these 10 representative stations. The BER was estimated in order to determine the statistical variations in the drought related statistics as two individual parameters, firstly on the highest number of consecutive drought days and secondly, on the total number of drought days in a month.

A simple Turbo C++ programme (Appendix B-1) was developed to calculate the drought statistics from the ASCII data file formats. A Lotus 1-2-3 macro programme was run to convert the rainfall database into ASCII files and the calculated drought statistics back to the database files. The calculated drought statistics in terms of the total number of non-rainy days and the maximum number of consecutive dry days are presented in Appendix B-2(a) through B-2(t).

3.4 Determination of Linear Trends

A number of parametric and non-parametric tests for the identification of trends have been suggested in the literature. Computer programmes for several of these tests are also available (Salas et al, 1991). Some of these tests for trends and estimates thereof are relatively simple under certain assumptions while others are more complex requiring modelling of the underlying time series such as in the so-called intervention analysis (Box & Tiao, 1975; Hipel et al, 1975). Detailed estimations with complex and accurate underlying assumptions were beyond the scope of this study. The general objectives of the time series analysis was to see if the 30 year time series under investigation was relatively free from trends, shifts or unaccounted periodicity fluctuations. This was to see if the assumption of general stationarity of the time series, made later in the distributed hydrological modelling exercise was violated. A simple test for the detection and estimation of linear trend was conducted to achieve this, using student T distribution statistics.

3.4.1 Theory

Assuming that Y_t, t= 1,2,....N is a time series with N sample size, if Y_t has a linear trend, it can be conveniently written as a simple linear regression model as a function of t (Eq. 3.2).

$$Y_t = a + b\,t \qquad \text{(Eq. 3.2)}$$

where a and b are the parameters of the regression model.

If it has no significant linear trend, the value of b should be equal to 0. Then, testing the hypothesis that Y_t has no significant trend is the same as testing the hypothesis that b=0 in the model (Eq. 3.2). Thus, a rejection of the hypothesis b=0 was considered as a detection of a linear trend.

According to Salas and Ormijana (1992), the hypothesis b=0 could be rejected if

$$T_c = \left| \frac{\hat{r}\sqrt{N-2}}{\sqrt{1-\hat{r}^2}} \right| \quad > \quad T_{(1-\frac{\alpha}{2})(N-2)} \qquad \text{(Eq. 3.3)}$$

where $\hat{r}$ is the cross correlation coefficient between the sequence Y_1, Y_2, ...Y_N and 1,2,...N.

$T_{(1-\frac{\alpha}{2})(N-2)}$ is the $(1-\frac{\alpha}{2})$ quantile of the student t-distribution with (N -2) degrees of freedom.

3.4.2 Statistical Analysis

Monthly time series of rainfall were divided into two independent series accounting for the periods prior to 1977 and after 1977. For each sub series, cross correlation between the sequences Y_1, Y_2, ...Y_N and 1,2,...N (N=30) series were estimated. The test statistics (T_c) were calculated for each time series by introducing cross correlation coefficient ($\hat{r}$) and sample size as input parameters into the Equation 3.3. The results of the tests are tabulated in Appendix B-3(a) through B-3(j) and the summary is graphically shown in Figures 3.1(a) and 3.1(b). The same methodology was applied upon the drought statistics separately for each criteria i.e. maximum number of consecutive non-rainy days and total number of non-rainy days in a month. The resultant trend statistics is tabulated in Appendix B-3(k) through B-3(t) and the summary is graphically shown in Figures 3.1(c) through 3.1(f).

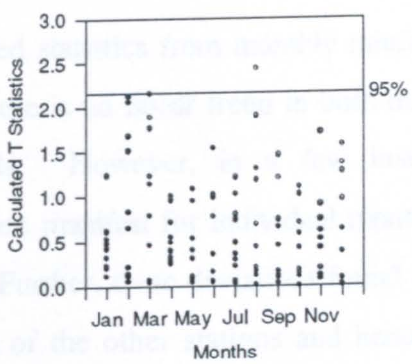


Figure 3.1(a) T Test Statistics of Linear Trend Determination - Ranfall Before 1977

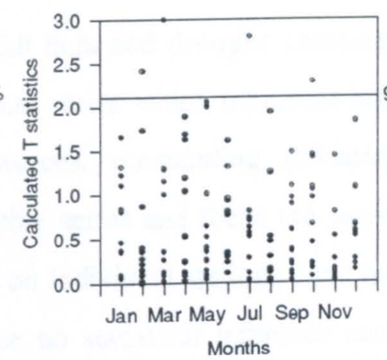


Figure 3.1(b) T Test Statistics of Linear Trend Determination - Ranfall After 1977

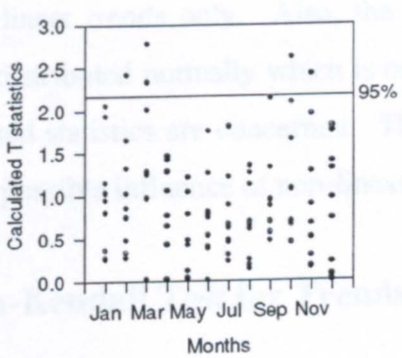


Figure 3.1(c) Test Statistics of Trend Determination Max. No. of Consecutive Dry Days in a Month Before 1977

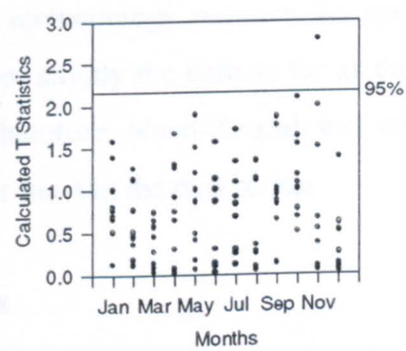


Figure 3.1(d) Test Statistics of Trend Determination Max. No. of Consecutive Dry Days in a Month After 1977

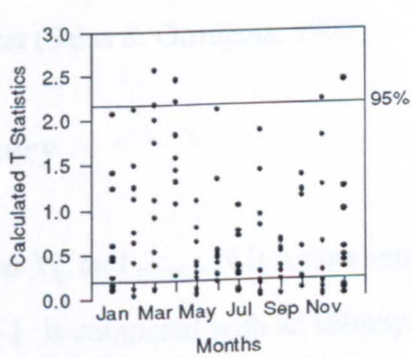


Figure 3.1(e) Test Statistics of Trend Determination Total No. of Dry Days Before 1977

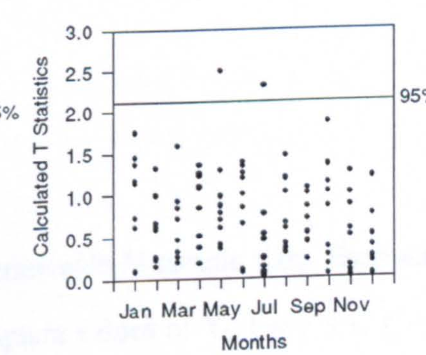


Figure 3.1(f) Test Statistics of Trend Determination Total No. of Dry Days After 1977

3.4.3 Evaluation of Linear Trend Statistics

The calculated statistics from monthly rainfall data and drought characteristics clearly show that there is no linear trend in both data series which represent before and after 1977 periods. However, in a few instances, outstanding deviations from the stationarity are manifest for individual monthly series and these are common for both time spans. Further, these deviations found on individual stations have no relevance to the statistics of the other stations and hence no statistical inference can be made on these deviations. These deviations can be attributed to measurement errors or faulty observations which were commonly experienced during the data collection process. It is emphasised that the statistics derived in this analysis can be used to recognise the presence of linear trends only. Also, the methodology requires the underlying time series to be distributed normally which is not strictly the case as far as the rainfall and drought related statistics are concerned. Therefore, Mann-Kendall test was conducted to detect the possible influence of non-linear trend in the data series.

3.5 Mann-Kendall Test for Trends

This is an improvement to the classical Kendall's coefficient of rank correlation (τ) theory where Kendall emphasised the importance of the ranks on their own and as pairs (Loveday, 1970). Statistics of the Mann-Kendall test identify non-linear trends as well and they are not sensitive to the normality of the time series because of it being a non-parametric test (Salas & Ormijana, 1992).

3.5.1 Theory

Assuming that Y_t, t= 1,2,...., N is a time series with N sample size. Each value of $Y_{t'}$, t = 1, 2, ..., N-1 is compared with all subsequent values of Y_t, t = $t'+1$, $t'+2$, ..., N. A new series z_k is generated by

$$z_k = 1 \qquad \text{if } Y_t > Y_{t'}$$

$z_k = 0 \qquad \text{if } Y_t = Y_{t'}$

$z_k = -1 \qquad \text{if } Y_t < Y_{t'}$ (Eq. 3.4)

in which $k = (t'-1)(2N-t')/2 + (t-t')$.

The Mann-Kendall statistic is given by the sum of z_k series (Hirsch et al, 1982).

$$S = \sum_{t'=1}^{N-1} \sum_{t=t'+1}^{N} z_k \qquad \text{(Eq. 3.5)}$$

The statistics represents the number of positive differences minus the number of negative differences for all the differences considered. The test statistics for N > 40 may be written as

$$U_c = \frac{S+m}{\sqrt{V(S)}} \qquad \text{(Eq. 3.6)}$$

$$V(S) = \frac{1}{18}\left[N(N-1)(2N+5) - \sum_{i=1}^{n} e_i(e_i-1)(2e_i+5)\right] \qquad \text{(Eq. 3.7)}$$

.where m = 1 if S < 0 and m = -1 if S > 0, n is the number of tied groups, and e_i is the number of data in the ith (tied) group.

The statistic U_c is assumed to be zero if S = 0. Then the hypothesis of an upward or downward trend cannot be rejected at the α significance level if $|U_c| > U_{1-\alpha/2}$. $U_{1-\alpha/2}$ is the (1 - α/2) quantile of the standard normal distribution. Kendall (1975) indicated that this test is even valid for N as low as 10 if there are not too many tied values.

3.5.2 Mann-Kendall Test Statistics

The monthly time series of rainfall were again considered as two independent series accounting for the periods prior to 1977 and after 1977. For each sub series, the number of positive and negative differences for all the possible lags were calculated using a Lotus 1-2-3 macro programme. The calculated test statistics $|U_c|$ and the threshold value at 95% confidence limit in standard normal distribution are shown in Figures 3.2(a) through 3.2(f).

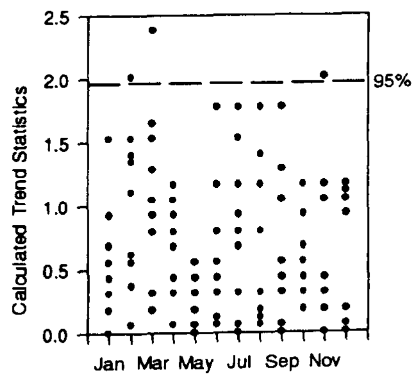


Figure 3.2(a) Test Statistics of Mann-Kendall Test for Rainfall Time Series Before 1977

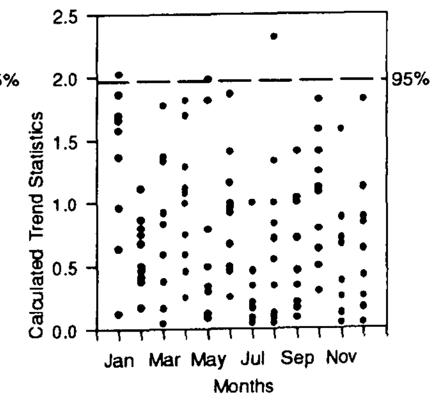


Figure 3.2(b) Test Statistics of Mann-Kendall Test for Rainfall Time Series After 1977

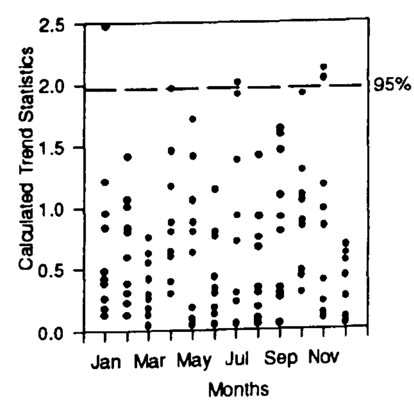


Figure 3.2(c) Test Statistics of Mann-Kendall Test for Maximum No. of Non-rainy days Before 1977

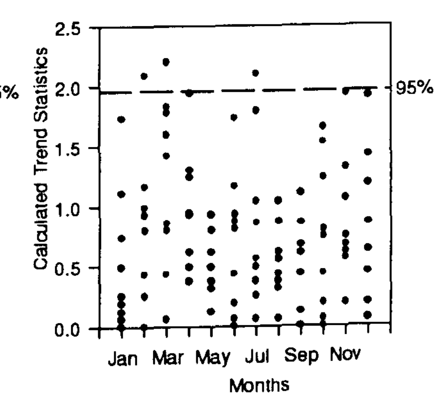


Figure 3.2(d) Test Statistics of Mann-Kendall Test for Maximum No. of Non-rainy Days After 1977

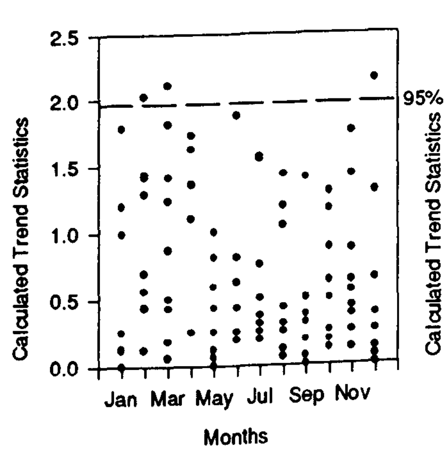


Figure 3.2(e) Test Statistics of Mann-Kendall Test for Total No. of Non-rainy days Before 1977

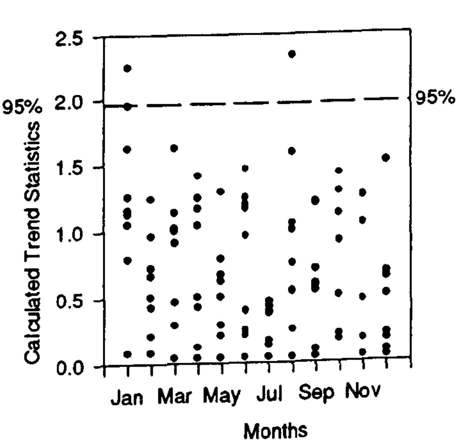


Figure 3.2(f) Test Statistics of Mann-Kendall Test for Total No. of Non-rainy Days After 1977

3.5.3 Evaluation of Non-linear Trend

Mann-Kendall statistics confirm that there is no trend in the data series after 1977 period. The instances where the 95% confidence limit is exceeded are common for both before and after 1977 periods suggesting that the deviations can be due to possible errors in the data sequences or the stochastic nature of the data rather than being presence of any trend components. Although the time series data were subjected to intensive scrutiny, the presence of observational and recording errors cannot be ruled out. Accordingly, the hypothesis of the presence of linear or non-linear trend in data series can be rejected confirming the stationarity of the data. However, this does not preclude the other possible sources of deviations from stationarity and the subsequent sections are devoted to investigate these cases.

3.6 Determination and Testing for Shifts (Jumps)

Several parametric and non parametric tests are available for testing and determining shifts (jumps) in statistical properties of time series such as mean and variance (Snedecor & Cochran, 1980; Gilbert, 1987 as quoted by Salas & Ormijana, 1992; Salas et al., 1991).

The major land use changes and the associated transformations in UMCA were more or less confined to a short period of time. The hypothesis being tested here is that whether the drastic changes in the catchment environment caused by the Accelerated Development Programme, in addition to the sporadic changes occurred over long period of time, have possibly led to an instantaneous change in the hydrological regime at the annual and monthly scales.

3.6.1 Theory

Mann-Whitney test for shift (jump) in the mean is a non-parametric test where no assumptions on data distribution are to be made. It is highly resistant to the effects of the outliers in the data series. In this test, the monthly time series Y_1, Y_2,.....Y_{N1} and Y_{N1+1}, Y_{N1+2}...Y_N of sizes N1 and N2, respectively, are divided such that $N_1 + N_2 = N$.

A new series, Z_t, t = 1, 2,.....N was defined as the series with the observations of series Y_t arranged in increasing order of magnitude. The hypothesis that the mean of the first sub series is equal to that of the second, was tested by using the statistics as defined by Snedecor & Cochran (1980).

$$Uc = \sum_{t=1}^{N1} \frac{R_{(Y_t)} - N_1(N_1 + N_2 + 1)/2}{N_1 N_2 (N_1 + N_2 + 1)/12} \quad \text{(Eq. 3.8)}$$

where $R(Y_t)$ is the rank of the observation Y_t in ordered series of Z_t.

The hypothesis of equal means of the two sub series cannot be rejected if $|U_c| \leq U_{(1-\alpha/2)}$ where $U_{(1-\alpha/2)}$ is the 1-α/2 quantile of the standard normal distribution and α is the significance level of the test. When the test statistics of the $|U_c|$ is greater than $U_{(1-\alpha/2)}$, the hypothesis of equal means can be rejected.

3.6.2 Statistical Analysis

The Mann-Whitney test was conducted with the same rainfall and drought statistics used in the previous tests in order to determine the presence of shifts (jumps) of the mean series. The methodology was applied on the monthly rainfall series and on the individual drought statistics separately i.e. the maximum number of consecutive non-rainy days and the total number of non-rainy days in a month, and the estimated test statistics are presented in Table 3.1(a) through Table 3.1(c). The significance level (α) considered here is 0.05.

Table 3.1(a) Mann-Whitney Test Statistics for Monthly Rainfall Data ($U_{(1-\alpha/2)}$ = 1.96)

Month / Station	Jan Jul	Feb Aug	Mar Sep	Apr Oct	May Nov	Jun Dec
Peradeniya	0.52	1.23	0.10	1.11	1.28	1.03
	0.40	1.19	0.61	0.52	0.82	**2.36**
Kirimetiya	1.15	1.44	0.48	1.86	0.77	1.49
	1.11	0.98	0.44	0.77	0.40	**2.57**
Nawalapitiya	0.98	0.61	0.52	1.65	0.02	0.23
	0.10	0.57	0.86	0.94	0.57	1.74
Hatton	0.15	1.07	0.063	1.07	0.31	1.07
	0.57	0.90	0.02	0.94	0.65	1.65
Dunsinane	0.06	0.73	0.44	1.70	1.32	1.16
	1.49	0.36	0.15	0.23	1.61	1.95
Hakgala	0.48	1.53	1.44	1.62	1.90	1.90
	1.07	1.65	1.07	0.10	0.48	**2.70**
Woodside	0.94	136	0.19	1.28	1.15	0.57
	0.77	1.16	0.65	0.44	0.90	1.70
Liddesdale	1.19	1.95	0.10	1.03	0.65	0.65
	0.27	0.36	0.90	0.48	0.10	1.07
Dyraba	0.69	0.82	0.02	1.82	1.45	1.03
	0.06	1.19	0.98	0.77	0.10	**2.65**
Bandaraeliya	0.36	0.69	0.02	1.82	0.52	0.86
	0.02	1.57	0.44	0.19	0.69	1.90

Table 3.1(b) Mann-Whitney Test Statistics for Maximum Number of Consecutive Non-rainy Days in the Monthly Series ($U_{(1-\alpha/2)} = 1.96$)

Month / Station	Jan / Jul	Feb / Aug	Mar / Sep	Apr / Oct	May / Nov	Jun / Dec
Peradeniya	0.56	0.65	0.15	1.11	1.40	1.69
	0.48	1.86	0.10	0.94	0.10	1.36
Kirimetiya	1.78	0.86	0.61	1.65	0.36	0.10
	1.07	1.07	0.56	1.36	0.23	1.19
Nawalapitiya	0.36	0.27	1.69	2.74	1.15	0.40
	0.44	0.15	0.40	0.36	0.77	**2.07**
Hatton	1.32	0.61	0.02	0.65	1.19	1.53
	0.73	0.90	0.40	0.40	0.06	**2.03**
Dunsinane	1.57	0.90	0.73	1.24	1.57	1.44
	1.16	0.36	0.19	0.23	1.11	0.44
Hakgala	0.82	1.95	0.52	1.08	1.40	0.69
	1.61	1.61	0.48	0.06	0.36	0.40
Woodside	1.53	1.66	0.31	1.44	0.31	0.31
	0.73	1.03	1.20	0.86	0.86	**2.28**
Liddesdale	0.52	1.32	0.48	2.24	1.40	0.48
	1.03	1.44	0.19	0.65	1.03	0.65
Dyraba	0.61	1.15	0.15	1.15	**2.57**	0.77
	0.94	1.95	1.78	0.44	0.86	0.15
Bandaraeliya	1.23	0.69	0.52	1.16	0.10	1.53
	0.65	1.57	0.98	0.27	0.65	1.65

Table 3.1(c) Mann-Whitney Test Statistics for Total Number of Non-rainy Days in the Monthly Series ($U_{(1-\alpha/2)}$ = 1.96)

Month / Station	Jan / Jul	Feb / Aug	Mar / Sep	Apr / Oct	May / Nov	Jun / Dec
Peradeniya	0.27	0.77	1.36	1.82	1.57	0.94
	0.27	1.44	1.19	0.82	0.94	**2.53**
Kirimetiya	1.36	1.44	0.48	0.86	1.11	0.40
	1.03	0.94	0.48	0.69	0.27	1.74
Nawalapitiya	1.53	0.82	0.31	1.69	1.95	0.27
	0.82	0.69	0.02	0.65	0.15	0.56
Hatton	0.56	0.56	0.44	1.07	1.69	1.86
	0.90	0.27	0.02	0.10	1.11	1.78
Dunsinane	1.36	0.36	0.15	1.86	1.74	0.48
	2.03	0.69	0.44	0.36	0.82	0.77
Hakgala	2.28	1.99	1.69	2.41	1.99	1.36
	1.82	1.61	1.32	0.06	0.40	1.49
Woodside	1.74	1.49	1.19	1.74	0.19	0.31
	1.07	1.99	1.32	1.07	1.40	**3.41**
Liddesdale	1.53	0.82	0.31	1.69	1.95	0.27
	0.82	0.69	0.02	0.65	0.15	0.56
Dyraba	1.86	0.52	0.36	1.49	1.74	0.36
	1.49	1.40	0.52	0.36	0.52	0.86
Bandaraeliya	0.77	0.44	0.56	3.20	0.82	0.10
	1.15	1.90	0.69	0.65	0.10	**2.16**

3.6.3 Evaluation of Statistics

In general, the calculated statistics (U_c) are lower than the threshold value of normal distribution at the confidence level (α) of 0.05 confirming that there are no shifts (jumps) of the monthly series of the rainfall and drought statistics. However, in certain months, the test statistics exceed the threshold value of 1.96 of the normal distribution. This is common for most of the gauging stations in the month of December. Further analysis revealed that the mean monthly rainfall in December is, almost in all cases, lower in these stations after 1977 compared to the figures before 1977 (Table 3.2). This general deviation is experienced in gauging stations located both windward and leeward sides for monsoon thus suggesting relative dryness of the monsoon air masses after 1977. It can even be due to the highly variabale onset of the Northeast monsoon.

Table 3.2 Average Monthly Rainfall During Northeast Monsoon Before and After 1977 at Selected Rain Gauging Stations for Different Agro-ecological Zones.

Station	Jan (64-76)/ (77-93)	Feb (64-76)/ (77-93)	Dec (64-76)/ (77-93)
Bandaraeliya	116.14/ 107.12	108.04/ 85.73	310.35/ 187.60
Kirimetiya	215.21/ 98.69	98.08/ 57.31	233.49/ 175.00
Nawalapitiya	25.32/ 88.09	72.59/ 85.01	182.61/ 106.49
Hatton	31.56/ 41.03	48.13/ 40.26	113.14/ 90.21
Dunsinane	46.38/ 79.46	62.31/ 51.91	192.49/ 128.18
Hakgala	167.82/ 164.53	128.95/ 73.95	335.84/ 203.56
Woodside	188.86/ 164.31	178.47/ 65.81	409.09/ 297.76
Liddesdale	312.58/ 277.06	195.56/ 101.14	513.51/ 431.29
Peradeniya	45.66/ 69.66	68.05/ 87.96	198.72/ 122.76
Dyraba	117.11/ 130.20	74.25/ 59.29	252.42/ 196.05

However, in contrary, there was no evidence of exceeding the threshold value in the calculated statistics for shifts (jumps) in the months of January and February which also cover the Northeast monsoon. Accordingly, the possibility of general dryness in the monsoon is questionable for the high level of exceedance in the calculated statistics of December. The analysis was further extended to look into the relative distribution of rainfall within the monsoon period. The percentage of seasonal rainfall for individual months for the selected 10 stations is shown in Figure 3.3. The mean monthly rainfall during the Northwest monsoon and the monthly percentages of the seasonal rainfall are tabulated in Appendix B-4.

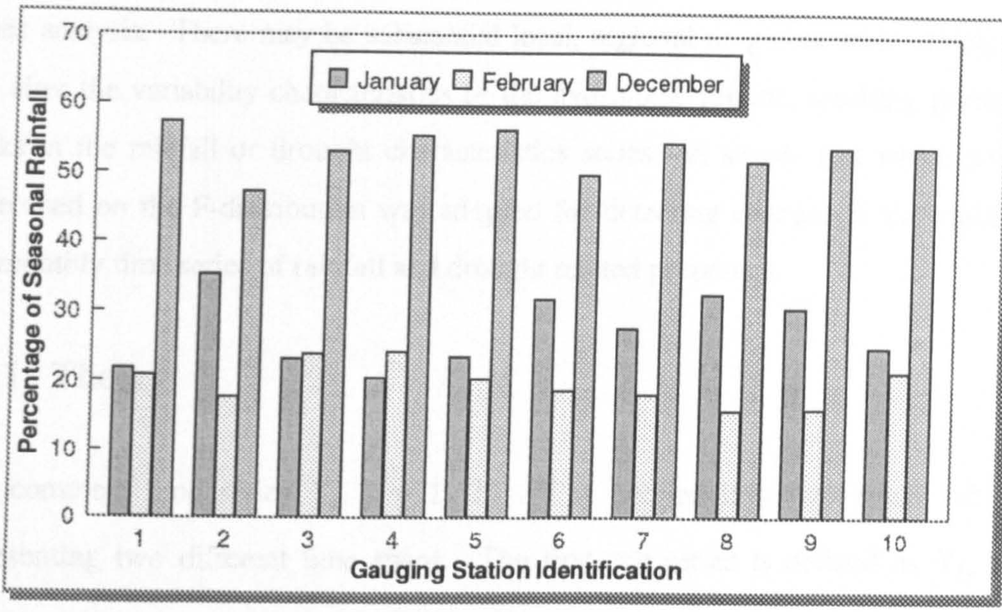


Figure 3.3 Percentage of Monthly Rainfall During Northeast Monsoon Season

Almost 50 percent of the seasonal rainfall was in the month of December in all the 10 gauging stations. The presence of occasional shift (jump) in the monthly time series of December can probably due to a upward trend of the variability of the data series rather than an actual shift (jump) of the mean series. The variability status of the rainfall distribution is investigated and discussed in the subsequent sections of this chapter.

The point of possible change in the time series was considered to be after the year 1977 in this analysis. This assumption was made due the reason that the most of the development activities were concentrated in this period. However, when the point of change is unknown, Bayesian analysis can be used to detect the exact point of change and its amount (Lee & Heghinian, 1977 as quoted by Salas & Ormijana, 1992). Another assumption made in this test was that the underlying time series were uncorrelated and unrelated. Intervention analysis (Lettenmaier, 1976) is an effective approach whenever it is required to deal with the serial correlation.

3.7 Assessment of Variability

Even when there is no actual trend or shift in the time series, a change in the variance can appear as a trend or shift due to the relatively short period of records used for time series analysis. There may be substantial local, regional or global scale effects which can alter the variability characteristics of the hydrologic regime, resulting pronounced peaks in the rainfall or drought characteristics series. A simple test which has been developed on the F-distribution was adopted for detecting changes in the variance of the monthly time series of rainfall and drought related properties.

3.7.1 Theory

The complete time series Y_t, t = 1, 2,.....N is divided into two equal sub series representing two different time spans. The first sub series is defined as Y_t, t = 1, 2,.....N_1 and assumed to be normally distributed with mean (μ_1) and variance (σ_1^2). The second sub series is defined as Y_t, t = N_1+1, N_1+2,.....N and also assumed to be normally distributed with mean (μ_2)and variance (σ_2^2).

The F-test is used to test the equality of the variance of the sub series under the following hypotheses .

$$(i) H_o: \sigma_1^2 = \sigma_2^2 \quad \text{vs} \quad H_a: \sigma_1^2 \neq \sigma_2^2$$

$$(ii) H_o: \sigma_1^2 = \sigma_2^2 \quad \text{vs} \quad H_a: \sigma_1^2 < \sigma_2^2$$

$$(iii) H_o: \sigma_1^2 = \sigma_2^2 \quad \text{vs} \quad H_a: \sigma_1^2 > \sigma_2^2$$

where H_0 and H_a are the null and alternate hypotheses.

The statistic for the F-test is defined as

$$F_c = \frac{\hat{\sigma}_1^2}{\hat{\sigma}_2^2} \qquad \text{(Eq. 3.9)}$$

The first hypothesis of equal variances cannot be rejected if

$$F_{(\sigma/2)(N_1 - 1, N - N_1 - 1)} \leq F_c \leq F_{(1 - \sigma/2)(N_1 - 1, N - N_1 - 1)} \qquad \text{(Eq. 3.10)}$$

The second hypothesis of equal variances cannot be rejected if

$$F_c \geq F_{(\sigma)(N_1 - 1, N - N_1 - 1)} \qquad \text{(Eq. 3.11)}$$

Finally, the third hypothesis of equal variance cannot be rejected if

$$F_c \leq F_{(1 - \sigma)(N_1 - 1, N - N_1 - 1)} \qquad \text{(Eq. 2.12)}$$

where $F_{(\sigma)(N_1, N_2)}$ is the α quantile of the F-distribution with N_1 and N_2 degrees of freedom (Salas & Ormijana, 1992).

3.7.2 Variability Statistics

The test for the comparison of variance was conducted with the rainfall and drought statistics of the same set of stations representing each Agro-ecological zone in order to determine the deviation from the historical range of variance. The two sub series were again made for periods before and after 1977. The calculated F-test statistics for rainfall and drought related properties are presented in Table 3.3(a) through Table 3.3(c).

Table 3.3(a) F-test Statistics of the Monthly Rainfall Series (0.385 & 2.42)*

Months / Station	Jan / Jul	Feb / Aug	Mar / Sep	Apr / Oct	May / Nov	Jun / Dec
Liddesdale	0.54	**2.71+**	0.63	0.99	1.76	0.43
	0.39	1.5	1.84	1.24	2.29	0.93
Dyraba	0.17-	0.76	0.23-	0.29	0.4	2.14
	0.66	**2.54+**	1.43	1.2	0.86	1.64
Peradeniya	0.27-	0.65	0.56	0.44	1.71	0.5
	0.66	0.64	1.68	0.91	0.22	0.79
Woodside	0.59	**4.76+**	0.65	1.42	**6.77+**	0.39
	0.74	**2.9+**	0.89	1.04	1.08	1.08
Hakgala	0.39	1.58	1.17	**3.86+**	0.71	0.23-
	0.44	2.04	**4.28+**	2.71	1.69	1.38
Bandaraeliya	0.68	1.33	0.48	1.67	1.18	0.15-
	1.13	**5.04+**	1.03	1.39	0.69	3.4
Hatton	0.44	0.54	0.7	**2.47+**	1.87	0.7
	1.97	1.46	1.04	0.94	**2.87+**	0.47
Nawalapitiya	**3.04+**	1.34	0.67	0.44	1.09	0.54
	1.36	0.48	1.53	1.02	1.11	0.56
Dunsinane	0.59	0.68	0.51	0.96	0.99	0.87
	0.73	1.44	1.95	0.36-	0.81	**2.52+**
Kirimetiya	**14.89+**	0.84	0.82	1.19	1.36	0.28-
	0.63	**2.49+**	**2.6+**	0.76	0.68	0.40

* Lower and upper values of F distribution

+ Cases which are significantly high

- Cases which are significantly low

Table 3.3(b) F-test Statistics of the Monthly Series of Maximum Number of Consecutive Non-rainy Days (0.385 & 2.42)*

Months / Station	Jan / Jul	Feb / Aug	Mar / Sep	Apr / Oct	May / Nov	Jun / Dec
Peradeniya	0.89	0.74	1.18	1.18	1.83	1.46
	0.53	0.88	1.1	0.8	0.42	0.41
Kirimetiya	0.85	1.01	0.68	0.56	1.97	1.03
	0.49	0.84	0.49	0.46	0.51	0.57
Nawalapitiya	0.7	0.86	0.47	0.18	0.73	1.55
	0.38-	0.83	0.97	1.31	0.76	0.4
Hatton	0.73	0.52	1.11	1.97	**3.48+**	**3.9+**
	0.52	1.19	0.58	0.66	0.57	0.45
Dunsinane	1.26	0.95	0.67	0.46	2.3	1.81
	0.73	1.64	1.37	1.15	0.9	0.44
Hakgala	0.75	0.69	0.98	0.47	1.73	0.48
	0.53	0.81	0.53	0.57	**2.75+**	0.94
Woodside	0.94	0.76	1.45	0.25	**4.43+**	1.22
	1.22	0.7	1.42	0.7	0.43	0.58
Liddesdale	0.99	0.55	0.47	0.1-	**2.46+**	1.03
	0.67	1.41	1.36	1.72	1.2	0.49
Dyraba	0.63	1.3	1.1	0.26	**2.63+**	2.35
	0.83	0.33-	0.74	1.19	0.4	**2.51+**
Bandaraeliya	0.45	0.58	0.42	0.61	0.63	0.85
	1.42	0.77	1.09	0.91	0.39	0.48

* Lower and upper values of F distribution

\+ Cases which are significantly high

\- Cases which are significantly low

Table 3.3(c) F-test Statistics of the Monthly Series of Total Number of Non-rainy Days (0.385 & 2.42)*

Months / Station	Jan / Jul	Feb / Aug	Mar / Sep	Apr / Oct	May / Nov	Jun / Dec
Peradeniya	0.87 1.74	1.01 1.06	0.4 1.2	0.46 1.03	1.39 0.79	0.58 0.42
Kirimetiya	0.77 0.94	1.06 0.98	1.14 0.82	0.77 0.91	0.88 0.49	0.38 0.66
Nawalapitiya	0.85 0.75	0.88 **2.42+**	1.25 1.36	0.47 1.29	1.35 2.27	0.66 0.36
Hatton	0.84 0.85	0.43 0.88	0.44 1.2	1.63 0.53	1.73 **2.49+**	1.65 0.5
Dunsinane	0.4 0.53	0.83 0.92	0.47 1.42	0.84 0.71	1.65 1.46	0.85 1.24
Hakgala	1.07 1.78	1.48 **2.98+**	1.12 2.01	1.41 1.07	1.11 1.97	0.55 0.67
Woodside	2.1 1.18	1.24 **5.85+**	**2.77+** **4.25+**	1.64 0.98	**3.69+** 1.26	0.79 0.51
Liddesdale	0.85 0.75	0.88 2.24	1.25 1.36	0.47 1.29	1.35 2.27	0.66 0.36-
Dyraba	1.06 0.79	1.26 1.65	0.43 1.14	0.59 0.89	0.46 0.97	1.73 1.27
Bandaraeliya	1.08 1.39	1.2 **2.93+**	0.33 0.75	1.52 0.69	1.16 0.49	0.59 1.28

* Lower and upper values of F distribution
+ Cases which are significantly high
- Cases which are significantly low

3.7.3 Evaluation of Variability

The results of the F-test on the variance exhibit an upward shift of the variance not only in the monthly rainfall series but also in the drought statistics confirming the presence of prolonged dry spells after 1977 period. Most of the test statistics which were found to be outside the defined F-range are on the high side and whenever it was not the case, deviation from the minimum threshold was marginal. However, further statistical analyses are required to assess the degree of enhanced variability.

In the case of monthly rainfall statistics, a shift in the variability while there was no significant trend or shift in the series indicates the occurrence of relatively a few extreme rainfall events. This can lead to generate catastrophic floods. This situation can be further aggravated by the land use changes occurred after 1977, making response time of the catchment lower in terms of rainfall-runoff transformation. The occurrence of extreme rainfall events is further confirmed by the statistics of the drought related properties. The concentration of rain into a few high yielding storm events can also create heavy lags in terms of the inter-storm duration or inter-arrival time. Fortunately, the construction of the cascading reservoir system under the Mahaweli Development programme could buffer and ameliorate the consequences of the catastrophic flood generation in the catchment. However, because of the increased variability of rainfall, an utmost caution should be placed on the use of the extreme values of the historical time series for design and management of water resources.

3.8 Concluding Remarks

3.8.1 Discussion

The results of the hydrological time series analysis provide useful information on the applicability and potential problems of the use of the historical hydrological data in UMCA.

Further, the identification of drought related properties is of great importance though the required detailed analysis extends beyond the scope of the present study. In addition to the direct use of the results in this study, the drought related characteristics in terms of the maximum number of consecutive non rainy days and the total number of non rainy days in a month are very useful indices to formulate cropping calendars avoiding prolonged dry spells during the early vegetative growth stages, thus minimising the irrigation requirements. Vegetatively Propagated Tea (VPT) which has a higher green leaf yield and soil and water conservation benefits because of the uniform and dense ground cover, is being introduced to tea plantations which are the .dominant mono-crop cover in the catchment. The VPT is highly susceptible to water stress specially in the early stages of establishment. Development of regional dryness index for each month using an extreme value distribution will enable the user to choose the best time intervals for replanting with a sufficiently flexibility for a particular return period

Most of the hydrological parameters and tests used for the time series analysis in the foregoing sections do not require the time series to be normally distributed. The estimations of skewness coefficient shows the nature of the deviations from the normality assumption. Further, logarithmic transformations or so-called Box-Cox transformations can be employed whenever it seems to be necessary. It is also noted that in UMCA, a gradual process of land use change takes place in addition to the instantaneous transformations made under the Mahaweli Development Programme. The time scale of the data used in this study is not sufficient to model these gradual processes. It also requires a comprehensive analysis of social and behavioural changes of the catchment population and the government policies which are associated with the land use transformations. Further, it is not possible to determine the exact point of change in the time series due to the development programme, if any. The analysis can be further strengthened by incorporating Bayesian analysis to detect the exact point of change and the magnitude of such change.

The time series analysis did not reveal the presence of any linear or non linear trend or shift (jump) of the hydrological and drought related statistics. However, it clearly shows that the variability of the hydrological behaviour has taken a considerable upward trend, thus making the catchment vulnerable to extreme hydrological events. If this trend continues, there will be serious repercussions on the stability and safety of the hydrological structures in the catchment. It can also affect the hydro-power generation because of the probable erroneous decisions taken, in terms of the reservoir releases. This was clearly evident during the extreme events occurred in 1994 and 1995. After the heavy monsoon downfalls in 1994, which was a high rainfall year with 45-50 year return period, more water was diverted to the dry zone leaving marginal levels at the hydro power reservoirs. The year 1995 was relatively dry and the low rainfall amount was more or less evenly distributed throughout the year making heavy losses and thus reducing river flow to the hydro-power reservoirs drastically. This led the country to the worst hydro power crisis ever in the history. The domestic power-cut was extended to 10 hours making most of the small scale industries wiped out from the economy leaving thousands of people unemployed. The completion of the field data collection work of this study was also delayed considerably due to the imposed island-wide power cut. In order to avoid this sort of future catastrophe, careful planning is needed to launch mitigation measures, in view of the increased variability of the hydrological behaviour in the UMCA.

3.8.2 Conclusions

1. There is no linear or non-linear trend, shift (jumps) in the monthly rainfall time series or drought statistics during the period from 1964 to 1993. Hence, the presence of a major change in the UMCA hydrological regime can be ruled out.

2. The variability of rainfall has increased considerably in several occasions during the period after implementing the Mahaweli Development programme. However, the length of the hydrological data used for the analysis was not sufficient to determine the possible cause of this change.

3. The derived drought related properties can be presented in the form of regional indices to support the decision making process of agricultural operations in UMCA.

4. The information derived from the long term historical records requires further scrutiny for the safe use in water resources management decisions.

5. Further studies with longer period of hydrological records are required to monitor the hydrological variability in the catchment both for engineering and agricultural applications.

Chapter 4

4. HYDROLOGICAL PROCESSES AND PROCESS BASED MODELLING

4.1 Introduction - Hydrological Processes in General

There are complex environmental factors which independently or interactively determine the hydrological regime of an area (Falkenmark, 1989). A successful water resources development always needs to be accompanied by proper land use and water management strategies which largely depend on the general understanding of local hydrology, preferably at catchment scale.

Hydrological behaviour is commonly represented in the form of a continuous cycle conceptualised as the hydrological cycle, which is based on the interdependence and continuous movement of all forms of water (Abbolt et al, 1986). Irrespective of the scale of the catchment, the hydrological cycle systematically divides the water environment into a number of storage phases which are interconnected by water flows or fluxes. Thus, a systems approach is applied to the hydrological environment where a variety of theories, concepts, mathematical relationships and statistical techniques are seamlessly integrated to describe the general hydrological behaviour (Beven, 1989).

Hydrologists are mainly concerned with the runoff component of the water resource where the magnitude and the actual time of occurrence of stream flow are the key components. The other important hydrological processes of interest include precipitation, interception, evaporation and the storage of soil moisture (Arnold & Allen, 1995; Reynold & Thompson, 1988). The main focus of this chapter is to review hydrological processes in the context of UMCA. An attempt is also made to combine these basic processes into a model in order to represent the hydrological dynamics of the catchment using theoretical considerations of basic physical laws and mathematical approaches.

4.2 Precipitation including Cloud Deposition in UMCA

The importance of adequately defining the spatial and temporal distribution of precipitation for modelling stream flow and evaluating runoff response of a catchment has been well documented (Fischer et al., 1996; Wang & Chen, 1996; Watts & Calver, 1991; Bras et al., 1985; Beven & Hornberger, 1982). The importance of the precipitation distribution is critical for mountainous catchments where the weather systems interact with the topography resulting in highly non-uniform precipitation over the area (Loukas & Quick, 1996). Hence, it is necessary to study the precipitation process in UMCA in detail, in order to understand its distribution both in spatial and temporal scales and consequently to be able to predict the river flows with improved accuracy.

The precipitation in UMCA mainly comprises monsoon and inter-monsoon rainfall. In addition, orographic or advective fogs represent a significant unmeasured and potentially valuable moisture source in the uplands of Sri Lanka (Gunawardene, 1991). A detailed analysis of rainfall regime in UMCA is presented in Chapter 2.

In the catchments where cloud forests are considerable, underestimation of total catchment precipitation due to the occurrence and non-measurement of cloud moisture interception has been identified as a major limitation in modelling hydrology. This has been further highlighted by the increased efficiency of fog interception in dry seasons. Hence, deforestation of cloud forest may cause a substantial decrease in water yield both in rainy periods and in dry spells, and is considered to be of great hydrological importance in the tropics (Zadroga, 1981).

4.2.1 Measurement of Fog Interception

Loewe (1960) and Kerfoot (1968) have published extensive reviews of the literature pertaining to the collection, measurement and importance of fog drip. These reviews demonstrate the consensus in the research community with respect to the existence of fog drip as well as its ecological and hydrological importance.

The collection of fog is usually done either by outfitting a standard rain gauge with a screen or other devices to catch blowing fog or by placing a standard rain gauge under the canopy in foggy areas. Both methods have been successful in demonstrating the existence of fog drips by recording impressive amounts of water (Ingraham & Matthews, 1988).

4.2.2 Estimates of Fog Interception

Because of the inherent weaknesses in the measurement of fog interception and non-availability of standard measuring devices, attempts have been focused on the use of estimates of fog interception in accounting total water gain in catchments. In this respect, commonly, the amount of fog interception or horizontal precipitation is determined by the combined effects of climate and physiographic factors of the catchment. A reliable quantitative estimation of fog interception is difficult and not included in standard observations of meteorological measurements.

After a series of observations made over a four year period, Protopow (1975) concluded that fog condensation in total under the canopy varies from 10 mm over the warm periods to around 16 mm over the cold periods. Further, the fog interception in the Western Sajar mountains in USSR was found to be about 7-10% of total precipitation. Bruijnzeel (1986) as quoted by Gunawardene (1991) and Juvik & Ekern (1978) had concluded fog interception to be between 7-18% of average rainfall during rainy season and over 100% of the rainfall during the dry season.

A wide range of estimates made of fog interception suggest that any attempt at the approximation of fog should be based on the local observations made in different seasons over a period of several years.

4.2.3 Moisture Contribution of Cloud Forests in Sri Lanka

Despite the comments made by several researchers on the importance of cloud moisture interception in the central highlands of Sri Lanka, no successful attempt had been made locally to quantify the amounts and identify the priority areas until recently. In 1993, under the UP/OFI Link Project, fully automated fog collection gauges were installed and made operational. Although controversies exist as to how the gauge collections are related to the actual occurrence of fog interception in cloud forests, these data are of immense importance as a source of baseline information for deriving a realistic estimation procedure.

4.2.4 Fog Estimations in Hydrological Modelling

The relationships for fog estimations, derived by Gunawardene (1996), using a three year daily data set with other related climatic data inputs and physiographic identification, are the basis of fog estimation in the hydrological model used in this study and are as follows:

From May to September $Y = -43.6 + 0.0436\,X$ (Eq. 4.1)

October to April $Y = -11.8 + 0.0118\,X$ (Eq. 4.2)

where X is the elevation above mean sea level in m (applicable only to the stations located above 1000 m elevation) and

Y is the fog as a percentage of daily, monthly or seasonal rainfall in cloud forest areas.

These relationships were incorporated into the hydrological model with the elevation data from rain gauging locations to provide the gross estimation of additional moisture received by the catchment in addition to measured rainfall data series. It is understood that further improvements are required for a better representation of fog in the hydrological model by incorporating land use as a function to determine the interception efficiency for fog. Further, proper representation of elevation in the catchment through a digital elevation model would provide better estimations of fog interception based on the above formulae in the highly varying terrain in UMCA.

4.3 Interception

4.3.1 Interception Loss

Interception is defined as the process whereby precipitation is retained on the leaves, branches and stems of the vegetation and later evaporated back to the atmosphere or absorbed by the canopy. In the process of interception, undoubtedly, the most important factor is vegetation cover (Ward, 1974). Interception in the forest occurs at two levels within the cover, firstly at the canopy and secondly at the ground level (Reynold & Thompson, 1988). However, interception loss refers only to the water retained by the canopy and later evaporated away making an actual loss of precipitation received under the canopy. The development of the hydrological model required a rigorous method for estimating interception loss due to the predominantly high canopy density of the major land uses in UMCA.

4.3.2 Research Focus on Interception

Most of the research work on interception has dealt with temperate latitude vegetation (Calder, 1986b; Gash, 1979; Rutter et al., 1971). It is expected that the nature of tropical rainfall and tropical vegetation canopies, as in the UMCA, would result in different patterns of interception from those in temperate areas (Jackson, 1975). Interception is a complex process, with a variety of canopy parameters involved and a high degree of variability, so attempts to derive meaningful, universal predictive relationships have often been unsatisfactory (Gash, 1979).

Further, most of the previous studies have attempted to express interception in the form of regression equations (Gash, 1979; Blake, 1975, Zinke, 1967). In contrast, Rutter et al. (1971) have presented a physically based computer model for the estimation of interception. However, in practice, estimation with the model is greatly constrained due to its requirement for hourly meteorological data as input and the use of a complex computer programme. Alternatively, a stochastic approach for estimation of interception has been proposed by Calder (1996) and Calder (1986b) with a few critical parameters based on Poisson distribution. This model has been extensively tested in the tropical rain-forests in West Java, Indonesia (Calder et al., 1986) and the performance has further been verified with a small set of data collected at a low altitude Kandyan Forest Garden site, in patna grassland and in indigenous cloud forest in UMCA (Calder et al., 1996; Hall et al., 1995).

4.3.3 Estimation of Interception in the Hydrological Model

Estimation of interception in the hydrological model is based on the exponential formulation given by Calder (1986b) using the mean number of raindrops retained per surface element in a stochastic model as follows:.

$$I_{(d)} = \gamma[1 - EXP(-q \times P / \gamma)] \qquad \text{(Eq. 4.3)}$$

where $I_{(d)}$ = storage depth,

γ = maximum storage depth,

q = mean number of rain drops retained per surface element and

P = cumulative depth of precipitation for a day.

Extensive research trials and verifications have yielded the numerical approximations for the γ and q parameters for different land uses as given in Table 4.1.

Table 4.1 Interception Parameters for the Stochastic Interception Model
(Source : Land Use Model, Sri Lanka; Calder et al., 1996)

Land use	q	γ (mm)
Grass	0	0
Indigenous Forest	0.684	6.91
Pine (Plantation Forest)	0.684	6.91
Tea	0.954	2.65

The main hydrological impact of interception is that it reduces the precipitation reaching the ground by the amount of water which is evaporated from the wetted parts of vegetation surfaces during and after the process of precipitation. The proportion of the precipitation lost varies according to the nature of vegetation, specifically its interception storage capacity, the precipitation regime and the potential evaporation (Arnold & Allen, 1995).

4.4 Evapotranspiration

4.4.1 Process of Evapotranspiration

Evaporation is the process of movement of water in vapour from a water surface into the overlying air using the energy from solar radiation, heat advected by warm wind, or stored in land masses including water. In the context of hydrological modelling, evapotranspiration includes evaporation from land and water surfaces and transpiration from vegetation.

4.4.2 Evapotranspiration Losses in UMCA

Radiation, temperature, relative humidity and wind velocity are the key climatological factors which govern the process of evaporation (Monteith, 1965 as quoted by Calder, 1994; Ritchie, 1972). In UMCA, these factors are relatively spatially uniform but vary considerably within a year. Therefore, estimates of evapotranspiration losses should be focused on the monthly or seasonal variations. Hence, pan evaporation data was collected to identify the monthly distribution of potential evapotranspiration in the catchment (Table 4.2).

Table 4.2 Distribution of Mean Monthly Pan Evaporation* Within a Year

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
B'darawela	72	88	105	88	94	116	110	114	98	82	63	56	1086
Sitaeliya	87	114	134	131	130	107	97	100	90	91	77	80	1238
Kande-ela	103	115	130	91	101	105	99	96	98	90	84	82	1194
Talawakele	96	115	126	104	90	57	56	65	67	69	70	78	993
Giragama	109	133	152	102	95	84	76	95	80	88	62	79	1155
Kundasale	105	126	149	125	128	112	106	113	114	105	75	87	1345
Peradeniya	131	148	155	127	129	99	102	103	107	102	93	112	1408

* measurements in mm.

According to the recommendations of the UP/OFI Link Project, an annual open water evaporation value of 1408 mm (Land Use Model - Sri Lanka, 1994) was used for the entire catchment. Monthly evaporation values shown in Table 4.2 were used to calculate the evaporation in each month as a percentage of mean annual evaporation of each station. Subsequently, the annual value of 1408 mm was divided to individual months for each stations based on the calculated monthly percentage values. The conversion factor for potential evaporation from open water evaporation was considered to be 0.7 for the UMCA (Land Use Model - Sri Lanka, 1994).

4.4.3 Estimation of Evapotranspiration in the Hydrological Model

The estimation of evapotranspiration in the hydrological model was based on a slightly modified version of the Annual Forest, Heather, and Grass model proposed by Calder (1994) to account for soil water limiting conditions.

For all the land uses except grass: $E_{(d)} = F_{(d)} \times \beta \times E_T \times (1-w)$ (Eq. 4.4)

For grass : $E_{(d)} = F_{(d)} \times \beta \times E_T$ (Eq. 4.5)

where $E_{(d)}$ = daily evapotranspiration in mm,

$F_{(d)}$ = dimensionless soil moisture stress moderator,

β = transpiration parameter which depends on land use (Table 4.3) and

E_T = daily Penman evaporation in mm.

The fraction of the day the canopy is dry and is able to transpire is described by (1 - w).

$$w = \frac{I_{(d)}}{\gamma}$$ (Eq. 4.6)

From Equation 4.3 $I_{(d)} = \gamma\left(1 - EXP(-q \times P / \gamma)\right)$

$$\delta = \frac{-q}{\gamma}$$ (Eq. 4.7)

where δ = mean number of rain drops retained per surface element per unit maximum storage depth.

Hence $I_{(d)} = \gamma\left(1 - EXP(-\delta \times P)\right)$

$$w = (1 - EXP(-\delta \times P))$$

$$(1 - w) = \left(EXP(-\delta \times P)\right) \qquad \text{(Eq. 4.8)}$$

Table 4.3 Parameters Required for Estimation of Evapotranspiration

Land use	β*	δ+	AW#
Grass	1	0	150
Indigenous Forest	0.85	0.099	380
Pine (Plantation Forest)	0. 9	0.099	380
Tea	1	0.36	300

* transpiration parameters in mm^{-1},

+ interception parameters in mm^{-1},

available water in mm.

4.5 Soil Moisture

Soil moisture is commonly regarded as comprising all the moisture in the zone of aeration which includes both unsaturated soil and soil layers above the water table which are in the zone of saturation (Sharma & Luxmoore, 1979).

4.5.1 Effects of Moisture deficit on Evapotranspiration

Soil water limitations have a profound effect on transpiration rates of crops (Ritchie, 1972). These effects have been taken into account using a moderator function or 'root constant' where the actual evaporation is equal to the product of the moderator and the potential value. Various soil moisture moderator functions have been proposed, the simplest of which assumes that the moderator is equal to the ratio of the water content to the available water capacity of the soil profile (Calder, 1994). The complex functions assume the profile is composed of different layers with different available water capacity values and different moderator functions. The layer models have the advantage that following rainfall into a previously dry soil, the model allows for evaporation at the potential rate if the surface layer is wet even though the total soil profile remains at a high deficit (Calder, 1994).

4.5.2 Accounting for Soil Moisture in the Hydrological Model

In the hydrological model, soil moisture is defined using two parameters. Available Water (AW) is introduced as the total water available as a function of land use. Soil Moisture (SM) in a particular day is defined as the result of a net water balance where soil moisture content of the previous day is balanced out against the inputs and outputs of water in that particular day (Fischer et al., 1996; Robert & Harding, 1995; Calder et al., 1983).

The soil moisture stress moderator is defined in the hydrological model as a ratio of soil moisture and available water.

$$F_{(d)} = \frac{SM_{(d)}}{AW} \times 2 \qquad \text{(Eq. 4.9)}$$

where $F_{(d)}$ = soil moisture stress moderator,

$SM_{(d)}$ = soil moisture in a particular day (initially set to AW) in mm and

AW = available water in soil defined as a function of land use (Table 4.3) in mm.

Whenever the soil moisture stress moderator becomes greater than unity, the $F_{(d)}$ is threshold to be equal to unity. Soil moisture stress moderator is assumed to be directly controlling the evaporation loss when soil moisture depletes below a certain threshold level. In the Equation 4.9, multiplication by factor 2 makes soil moisture stress moderator to be effective only when the soil moisture depletes below 50 percent of the available water in each land use.

4.6 Water Yield and Characteristics

Water yield is defined as the discharge of a stream or a river at a particular cross section as calculated over a specified period of time; a day, a month, a season, a year or over a number of such intervals (Reynolds & Thompson, 1988). The design, construction and operation of many hydraulic and hydrologic projects require an adequate knowledge of the variations of catchment water yield. For most of these issues, it would be ideal to know the exact magnitude and the actual time of occurrence of streamflow events (Pattison, 1976 as quoted by Pattison & McMahon, 1993).

4.6.1 Management of Water Yield

Management of the water yield of a catchment is an integral part of sustainable watershed management where the focus is to protect the water resources environment from catchment degradation and erosion. In this process, the main streamflow characteristics requiring intensive management are the water yield of the catchment, flood flow, water quality, erosion and sediment yield. Hydrological response in terms of water yield for a particular rainfall event is primarily based on the land use of the catchment and hence, an effective land utilisation strategy is a prime need in the management of water yield. However, there is a lack of quantitative and conclusive evidence from the hydrological research for the estimation of water yield or response to management decisions (Burton, 1969 as quoted by Fahey & Watson, 1991; Haimes, et al., 1979), largely due to the complex and stochastic nature of the runoff processes.

4.6.2 Estimation of Water Yield in the Hydrological Model

Despite the fact that streamflow is generated by a combination of base-flow, inter-flow and saturated overland flow, the hydrological model accommodates only the total flow to be expected from each land use category by means of a basic water balance function. The individual flow components were not considered separately because the total output flow at any given point was the important element to be estimated by the model.

$$Runoff = P - I_{(d)} - E_{(d)} \pm \Delta S \qquad \text{(Eq. 4.10)}$$

where P = daily precipitation including fog interception in mm,

$I_{(d)}$ = interception loss in mm,

$E_{(d)}$ = evapotranspiration in mm and

ΔS = change in soil moisture regime in a day in mm.

4.7 Modelling Hydrological Processes: An Introduction

In hydrological modelling, the main theme is to determine the deposition of rainfall; how much of it becomes runoff, infiltration, ground water recharge, evaporation and water storage. Each process can be represented in a sub model and factors influencing the performance of each sub model can be identified separately. In this exercise, each process is considered to be three dimensional i.e. spatial, time and data dimensions. Modelling efforts are generally hampered by limitations in the representation of these three dimensions in a model.

In most of the available models, only two dimensions are represented and a process of spatially or temporally averaging the data is commonly employed in order to account for the third dimension. It is most common to treat watersheds as lumped systems by spatially averaging the properties and no attempt is usually made to describe the topology of the watershed and its stream network. In this respect, the popular surface and subsurface hydrological models are summarised in Table 4.4.

Table 4.4 A Summary of Commonly Used Models for Hydrological Modelling (Adopted from Maidment, 1993).

Surface Water Hydrology Models

(1) Single-event rainfall runoff models

HEC-1 - US Army Corps of Engineers, Davis, California.

TR-20 - Soil Conservation Service, USDA, Washington DC.

Illudas - Illinois State Water Survey, Virginia

(2) Continuous Streamflow Simulation

SWRRB - Agricultural Research Service, USDA, Texas.

PRMS - US Geological Survey, Virginia.

SHE - Institute of Hydrology, Wallingford, UK.

(3) Flood Hydraulics

HEC-2 - US Army Corps of Engineers, Davis, California.

WSPRO - US Department of Transportation, Washington DC.

DMBRK - US National Weather Service, Silver Spring, Maryland.

DWOPER - US National Weather Service, Silver Spring, Maryland.

(4) Water Quality

SWMM - University of Florida Water Resources Centre, Florida.

HSPF - USEPA Environmental Research Laboratory, Georgia.

Qual2 - USEPA Environmental Research Laboratory, Georgia.

WASP - USEPA Environmental Research Laboratory, Georgia.

Subsurface Water Hydrology Models

(1) Groundwater Flow

PLASM - International Groundwater Modelling Centre, Colorado.

MODFLOW - US Geological Survey, Virginia.

AQUIFEM-1 - Geocomp Corporation.

(2) Groundwater Contaminant Transport

AT123D - IGWMC, Golden, Colorado.

BIOID - Geotrans Inc., Virginia.

RNDWALK - IGWMC, Golden, Colorado.

USGS MOC - US Geological Survey, Virginia.

MT3D - S.S. Papadopulis and Associates Inc.

MODPATH - US Geological Survey, Virginia.

(3) Variably Saturated Flow and Transport

VS2D - US Geological Survey, Virginia.

SUTRA - US Geological Survey, Virginia.

4.7.1 Overview of Hydrological Modelling

A hydrological model could be defined as a grouping of mathematically derived functional relationships to represent water flow and its constituents from the atmosphere through the land surface and in the subsurface environment. All of the water of the earth can be classified into three basic types: atmospheric water, surface water and subsurface water. Atmospheric water includes water vapour in the atmosphere and also water and ice droplets carried by clouds or falling as precipitation. Surface water is the water flowing on the land surface or stored in pools, lakes and reservoirs. Subsurface water is retained within the soil and the rock matrix beneath the land surface (Maidment, 1993). Hydrological models represent these different phases of water in varying proportions in accordance with the objectives of the formulations.

Recent advances in computer processing, speed and the general availability of personal computers have led to a great success in the efforts of hydrological simulations. However, the accuracy of the computer simulation results depends on the availability and reliability of the data input into the models.

4.7.2 Approaches in Mathematical Modelling in Hydrology

Three general approaches for hydrological modelling have been suggested by Kirkby (1978). (i) Stochastic models relate the inputs used and the outputs generated. In these models, the magnitude of the hydrological variables is determined by probabilistic theories and assumed to be following a probabilistic distribution. (ii) Parametric models rely on physical parameter definitions involved in hydrological events and use the analytical and developed relationships to generate hydrological outputs based on historical hydrological records. This approach defines relationships by using rational and empirical parametric expressions and is suited to complex systems such as most natural systems where the relationships cannot be explicitly expressed (Committee on

Surface Water Hydrology, 1965). (iii) Deterministic models have a theoretical structure based on the laws of conservation of mass, energy and momentum. The deterministic element is brought about by the fact that when initial boundary conditions and inputs are specified, the output is known with a degree of certainty (Woolhiser, 1971).

In addition to these three types of models, empirical solutions for hydrological problems exist. This type of approach is based on observations or experiments and not derived from theory (Hudson, 1995). A taxonomy of hydrological models (Figure 4.1) presented by Chow et al. (1988) summarises the assumptions made in terms of space, time and randomness of hydrological systems.

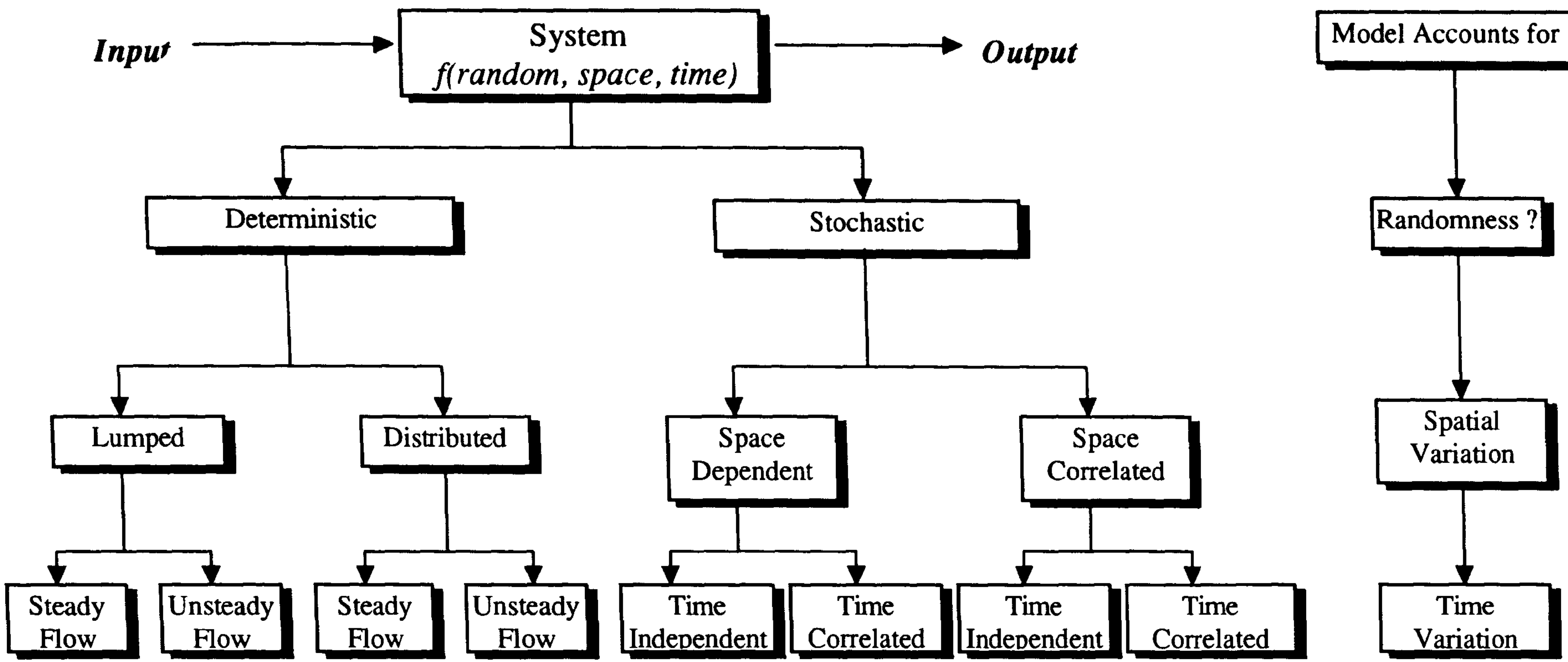


Figure 4.1 A Taxonomy of Hydrological Models

(Source: Chow et al., 1988)

4.7.3 Research Trends in Hydrological Modelling

There has been a great emphasis on physically based distributed models due to the rationale that models treating the catchment as being spatially variable are better and therefore have the theoretical advantage of being suitable for a wider range of conditions (Ward & Robinson, 1990). However, such models demand data from a variety of sources and specialised computational requirements including software and hardware. Further, it has not been possible to find developed hydrological models simultaneously using spatial distribution parameters with seamless integration of temporal distribution.

4.8 Formulation of UMCA Hydrological Model

The UMCA hydrological model is a simplified version of a set of water balance equations to calculate runoff response from the catchment. It calculates daily runoff depending on the daily precipitation while taking water losses and soil moisture fluctuations into account. The basic structure for the hydrological model was adopted from Land and Water Use Model, Sri Lanka (1993) compiled by the Institute of Hydrology, Wallingford, UK. The generic model structure is shown in Figure 4.2.

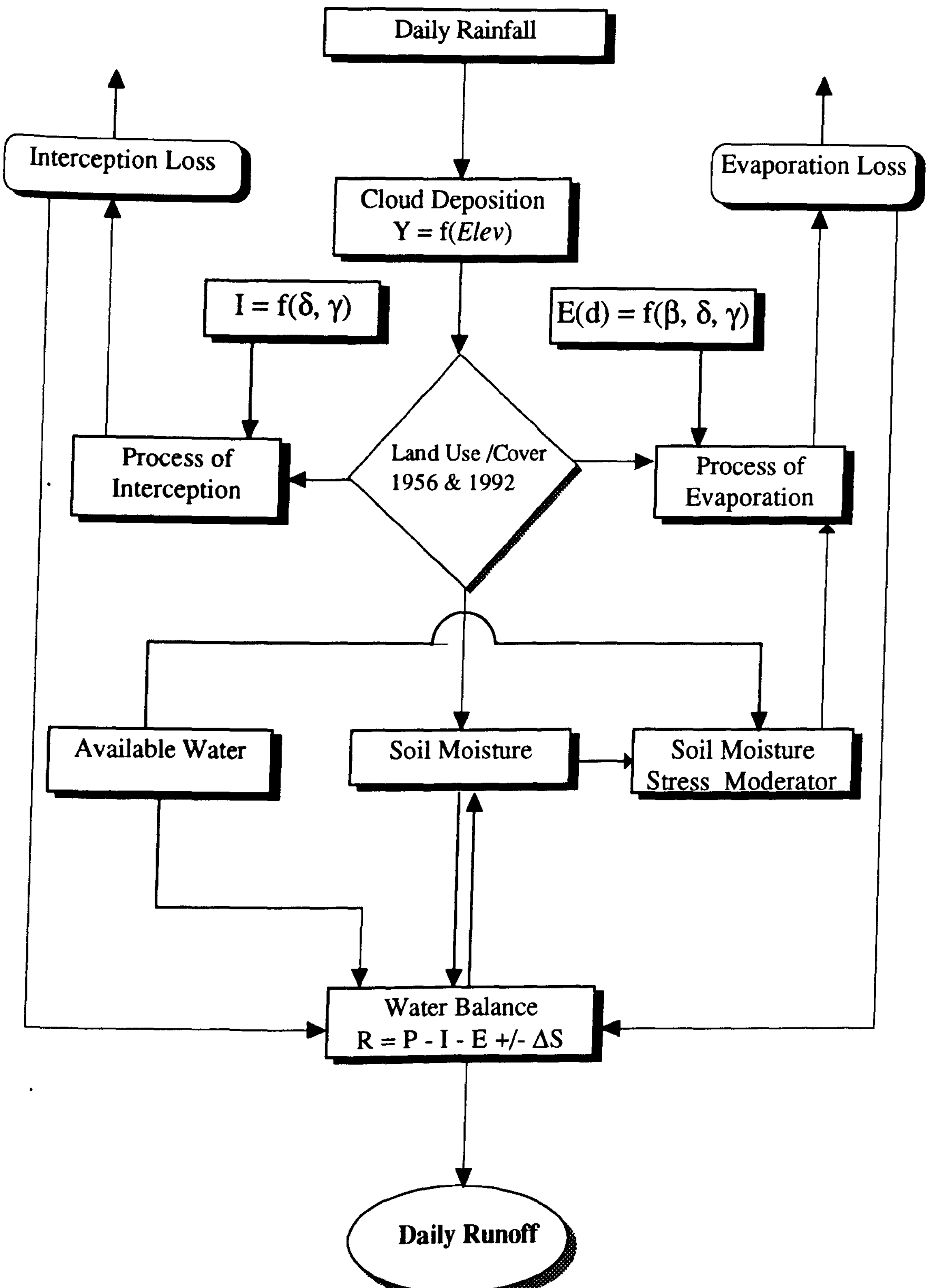


Figure 4.2 Generic Structure of the Hydrological Model

4.8.1 Model Structure

The model includes the basic processes detailed in the foregoing sections of this chapter. The total precipitation includes rainfall and fog interception in natural forests and forest plantations where elevation is 1000 m above mean sea level. The interception is estimated by the exponential stochastic interception model. The evapotranspiration is approximated by the evapotranspiration model using the soil moisture and the moisture stress moderator. Finally, a water balance is simulated for each day and depending on the available water status, runoff predictions are made for each day.

The lumped model structure was developed in Turbo C++ with a view to extend the lumped formulations for a spatially distributed phenomenon in GIS. The developed Turbo C++ programme is listed in Appendix C.

4.8.2 Assumptions and Limitations of Model Structure

Hydrological model predictions were made based on several assumptions and approximations. Further, certain limitations were inherent in the process of avoiding complex relationships that exist in nature.

The model assumes that the spatial variation in available water, soil moisture, interception and evaporation is solely determined by the existing land use. This assumption is supported by the fact that two major soil groups found in the catchment, reddish brown latosols and red yellow podzolic soils, are mostly similar in structure and texture (Premalal, 1990) with the exception of immature brown loams which cover only a limited area of the catchment.

In addition to the rainfall, a contribution from fog was assumed to be an input depending on the elevation as per the relationship given in section 4.2.4.

The losses were assumed to be only in the form of interception and evapotranspiration which were derived by using relevant parameters related to the land use. The other forms of water losses including channel storage, surface storage, and ground water storage were not included in the model structure. Further, there is no routing component associated with the model and within UMCA, sub catchments were identified to avoid lag differences extending more than a day. Winter (1981) discussed various types of errors associated with the measurement and computation of the various components of the water balance.

The model identifies only 4 different land use types for its parameter definitions. All the land use or cover types of the catchment were assumed to be in one of these four categories. When the soil profile retains water between maximum capacity and 50 percent depletion level, evapotranspiration was assumed to be at its potential rate. The actual evapotranspiration was considered to be a linearly decreasing function with the soil moisture depletion beyond 50 percent.

4.8.3 Modelling Results of Turbo C++ Programme

Several trial runs were carried out to verify proper functionality of the model before attempting spatial distribution in GIS. However, being a lumped model, it was not possible to compare the modelling results with actual observations which are spatially distributed products at sub catchment scale. Comparison of modelling results was only possible by treating the entire sub catchment as a lumped system and spatially averaging the hydrological processes. Spatial averaging which is called zero dimensional representation of spatial features (Maidment, 1993) was not attempted as the model was expected to run on a spatially distributed platform within GIS.

4.9 Riverflow Data for UMCA

Riverflow is the last land phase of the hydrological cycle which transfers water falling as rain or fog onto a catchment to the oceans. Riverflow rate at the catchment outlet integrates all the hydrological processes and storage occurring upstream (Mosley & Mckerchar, 1993). Flow rate depends on the spatial and temporal distribution of rainfall, soil conditions, vegetation type plus canopy conditions, topography of the terrain and also on the agriculture and other human activities in the catchment.

4.9.1 Need and Importance of Riverflow Data

Most hydrological modelling is directed at solving problems in pollution control and mitigation, water utilisation or flood control and mitigation (Maidment, 1993). However, accurate prediction or derivation of riverflow regime is commonly considered to be the ultimate aim of most of the hydrological modelling exercises (Shaw, 1988). Riverflow data are important in the management, utilisation and conservation of upstream catchment resources as well as the design, construction and maintenance of hydraulic structures in the downstream (Haimes, et al., 1979; Ward, 1974). Hydrological models developed for the simulation of riverflow of a catchment could also be used to derive hydrographs for similar ungauged catchments elsewhere (Ibrahim & Cordery, 1995).

Development and calibration of hydrological models generally require actual flow data measured in the form of continuous time series records. Flow measurement can be carried out using staff gauges and crest gauges to obtain instantaneous flow measurements or using automatic water level recording equipment to analyse the changes of the flow regime comprehensively even within a day. Accuracy and proper representation of the riverflow measurements are largely responsible for the accurate calibration of the hydrological models and the reliability of flow records generated by these models.

4.9.2 Data Availability and Quality

The gauging stations and flow records of the Mahaweli river was under the management of the Department of Irrigation and Land Use since the Mahaweli water was mainly used for irrigation in the downstream areas. However, after the Mahaweli Development Programme was launched the Mahaweli Development Authority and the Electricity Board of Sri Lanka are jointly responsible for the collection and processing of riverflow data.

Historical daily data of the Mahaweli riverflow is available only in the Department of Irrigation and Land Use and it needs high level authority to obtain access to this data.

Further, the quality of the data is questionable. However, the terms and conditions for the release of flow data from the Mahaweli Development Authority are more relaxed and most of the flow data are either in the public domain as printed publications or in the Mahaweli Authority data archives and can be retrieved free of charge with permission for academic and research uses.

The monthly riverflow data required to calibrate the hydrological model was collected for nine stations in UMCA. The gauging stations of the flow data and the length of available records are listed in Table 4.5.

Table 4.5 Available Flow Data Records for UMCA

Flow Gauging Station	Period of Data Available
Welimada	1964 - 1977
Victoria	1964 - 1977
Watawala	1964 - 1976
Talawakele	1964 - 1986*
Rantembe	1979 - 1986
Randenigala	1964 - 1983*
Morape	1964 - 1981
Gampola	1975 - 1978
Peradeniya	1964 - 1993*

* Includes derived data from other measurements

There are different methods used to measure riverflow at different gauging stations. Some methods directly measure flow rates while some others measure flow depths at regulated time intervals. Hence, all the data has been subjected to intensive processing and are finally in the form of either mean monthly flow rate or mean daily flow rate. Further, the reliability of the data is always a question as in some instances, the yielding flow heights from the flow rates are found to be higher than the equivalent rainfall depth for the same period.

4.10 Land Use Changes and Catchment Response

The effects of land use changes on the hydrological cycle in general and on the catchment response in terms of water yield or stream flow in particular, has been studied for a long time, yet many contradictory views still exist (Fahey & Watson, 1991; Haigh et al., 1990; Nik, 1988; Calder, 1986a; Sopper & Lull, 1967). The amount of research in this field has increased particularly since 1960s due to intensification of human activities causing land use changes in catchments.

Colman (1953) argued, however, that water yield should not be considered in terms of the total amount of runoff but should include rate of flow and its temporal variations as well as water quality, incorporating sediment yield. Although it is generally accepted that proper management of the catchment requires comprehensive studies on all the aspects of catchment response, the scope of this study is restricted to consider only the amount of stream flow variations due to changes in catchment land use.

4.10.1 Methods of Detecting Effects on Water Yield

According to Oyebande (1988), calibration of a catchment against a control, treatment of the catchment and analysis of the resulting data are the fundamentals of catchment studies in order to detect the effect of land use conversions on streamflow characteristics. However, long observation periods are necessary to identify the fluctuations of the flow regime which are temporary due to land use changes and revert back to the pre-conversion characteristics (Nik, 1988).

In addition to the on-site field experiments, catchment response models have been extensively used to simulate catchment response for a variety of land use change scenarios. These catchment response models have varying capabilities, varying degrees of reliability and varying levels of comprehension (Jolley & Wheater, 1996; Roberts & Harding, 1996; Calder, 1994; Pattison & McMahon, 1976).

4.10.2 Effects of Forests on Water Yield - Positive Aspects

Forest smoothes out the concentrated inputs from intense rainfall and releases a more regulated flow to stream (Pereira, 1989) thus avoiding flash floods in the rainy season and the drying out of streams in the dry season.

In addition, forests can positively contribute by interception of cloud moisture specially when located at high elevations or in coastal fog belts. This is particularly useful in the dry seasons because of the continuous ground water recharge, which results in perennial streams which otherwise would become ephemeral due to a decline in the water table and consequent reduction in base flow.

4.10.3 Effects of Forest on Water Yield - Negative Aspects

In spite of all the benefits from forests on water yield plus the issue of environmental conservation and sustainability, forests can negatively affect the water yield due to overall high transpiration losses. In dry climates, because of the widespread root system compared with the other vegetation, forests are able to access water in deep layers of soil (Gunawardene, 1991). In wet climates, when surface of vegetation remains wet for long periods, forests tend to evaporate intercepted water at a higher rate than shorter crops because of the rough leaf surface which assists the aerodynamic transport (Calder, 1994). Actual evapotranspiration losses from tropical forests continue throughout the year at near potential rates (Reynold & Thompson, 1988).

4.10.4 Land Use Changes and Water Yield

The influence of vegetation or land use changes upon the water yield has been an important theme for the research on catchment behaviour during the last two decades (Bren & Papworth, 1993; Shimizu et al., 1992; Abdul Rahim & Harding, 1987; Burch et al., 1987; Calder, 1986a).

Almost all the research findings confirm that forest cover transformations have yielded increases in water yield. Hibbert (1967) summarised 39 studies of clearing forests where he showed that the upper limit of water yield increase is 4.5 mm/ year for each percentage of reduction in forest cover. Further, it has also been shown that afforestation has effectively reduced the streamflow (Fahey & Watson, 1991). A summary of research on forest cover conversions and subsequent stream flow measurements is given in Table 4.6.

Table 4.6 Forest Cover Transformations in the Humid Tropics and Changes in Water Yield (Source Nik, 1988; Bruijnzeel, 1986)

Location	Type of Transformation	Catchment (ha)	MAR	Elev. (msl)	Change in water (mm year^{-1}) 1year	2year	3year	4 year	5 year	Reference
Babinda, Queensland	Lowland rainforest to grass(35%) & scrub (35%)	18.3	4035	1-200	+264 (7.0%)	+323[a] (13.4)				Gilmour 1977b
Lien-Hua-Chi, Taiwan	Clearcutting of mixed evergreen hill forest; regeneration	5.9	2100	725-785	+448 (58%)	+204[b] (51%)				Hsia & Koh, 1979
Mbeya, Tanzania	Evergreen montane forest (1/3 grass and shrub) vs. agric land use (50% annual crop & 50% grazing land)	16 vs 20	1900	2500					+408	Edwards, 1979
Java, Indonesia	Slightly disturbed rain forest vs 20y old plantation of *agathis dammara*	19	3000	70 vs 560					+175[c]	Murdiyarso, 1985 Bruijnzeel, 1983[a]
Sg. Tekam (A) Malaysia	Dipterocarp forest to cocoa	37.7 vs 56.3	1878	72.5	110 (117%)	706 (157%)	353 (94%)	263 (158%)		Nik, 1984
Sg. Tekam (B) Malaysia	Dipterocarp Forest to oil palm 60% and cocoa 40%	96.9 vs 56.3	1878	68.5	+145 (85%)	+155 (142%)	137 (97%)	822 (470%)		Nik, 1984

[a] wet year [b] dry year [c] computed via difference in ratio's between forest ET and Penman E_o

4.11 Discussion and Conclusions

4.11.1 Sustainability of Catchment Resources Vs Water Yield - A Controversy

With the initiation of the Accelerated Mahaweli Development Programme, the land use of the UMCA has changed drastically within a short period of time. Expansion of subsistence level home-garden agriculture, diversification of agriculture, urban growth and settlements have also contributed to gradual land use changes over the period of time. In the tea plantation sector, a considerable area under deep rooted seedling tea has been converted to vegetatively propagated tea during the last 2-3 decades with a 2-3 years transition period of land restoration and improvement with grass.

Because of the changes made on the land use of the upper catchment including large scale deforestation, soil erosion and other forms of land degradation have been clearly evident. Frequent small scale land slides are a potential hazard to human life and infrastructure. Reservoir siltation and eutrophication demand for a considerable national expenditure for restoration. Further, the critics say that the hydrological regime in the UMCA has been adversely affected by diminishing flows during the last two decades.

Dickinson (1980) as quoted by Gunawardene (1991) concluded that even complete deforestation of the tropical region is not likely to cause global climatic changes in excess of natural climatic fluctuations although there may be micro-climatic variations locally. The analysis of hydrological data in chapter 3 confirms that there is no significant climatic drift present in the hydrological data series. Nevertheless, because of the obvious impacts of land degradation, conservation of catchment resources has been a research priority during the last decade.

Accordingly, large scale afforestation programmes have been launched with native and exotic tree species to develop plantation forest for catchment conservation. Community and social forestry programmes are also underway for continuous supply of timber and other forest products while protecting the catchment environment. Provisions have been made in the legislation to declare forest reserves in the strategic locations, In short, although land use conversions are continuously taking place in the catchment, measures are being taken for the conservation of catchment resources and for minimising damage to the environment. However, the rate of deforestation is always higher than the intensity of afforestation and other remedial measures resulting in a cumulative net loss of forest over a period of time.

As far as the UMCA is concerned the water yield is a major concern in view of the massive investment on hydropower reservoir networks and also the success of downstream agriculture, especially in most parts of the dry zone of the country. Hence, it is necessary to focus attention on the land use conversions which influence the stream flow output. It is particularly clear that all the research findings to date confirm that forest cover transformations in the humid tropics have definitely increased the water yield. Accordingly, one would expect an increase in riverflow due to the continuous depletion of forest cover in UMCA. Since there is no major climatic drift towards a general dryness of monsoon air masses, the criticism of diminishing riverflow is totally contradictory.

In these circumstances, there is no doubt that catchment-wide reforestation or afforestation is an urgent need to mitigate environment hazards due to catchment degradation. Because of the high water use by forests and forest plantations, the maintenance of an adequate quantity of riverflow would become a problem. Hence, the priority of this research is to support the strategic planning of the forestry programmes by identifying the best locations for the new forest plantations so that cloud deposition from these forests would overcome the losses due to high water use by forests. The development of the hydrological model is expected to facilitate an improved understanding of catchment dynamics and to visualise the impacts of simulation scenarios for the planning and sustainable management of catchment resources.

4.11.2 Conclusions

1. Fog interception is an important process and a key factor determining the sustainability of the water yield of the UMCA. Although the available data and research emphasis have been satisfactory to initiate catchment modelling, a comprehensive collection of site specific data is required to represent realistic estimates for the entire UMCA. Fog interception measurements are required to be carried out in several sites covering at least major physiographic regions in the UMCA.

2. The interception and evaporation parameters used in the model have been derived elsewhere in similar situations. These model parameters need to be validated for the UMCA through a series of parallel experiments in the catchment.

3. The model relies heavily on parameters derived from land use information. Accordingly, the available water and water holding capacity of the soil were defined as a function of land use. Incorporation of the spatial distribution of soil types would make these parameters more meaningful.

4. The parameters used in the hydrological model are limited to four broad land use classes. However, in UMCA, land use categories are much more diverse and require a wider range of parametric estimates to develop more realistic water balance scenarios.

5. The preliminary results of the lumped hydrological model show the limitations in predicting water yield as a catchment response function. It is understood that the representation of the spatial dimension is compulsory to simulate the catchment dynamics and hence, the use of GIS which has the extensive capabilities to represent the spatial dimension is the key for the success in hydrological modelling endeavour.

6. The importance of historical riverflow records for hydrological modelling and calibration is emphasised. Either the lack of continuous reliable flow records or denial of access to the available records was a serious constraint hampering local modelling efforts.

7. Negative and positive effects of forest on water yield are understood and documented in this chapter. Although the water yield was the key issue in UMCA with respect to the Mahaweli Development Programme, any measures to improve water yield is required to accompany the efforts of sustainable utilisation of catchment resources.

Chapter 5

5. IDENTIFICATION OF LAND USE AND LAND COVER

5.1 Introduction

Vegetation cover is an important factor with respect to hydrology of the catchment because of its highly dynamic nature with short seasonal changes as well as long-term climatic variations and land management transitions (Harrison & Garg, 1993). The behaviour of catchment hydrology is largely dependent on the vegetation status and its temporal variations (Roberts et al., 1993).

In the case of UMCA, because of the Accelerated Mahaweli Development Programme, drastic land use changes have been made in the catchment environment and significant transformations are still being made. Hence, it is not possible to use historical land use information for modelling hydrology in UMCA. Accordingly, the UMCA hydrological model was designed making provisions for continuously updating land use information for its parameter definitions.

The need for a reliable and quick method for assessing the spatial distribution of land use status is emphasised in view of the hydrological modelling efforts. Further, the format of the land use information and classification criteria need to be compatible with the hydrological model structure for the purpose of maintaining a dynamic link. This chapter is dedicated to finding a solution for this problem related to identification of land use and land cover in UMCA.

5.1.1 Need for Remote Sensing Approach

Remotely sensed spatial data is as an important source of information in hydrological modelling (Cruise & Miller, 1993). Because of the capability of remote sensing for repeated observations and multi-spectral synoptic coverage, application of spectral classification techniques for land use/ land cover mapping as an input data source has been proven to be promising in several studies (Adinarayan et al., 1994; Roberts et al., 1993; Engman & Gurney, 1991; Davis et al., 1991; Rango et al., 1983; Ragan & Jackson, 1980). In addition to the quantitative measurements of vegetation properties, synoptic or large area mapping within relatively short period of time makes the choice for remote sensing preferable to other alternative approaches.

There are two main roles of remote sensing in hydrological modelling. Firstly, remote sensing provides source data as an aid for eliminating coefficients and model parameters based on various geomorphic descriptions of a basin (Lee et al., 1990; Price, 1980; Schultz & Kiatt, 1980). Secondly, hydrological models that are based on a land use component have been modified to use digital analysis or image interpretation of multi-spectral data to delineate land use classes (Davis et al., 1991; Engman & Gurney, 1991).

5.1.2 Land use and Land Cover Status in UMCA

During the last few decades, natural protective cover of the catchment environment has been destroyed for settlement or urban expansion and for peasant or plantation agriculture. The apparent consequences in the form of soil erosion, reservoir siltation, and poor water quality have driven the research and management interest towards catchment conservation scenarios. Several restoration programmes have been launched while practices leading to land degradation continue, making the catchment environment highly dynamic and vulnerable to change.

The simulation of hydrological dynamics using the UMCA hydrological model required continuous updating of land use information for the period from 1964 to 1993. Because of the resource constraints, two snapshots of land use status, before and after the development programme were used as the land cover basis for the model.

5.1.3 Land Use Classification Scheme

Land use and land cover mapping attempts should be accompanied by a suitable classification scheme for use at a desired scale, for a designated area and within the capability of information gathering techniques being used (Anderson et al., 1976; Boughey, 1957).

The definitions of land use and land cover are conceptually different (Townshend et al., 1987) former being related to man's activity on land and latter describes the spatial distribution of the actual land cover, mainly variation in vegetation. The classification scheme for land use with ten broad classes includes considerations of land use from a hydrological perspective. However, in view of the functional simplicity and available calibrated parameters in the hydrological model, it was later narrowed down to four distinct categories. The land use classification scheme with ten land use classes and reclassified four broad classes are presented in Table 5.1 along with a brief identification of vegetation types categorised in each class.

Table 5.1 Land Use Identification for UMCA and Reclassification Scheme

Land use category	Reclassified land use	Identification/ description
1. Dense woodlands	Forest	Primary forest, fully regenerated secondary forest, mixed forest
2. Urban & bare land	Grass	Settlements, urban, clearings, bare land, earth fills, sand deposits
3. Plantation forest	Plantation	Eucalyptus, pine, turpentine, silver oak, other planted tree species,
4. Open woodlands	Forest	Open natural and secondary forest, dense tree crops, scrubland
5. Grassland	Grass	Patna grassland, *Cymbopogun* species, other scattered grassland
6. Tea	Tea	Vegetatively propagated tea, seedling tea, diversified tea, new plantations
7. Paddy	Grass	Cultivated paddy fields, fallow land with a history of paddy cultivation
8. Kandyan forest gardens	Forest	Kandyan home gardens, minor export crop gardens, perennial plantations
9. Water	Grass	River, reservoirs, lakes, ponds, submerged low land, seasonally flooded land
10. Other crops	Grass	Upland annual crops, vegetables, seasonal cash crops, shifting cultivation, mixed agricultural crops, root crops

5.1.4 Historical Land Use Information

The catchment land use prior to the development programme was obtained from a map derived from 1:25000 air-photos from 1956. The map data was available in digital format from the Hydraulic Research Institute, Wallingford, UK. The data were in IDRISI raster format and required conversion, scale adjustments and georeferencing. Further, the classification scheme adopted for the land use in this digital map had not placed any importance upon the hydrological characteristics of the land use types. Hence, an attempt was made to reclassify the digital land use map based on the hydrologically oriented classification scheme with ten classes as listed in Table 5.1. The land use map of 1956 was then reclassified into four broad classes as shown in Plate 5.1 in order to be compatible with hydrological parameters defined in the model.

5.2 Image Pre-processing

5.2.1 Description and Assessment of Available IRS Imagery

The possibility of using land resource satellite data for upgrading land use and cover information in the hydrological model implied digital classification as the methodology for obtaining land use and cover information through time. The Forest Management and Plantation Project (FORMP), which is one of the three technical corporation projects within the forest sector in Sri Lanka funded by the UK Overseas Development Administration (ODA), provided the IRS LISS II (1992) imagery from the forest department satellite data archives.

The majority of the catchment area was covered by single quadrant (I2164A1) of the image. However, four quadrants were required to produce the mosaic for entire UMCA coverage. The details of the IRS LISS II imagery used are given in Table 5.2.

Table 5.2 List of IRS LISS II Quadrants Used for UMCA Coverage

Satellite path	Satellite row	Quadrant	Date of acquisition
21	63	A2	March 10, 1992
21	64	A1	March 10, 1992
22	63	B2	March 11, 1992
22	64	B1	March 11, 1992

IRS Satellites and Data

India's first indigenously developed operational remote sensing satellite, IRS-1A was successfully launched on March 17, 1988 (Satellite Remote Sensing, 1996). IRS-1A were placed in a sun-synchronous orbit of 904 km. altitude with an equatorial crossing time of the descending node at 10.25 a.m.. The repeat cycle of the IRS-1A orbital pattern is 22 days (Patel et al., 1991).

The payloads of IRS-1A are of two types of imaging sensors operating in pushbroom scanning mode using Linear Imaging Self Scanning Sensors (LISS). In this mode of operation, each line of the image is electronically scanned by a linear array of detectors, called charged coupled devices, consisting of 2048 elements and record 256 radiance levels. The first type of imaging sensor provides a spatial resolution of 72.5 m and is designated as LISS-I. The other type consists of two separate imaging sensors, each providing a spatial resolution of 36.25 m and designated as LISS-IIA and LISS-IIB. LISS-I provides a swath width of 148 km on the ground while LISS-IIA & IIB provide a composite swath width of 145 km on the ground (Satellite Remote Sensing, 1996).

As a follow-on to IRS-IA, the second operational remote sensing satellite IRS-1B in the IRS-1 series was launched successfully on August 29, 1991. IRS-IB is functionally identical to IRS-IA and placed in orbit in such a way as to provide a combined repeat cycle of 11 days. The spectral band in IRS-IA & IB are similar to the first four bands of Landsat TM Sensor (Murthy et al., 1996).

Applications of IRS Data

Applications of IRS-IA & IRS-IB include the field of geology, water resources and ground water, drought management, crop area and yield estimation and land use and cover mapping (Murthy et al., 1996; Adinarayana et al., 1994; Sadashivaiah & Ray, 1994; Patel et al., 1991). The application potential of IRS imaging sensors are listed in Table 5.3.

Table 5.3 Application Potential of IRS Imaging Sensors (Source: Satellite Remote Sensing, 1996).

Band	Spectral range (μ)	Fields of Applications
1	0.45 - 0.52	Coastal environmental studies, soil and vegetation differentiation, coniferous, deciduous vegetation discrimination
2	0.52-0.59	Vegetation vigour, rock/ soil discrimination, turbidity and bathymetry of shallow waters
3	0.62-0.68	Strong chlorophyll absorption leading to discriminate plant species
4	0.77-0.86	Delineation of water features, landform and geomorphic studies

5.2.2 Geometric Correction and Resampling

The images on the Computer Compatible Tapes (CCT) and optical disks were downloaded to a PC for digital image processing. Earth Resources Data Analysis System (ERDAS) VGA Ver. 7.5 was the available software for image processing both in Silsoe and in Peradeniya. The coverage of the study area on each image was identified using distinct surface features and then subsets were extracted to reduce the storage requirement of data.

In dealing with geographic data, one of the most important factors is the precise location of geographic features (Cutler & Saunders, 1995). Georeferencing or geometric correction is the process of adjusting image data to conform to a common geographic co-ordinate system (Yoshida & Omatu, 1995; Williams, 1979).

According to Richards (1986), geometric distortion inherent in image data could be due to a number of different factors including (i) the rotation of the earth during image acquisition, (ii) the finite scan rate of some sensors, (iii) the wide fields of view of some sensors, (iv) the curvature of the earth, (v) sensor non-idealities, (vi) variations in platform altitude, velocity and (vii) panoramic effects related to image geometry.

The process of geometric rectification basically involves three steps; selection of ground control points, computation of transformation matrix, and the creation of an output image by a resampling method (Lillesand & Kiefer, 1987).

An attempt was made to choose relatively permanent land features on the image for ground control point (GCP) selection. Land use maps at the scale of 1:63,360 and 1:50,000 for 1979, published by the Survey Department were used to find the Transverse Mercator (TM) projection co-ordinates of the selected GCP. Most of the GCPs are associated with the road network or drainage of the catchment and every effort was made to spread GCPs across the entire area of each quadrant (see Appendix D-1).

The four image quadrants were geometrically corrected individually using first order polynomial transform equations (Jensen, 1986) which were obtained from the GCPs using the method of least squares (ERDAS Field Guide, 1991). In this process, the transform equations were used to extract the correct pixel digital values from the original image quadrants for each location on the map grid, to form the corrected image. The error of geometric correction was maintained at less than the size of one image pixel by choosing RMS error threshold of 1 (Taylor et al., 1997). Finally, images were resampled to 20 m ground resolution using a cubic convolution technique (Fridemann, 1981). The interpolation involving cubic convolution yields an image that is generally sharper in appearance (Richards, 1986). The specifications used for the geometric correction process are listed in Table 5.4

Table 5.4 Selected GCPs and Acceptability Status

Image Identifier	No of GCPs Selected	Order of Transformation	RMS Error Threshold	No of GCPs Accepted
I2164A1	36	1	1	18
I2263B2	35	1	1	17
I2264B1	27	1	1	17
I2163A2	26	1	1	16

5.2.3 Radiometric Balancing

The majority of the catchment was covered by a geometrically corrected quadrant of path 21, row 64, top left quadrant of the image, I2164A1. The other quadrant on the same path (I2164A2) was from the same orbit as the main image and could be joined directly. However, the remaining quadrants I2263B2 & I2264B1 required radiometric balancing before generating the mosaic for the catchment (ERDAS Field Guide, 1991).

Radiometric balancing was carried out according to the methodology adopted by Taylor & Eva (1992). Overlapping areas of 272 columns and 1218 rows were subset (ERDAS Field Guide, 1991) and the statistical parameters were calculated for two mosaiced images in order to carry out radiometric calibration. The smaller mosaic covering the western strip of the UMCA was radiometrically corrected to adjust the relative brightness values.

$$DN_{out} = DN_{in} \times m - c \quad \text{(Eq. 5.1)}$$

$$m = \sigma_2 / \sigma_1 \quad \text{(Eq. 5.2)}$$

$$C = \mu_2 - m\mu_1 \quad \text{(Eq. 5.3)}$$

where μ_1 and μ_2 are the mean values of brightness and

m is the ratio of standard deviation of DN values of the overlapping areas of the mosaic.

The linear transformation function calculated for each band using Eq. 5.1 are given in Eq. 5.4 through 5.7.

Band 01 $$DN_{out} = 1.0001 \times DN_{in} - 2.01862 \quad \text{(Eq. 5.4)}$$

Band 02 $$DN_{out} = 1.0087 \times DN_{in} - 2.00673 \quad \text{(Eq. 5.5)}$$

Band 03 $$DN_{out} = 1.0525 \times DN_{in} + 1.54098 \quad \text{(Eq. 5.6)}$$

Band 04 $DN_{out} = 0.9599 \times DN_{in} - 3.1464$ (Eq. 5.7)

The effect of radiometric balancing was very distinct. The mosaiced extract without radiometric calibration clearly showed the boundary of image fusion. The join was not visible on the radiometrically corrected mosaic.

5.2.4 Catchment Delineation

The UMCA catchment boundary was determined from the 1:63,360 scale land use and contour maps (1979) published by Survey Department of Sri Lanka. Contour information was based on the contour interval of 33 m (100 feet) in the map. The catchment boundary was digitised using TYDAC SPANS TYDIG software running in OS/2 and then imported to the ERDAS image processing system via a polygon file (.DIG).

The catchment coverage was cut out from the mosaiced image using the boundary polygon file. The extraction of UMCA from the mosaiced image at an early stage of image processing was found to be very useful in maintaining minimum storage requirement for image data.

5.2.5 Evaluation of Spectral Bands

Spectral information is derived from any three spectral bands of digital data for visual identification of ground information. This is due to the limitation of display devices that only a combination of three bands can be visualised at a time. In order to make the most efficient use of multi-spectral data for display purposes, it was essential to identify the best possible three band combination (Dwivedi & Rao, 1992).

The Optimum Index Factor (OIF) introduced by Chavez et al. (1984) is based on the variance and the correlation among different bands (Eq. 5.8).

$$OIF = \sum_{j=1}^{3} SD_i \bigg/ \sum_{j=1}^{3} |CC_j| \qquad \text{(Eq. 5.8)}$$

Where SD_i is the standard deviation of band i and

$|CC_j|$ is the absolute value of the correlation coefficient between two of the three bands.

A four band correlation matrix (see Table 5.5) was derived for IRS LISS-II mosaic of UMCA. Correlation values were calculated from the covariance matrix generated in ERDAS using Eq. 5.9.

$$\text{Correlation Coefficient}_{(1,2)} = \frac{\sigma_{12}}{\sqrt{\sigma_{11}\sigma_{22}}} \qquad \text{(Eq. 5.9)}$$

Table 5.5 Correlation Matrix for IRS LISS-II Mosaic of UMCA

Spectral bands	1	2	3	4
1	1			
2	0.89	1		
3	0.88	0.92	1	
4	0.14	0.30	0.15	1
Mean (μ)	48.295	27.388	29.547	65.781
STD (σ)	4.036	3.460	7.317	9.450

Information content of mosaiced image as measured by OIF values for all the possible three band combinations was computed and presented in Table 5.6.

Table 5.6 OIF for IRS LISS-II Mosaiced Image of UMCA

No.	Band combination[a]	$\sum_{j=1}^{3}\|CC_j\|$	$\sum_{i=1}^{3} SD_i$	OIF
1	1,2,3	2.69	14.813	5.50
2	1,2,4	1.33	16.945	12.74
3	1,3,4[b]	1.17	20.80	17.78
4	2,3,4	1.37	20.227	14.76

[a] - 4 bands combined 3 at a time to produce all 4 possible combinations

[b] best band combination according to OIF

The 3 band combination having the largest OIF was selected for colour composite because it should display the most information with the least amount of duplication (Dwivedi & Rao, 1992). Interestingly, the commonly used standard False Colour Composite (FCC) from band 2, 3 and 4 derived from TM (Patel et al., 1991) or IRS (Kushwaha et al., 1996) ranks second according to OIF definition. The combination of band 1,3 and 4 was chosen (Hass & Waltz, 1983) for further processing. The pre-processing methodology is summarised in Figure 5.1.

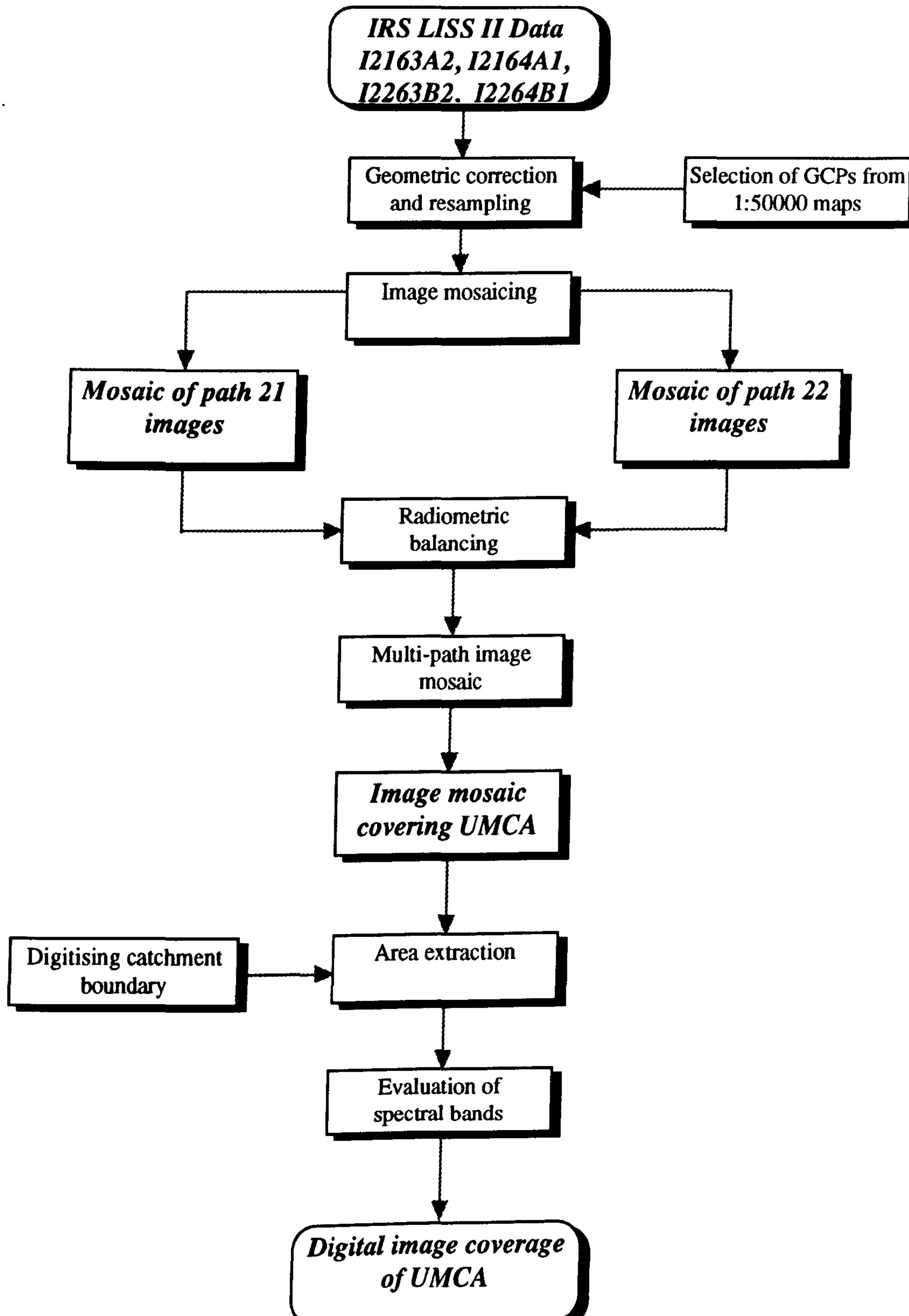


Figure 5.1 Paradigm of Image Pre-processing

5.2.6 Image Enhancement

Most image processing systems have a variety of automated contrast stretching facilities based on the generation of gaussian, equalised or other types of standard distribution in order to transfer original digital data to occupy the full dynamic range (Richards, 1986; Logan, 1979). Histogram equalisation, available in ERDAS for non-linear contrast stretch was applied to the image to obtain an improved visible and digital contrast stretch of the image. The contrast stretched FCC of UMCA produced using bands 1,3 and 4 is shown on Plate 5.2.

5.3 Preparation and Implementation of Ground Data Collection

Ground data collection is an integral part of the classification process where relationships are sought to relate spectral signatures of a satellite image with the corresponding ground features (Campbell, 1981; Jackson et al., 1976).

5.3.1 Overview and Need for Ground Data

The terms ground data and field survey data are synonymously used to refer to land use or land cover information collected during the field visits in UMCA. The field survey was carefully planned to collect ground data for (i) training spectral signatures using a supervised classification approach (Taylor et al., 1997; Campbell, 1981; Joyce. 1978), (ii) determination of accuracy of supervised classification (Story & Congalton, 1986; Hixson et al., 1980), (iii) assessment of the land cover classification generated by unsupervised classification (Campbell, 1981) and (iv) identification of empirical relationships between surface properties and satellite observations (Curran, 1992; Crippen, 1990).

5.3.2 Statistical Framework

Almost all remote sensing of the earth involves some form of ground support (Atkinson, 1991) and this is provided by sampling through a proper sampling strategy

(Curran & Williamson, 1985). Several sampling procedures have been suggested for ground data collection in image processing (Taylor et al., 1997; Taylor & Eva, 1992; Curran & Williamson, 1985; Cochran, 1977). In the statistical point of view, every approach has its own strengths and limitations.

The area-frame sampling methodology described by Taylor & Eva (1992) was adopted for this study. Unaligned systematic random sampling was chosen with 1 sq. km. fixed size ground segments. A 10 km. grid corresponding to 1:10000 map sheets was overlaid upon the image and the locations of ground segments were chosen randomly from each grid square of 10 sq. km.. The total number of ground segments was 38 and it produced a sampling frequency of 1.22% of the 3122 sq. km. study area. Stratification of the catchment was not done as there was no strong basis for defining regional strata in UMCA.

The location of ground segments is shown in Plate 5.3 and the geographical reference and corresponding image and file co-ordinates of these segments are given in Appendix D-2.

5.3.3 Field Data Formats and Documentation

Image Format for Ground Survey

In the process of ground survey, difficulties associated with spectral heterogeneity are frequently encountered, especially if it is concerned with high resolution data (Johnsson, 1994). Methodologies have been proposed in the literature to overcome this problem (Taylor et al., 1997; Gilmour, 1993 Lee et al., 1990; Atkinson et al., 1985; Curran & Williamson, 1985; Campbell, 1981). Accordingly, different filtering approaches were tested although none was found to be satisfactory in terms of visual interpretability of the ground segment. Hence, the original image data were used for the ground survey.

The FCC of band 1,3 and 4 (RGB) of IRS LISS-II UMCA coverage was used to produce the ground data segments of 1 sq. km.. A cubic convolution based resampling procedure produced 20 m ground resolution and resulted in an array of 50 rows and 50 columns of data for each segment. For each segment, a 400 m boundary was allowed to make the recognition of ground features easy and comparable with selected image segments. A typical ground segment produced at the scale of 1:10000 for ground data collection is shown in Plate 5.4 along with the field parcel boundaries drawn during the field survey. Further, a 5 km. x 5 km. area surrounding the ground segment was also printed out to obtain a synoptic view of the area and ground features (Plate 5.5). It also helped field navigation.

Field Documentation

In addition to the image segment for each ground data site, a transparent overlay of the available map sheet was also produced at 1:10000 scale. A limited area of UMCA is covered by 1:10000 scale land use and contour maps produced under the Agriculture Base Mapping Project in 1991. These overlays provided the facility to compare the land use status in the field with map overlays and image segments.

The enlarged overlays of land use maps at 1:50000 and 1:63360 provided the information required to locate the ground segments and to calculate relative distances between ground features whenever necessary.

A proforma was prepared to record field data corresponding to the features on the image segment. A typical example of a completed proforma is shown in Appendix D-3 corresponding to the ground segment shown in Plate 5.4. Every effort was made to record a detailed description of field conditions under remarks in the proforma. A transparency overlay was used to draw the field parcel boundaries and record the spatial extent of land use on the image segment.

5.3.4 Field Visits and Navigation

Field visits were made during the period between February and August, 1995. Only one ground data site was chosen for each day due to the requirements of detailed observations and recording of field conditions. It was necessary to make two visits for six ground segments due to the confusions of land use and land cover identification arising from land use changes between image acquisition and ground data collection.

A Trimble Geoexplorer GPS fitted with an external antenna provided the location information for navigation in the field. The land use and contour maps of 1:10000, 1:50000 and 1;63,360 were also used for route planning for the field visits.

5.3.5 Associated Problems in the Field Survey

Small, irregularly shaped land parcels commonly found in most parts of the catchment made field verification time consuming and less accurate in terms of spatial demarcation. Heterogeneity of crop growth stages even within small fields led to confusion in crop identification on the image segment. In some cases, subjective judgements were made to categorise field land uses into the classification scheme either due to mixed land uses or due to the classification scheme being not detailed enough to include all land use types. This inherent weakness of the classification scheme was unavoidable because the development of the classification scheme was based on the hydrological importance of the land use.

Some of the land parcels in ground segments were not totally accessible. In these cases, observations were made from a distance and the judgement from a distance may not be very accurate. One sample site was not accessible by any means. Another ground segment from the same 10 x 10 km grid square was chosen instead to maintain the sampling fraction. In this way, the randomness of the overall sample was not seriously violated.

Navigational problems were also encountered during the field survey. Trimble GPS readings were not available in some of the natural forest sites probably due to dense tree cover. Some of the road information found in topographic maps of 1980s was not very accurate.

5.3.6 Summary of Field Observations

The most extensive mono-cropping farming system found in UMCA was estate managed tea. Large scale crop diversification schemes were observed in most of the tea plantations. Intensive vegetable and potato farming on steep hill slopes without proper conservation measures was evident on some of the western slopes of N-Eliya district.

Isolated patches of natural forest still exist throughout the catchment in addition to the declared forest reserves. Successful small scale forest plantations with Pinus and Eucalyptus were found to be scattered all over the catchment. In addition, natural and plantation tree species were found and classified as open forest. Some of the high altitude montane cloud forests were also classified as open forest due to low plant density and poor canopy characteristics.

High value cash crops and vegetables were found in small fields and mostly related to small holder farmers. KFG was the predominant small holder land use system found in Kandy district. In terms of the canopy density, KFG has a very high rating and, in most cases, it was higher than that of open forest.

Paddy was the main lowland crop found alongside the drainage network. Small, well defined field boundaries were mostly typical in the highland paddy fields.

5.4 Processing of Ground Data

5.4.1 Digitising Sample Data Sets

The ground data sets were digitised via the digitising module of TYDAC SPANS software (TYDIG) with a Calcomp-Pro A0 size digitising table. The process of digitising was carried out twice for each segment in an attempt to minimise digitising errors and to obtain the average area measurements for direct expansion estimates. Digitised ground segments were imported to TYDAC SPANS GIS via a vector file series. The facilities available in SPANS GIS for map area analysis were used to obtain areas under each land use.

The average error of digitising was found to be ± 0.256 percent of the 1 sq. km. of true area in each ground segment. A summary of information derived from ground data is presented in Table 5.7.

Table 5.7 A Summary of Information Derived from Field Data Collection

Segment No.	Dense Forest	Grass	Tea	Water	Plant Forest	Open Forest	Urban	Paddy	Other	KFG	Total
1							95.55	4.04			*99.59*
2	45.70	25.70	21.97	1.39	5.11						*99.88*
3	22.35	20.38					7.23	1.00	19.96	28.27	*99.20*
4						20.25	1.37	16.84	58.13		*96.59*
5		27.96	63.44								*91.40*
6		9.17						9.96	34.10	46.77	*100.00*
7	5.93			91.21			2.97				*100.10*
8	13.47		47.01	5.38		26.94			7.05		*99.85*
9	41.64		52.24			6.12					*100.00*
10	92.07						7.70				*99.77*
11	6.68	1.06	49.70		10.58	2.45	19.23	1.70	8.33		*99.72*
12	64.85		11.58						3.05	20.23	*99.71*
13		40.36					8.43	30.21	20.01		*99.00*
14	1.96		15.30			17.55	29.09	12.63	16.16	6.62	*99.31*
15		32.44	47.62		2.15	1.63	5.67		8.99		*98.50*
16		18.76	20.31				40.49		20.74		*100.30*
17	25.84	30.04			9.77				2.18	32.11	*99.94*
18		20.45	10.61	5.08		0.32	2.06	11.32	51.17		*101.01*
19			56.11		16.85		21.72		4.94		*99.63*
20		2.75			6.48	2.62		11.65	47.98	28.60	*100.07*
21		35.66	10.49	2.72	4.47	4.21	2.39	6.99	6.79	26.28	*99.99*
22						4.01	2.24	8.02	29.98	55.13	*99.38*
23	0.25	13.71	13.98						18.31	53.90	*100.15*
24	1.41	47.01	15.23	2.06						33.67	*99.38*
25			21.10					24.76		53.11	*98.96*
26				4.45			4.63	7.36	27.33	56.23	*100.00*
27		32.80	16.10	0.00		39.67			10.08		*98.65*
28			0.00	7.30			1.20	6.71	63.32	22.58	*101.10*
29		16.75	12.21		2.60		6.49	8.57		52.37	*98.99*
30		1.24		8.18				8.93	23.86	57.78	*99.99*
31	23.17			0.00		26.83				49.99	*99.99*
32			12.97	11.80		32.71			42.61		*100.09*
33		35.52	1.26		19.87					45.00	*101.65*
34		25.19	40.19	6.59			12.45		4.33	11.25	*100.00*
35	9.55		2.29	26.85		12.61	9.12		16.58	23.01	*100.00*
36		44.06	3.70		18.56					33.45	*99.76*
37		60.01	8.28	5.25					26.45		*99.99*
38		76.09	19.63	4.28							*100.00*
Total*	354.87	617.12	573.32	182.53	96.43	197.90	280.03	170.68	572.43	736.34	*3781.66*
Total**	29316	50981	47362	15079	7967	16349	23134	14100	47289	60830	*312408*
Total %	9.39	16.33	15.17	4.83	2.55	5.24	7.33	4.52	15.15	19.49	*100*
Ratio***	15	26	24	8	4	8	12	8	24	31	159

* - Total area in ha. of each crop in all segments, ** - Total area in ha. of each crop in UMCA.

*** - Ratio for No. of training areas used.

5.4.2 Area Estimation by Direct Expansion

'Direct expansion estimates provide a quick way of quantifying the land use status of an area through a statistically valid sampling procedure. In this study, these estimates were not intended to provide crop area statistics in terms of the coverage. However, these provided the *a priori* weightings, used later in the digital classification procedure (ERDAS Field Guide, 1991; Swain & Davis, 1978). The area coverage of each crop based on direct expansion estimates were calculated using the method proposed by Gallego & Delince (1991) as quoted by Taylor and Eva (1992).

Theory

In the direct expansion approach, the mean area per ground segment of each land use category in the entire sampled area is given by Eq. 5.10.

$$\overline{Y_c} = \frac{1}{n}\sum_{i=1}^{n} Y_{ic} \qquad \text{(Eq. 5.10)}$$

where n is the total number of sample segments and

Y_{ic} is the proportion of land use for a particular class in the i^{th} segment.

For each land use class, the total coverage (Z_c) for the entire UMCA is then obtained from Eq. 5.11.

$$Z_c = D\overline{Y_c} \qquad \text{(Eq. 5.11)}$$

where D is the total area of UMCA.

According to Taylor and Eva (1992), the standard error of total class area and 95% confidence limits are calculated by Eq. 5.12 and Eq. 5.13 respectively.

$$SE(Z_c) = D\sqrt{(1-\frac{n}{N}).\frac{1}{n(n-1)}.\sum_{i=1}^{n}(Y_{ic} - \overline{Y}_c)^2} \quad \text{(Eq. 5.12)}$$

where N is the total population of segments from which the sample was drawn and is equal to the total area of UMCA (3122 sq. km) divided by the area of each ground segment (1 sq. km.).

$$C.I._{95} = Z_c \pm 1.96SE(Z_c) \quad \text{(Eq. 5.13)}$$

5.4.3 Results of Direct Expansion

It was assumed that the random sampling of 1 sq.km. represents the true proportions of the spatial distribution of land use within each grid square. Hence, results of direct expansion should provide approximate proportions of each cover type in the whole of the UMCA. The derived set of complete results of direct expansion estimates are summarised in Table 5.8.

Table 5.8 Analysis of Direct Expansion Results (in hectares)

Land use	$\sum_{i=1}^{n} Y_c$	$\overline{Y_c}$	Z_c	$SE(Z_c)$	SE %	C.I.95 (Z_c+1.96SE(Z_c))	C.I.95 (Z_c-1.96SE(Z_c))
Dense Forest	355.58	9.36	29233.27	10238.44	35.02	49300.61	9165.92
Grass	621.03	16.34	51056.72	9995.62	19.58	70648.14	31465.31
Tea	581.05	15.29	47769.43	9534.03	19.96	66456.14	29082.72
Water	182.32	4.80	14989.01	7687.37	51.29	30056.25	0.00
Plant. Forest	96.32	2.53	7918.44	2731.02	24.49	13271.25	2565.63
Open Forest	199.35	5.25	16388.78	5257.63	32.08	26693.73	6083.83
Urban	280.98	7.39	23100.37	8669.66	37.53	40092.90	6107.83
Paddy	171.90	4.52	14132.39	3661.39	25.91	21308.71	6956.06
Other Crops	574.12	15.11	47200.00	9112.94	19.31	65061.37	29338.64
KFG	737.35	19.40	60619.60	11016.76	18.17	82212.45	39026.74
TOTAL	3800	100	312408				

5.5 Digital Image Classification

5.5.1 Overview of Digital Image Classification

Digital image classification is the process of assigning pixels to different classes based on the Digital Numbers (DN), which are measures of the surface reflectance, in order to produce a meaningful identification of surface features or cover types (Campbell, 1981). Classification techniques use the spectral, and some times, the spatial properties of digital imagery to identify the clusters in the multi-spectral space (Swain and Davis, 1978). However, in many cases, pre-determined classes according to a classification scheme do not form distinct clusters or groups of clusters but rather are part of a continuum of data in the multi-spectral space (Richards, 1986).

Multi-spectral satellite data represent an area average quantification of reflected or emitted energy within each pixel. The specified area of the pixels over which such measurements are made is referred to as spatial resolution. Reflectance or emission is calibrated to a restricted range of discrete digital numbers, normally 256 levels (Saxena et al., 1992).

5.5.2 Classification Methodology

In general, there are two main approaches for calibration of digital classification procedure; namely unsupervised classification and supervised classification (Lillesand & Kiefer, 1987). However, often, combination of these two approaches, known as hybrid classification, is used (Campbell, 1981).

5.5.3 Unsupervised Classification

Unsupervised classification is the process of defining, identifying, labelling and mapping natural groupings in the multi spectral space (Campbell, 1981) without having knowledge on existing classes. Clustering procedures are commonly used for unsupervised classification (Richards, 1986). Advantages, disadvantages and limitations of unsupervised classification are found in great detail in the literature (ERDAS Field Guide, 1991; Lillesand & Keifer, 1987; Mather, 1987; Richards, 1986; Swain & Davis, 1978).

The unsupervised classification methodology adopted in this study was similar to the optimal structure tree classification approach introduced by Andrianasolo (1996) with the exception that the selection of number of classes in the classification was based on a subjective judgement.

Initially, the sequential clustering (ISODATA) option available in ERDAS was employed to identify 50 classes and corresponding spectral signatures from the image multi spectral space. The mean and standard deviation of DNs belonging to each class were calculated individually. The calculated statistics are tabulated in Appendix D-4(a).

The calculated class statistics were copied into SPSS software for Hierarchical Cluster Analysis (SPSS User Manual Ver 6.0, 1993) using the Ward method (Andrianasolo, 1996). The basis for using this algorithm was to produce a lower number of classes through a process of agglomeration from a large population of classes minimising the variance within each spectral class and while maximising the variance among different classes (Hung, 1994; Richards, 1986). The algorithm tries to find the optimal spectral class combinations for the number of user specified classes and results in a tree structure which is shown as a fusion dendogram.

In this exercise, the final number of spectral classes was defined to be 10 so that it could be directly comparable with the classification scheme developed for the supervised classification. The fusion dendogram showing optimum class combinations is shown in Appendix D-4(b).

The spectral signatures produced for 50 classes were regrouped according to the combination given in the fusion dendogram in order to obtain the final 10 signatures, which was assumed to correspond to the defined classification scheme. Finally, the UMCA coverage of IRS images was classified using these 10 signatures by employing the maximum likelihood classifier. The results of the unsupervised classification are shown in Plate 5.6.

5.5.4 Mosaicing of Ground Data Segments

A mosaiced image was created by extracting all the ground segments using FILQUILT Turbo C^{++} programme (Thomas, 1994) from the image covering UMCA. The collection of imagettes into a single image (QUILT) was useful in identifying and evaluating training data for the maximum likelihood classifier and also in assessing the accuracy of classification (Taylor & Eva, 1992). The QUILT image is shown in Plate 5.7. In addition, another QUILT image was created from the resulting map of unsupervised classification (Plate 5.8).

5.5.5 Recognition of Spectral Signatures for Supervised Classification

The aim of providing training data to the classifier is to obtain spectral information which could be used to determine the decision boundaries for the classification of the whole mosaiced image (Richard, 1986; Swain & Davis, 1978). The mean DN values of each band for forest and non-forest land uses are presented in Figure 5.2(a) and 5.2(b). The classification scheme consisted of the ten land use classes previously defined. The total number of training sites chosen was 159 while the number for each class was proportional to the area of that class in the total ground survey data (see Table 5.8). The training pixels were randomly selected from the QUILT image. However, an effort was made to choose training sites from almost all the ground survey segments.

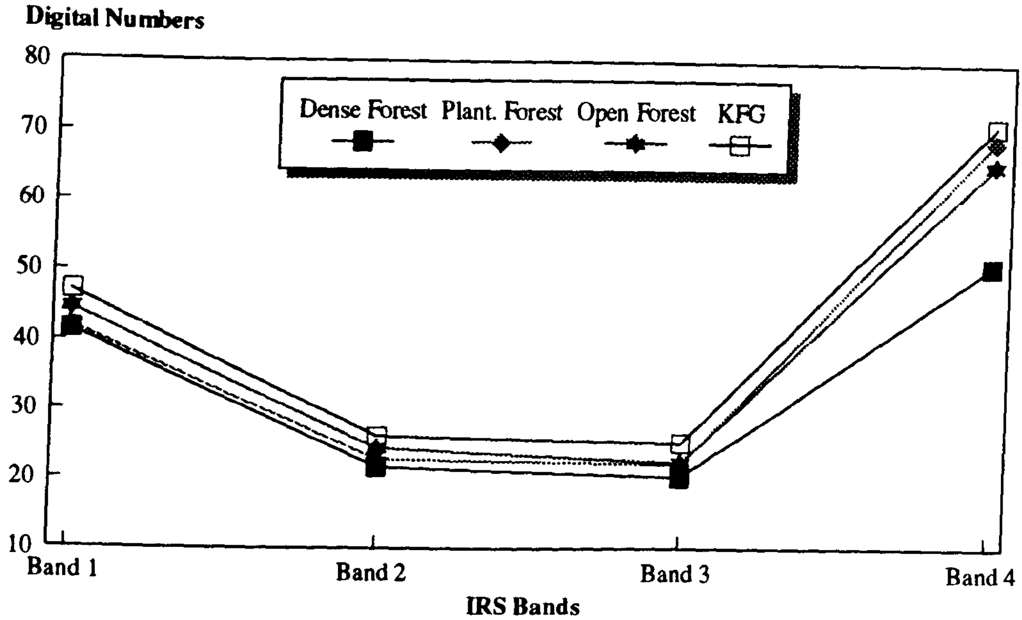


Figure 5.2(a) Distribution of DNs in different bands for Forest Cover Types in UMCA

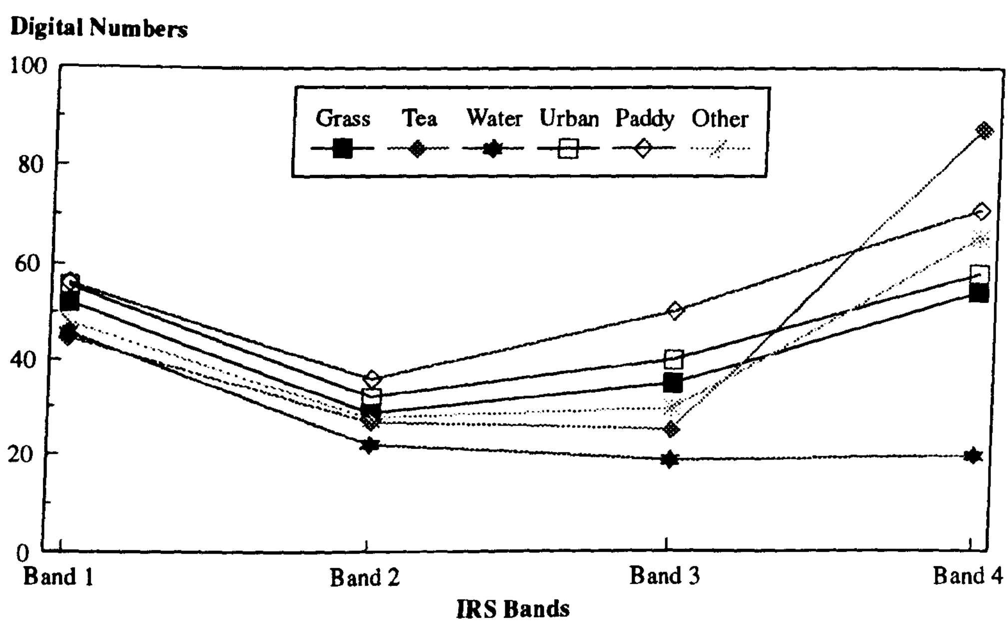


Figure 5.2(b) Distribution of DNs in Different Bands for Non-forest Land Uses in UMCA

5.5.6 Spectral Homogeneity and Class Separability

·Spectral uniformity was verified for all the signatures by overlaying them upon the QUILT of unsupervised classification. This process was very useful to avoid spectral confusion to a great extent by avoiding the selection of mixed pixels of different classes. All the individual signatures were combined together to produce class signatures (10 classes) for the classification. Statistics for the selected class signatures are given in Table 5.9.

Table 5.9 Statistics of Signatures Used for Maximum Likelihood Classification

Land Use	Band 1		Band 2		Band 3		Band 4	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Dense Forest	41.60	0.98	21.74	0.80	20.46	1.54	50.9	2.79
Grassland	52.12	5.10	28.85	3.07	35.4	5.21	53.98	8.17
Tea	44.75	1.44	27.00	1.59	25.56	2.67	87.52	4.55
Water	45.77	3.17	22.16	2.93	18.98	4.34	20.13	3.27
Plant. Forest	42.14	1.46	22.85	1.56	22.28	2.25	68.94	3.42
Open Forest	44.66	1.61	24.50	1.28	22.49	2.07	65.56	4.25
Urban & Bare	55.58	1.82	32.32	1.25	40.31	2.46	57.62	3.99
Paddy	56.09	2.38	36.17	2.4	50.27	4.79	70.73	4.53
Other Crops	47.99	1.85	27.81	1.69	30.11	3.62	64.99	4.29
KFG	47.19	1.13	26.20	1.10	25.39	2.27	71.15	3.26

Two evaluations were made on the signature files. Scatterplots were viewed in two dimensional space taking each band combination using ELLIPSE. The Jeffries-Matusita distance was calculated for all the signatures. Histograms and statistics were computed for each signature. Spectral confusion was evident in paddy and urban, tea and open forest, and plantation and open forest. Polygons for these signatures were separated and the clusters were formed using ISODATA unsupervised classification. Thus the predominant cases of spectral confusion were eliminated and signature files were purified.

The scatterplots of mean reflectance of different class combinations, separately for forest and non-forest land use types, were viewed in two dimensional spectral space (Figure 5.3(a) through 5.3(d)) using the ELLIPSE option in ERDAS. The overlap of scatterplots represents the extent of spectral confusion when they are used for the decision rule in classification.

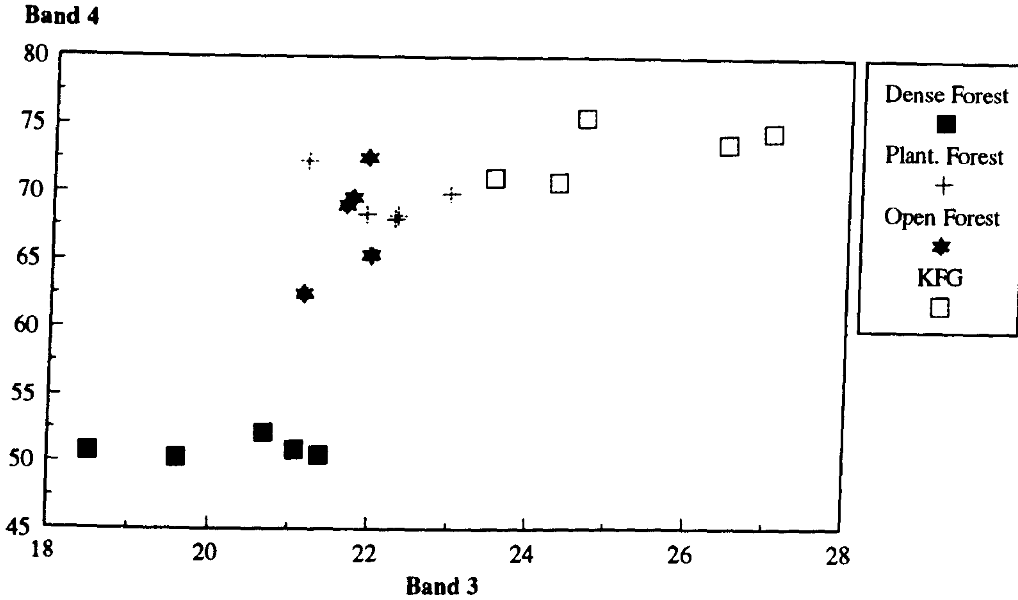


Figure 5.3(a) Scatterplot of Mean Reflectance in IRS Bands 3 & 4 for Forest Cover Types

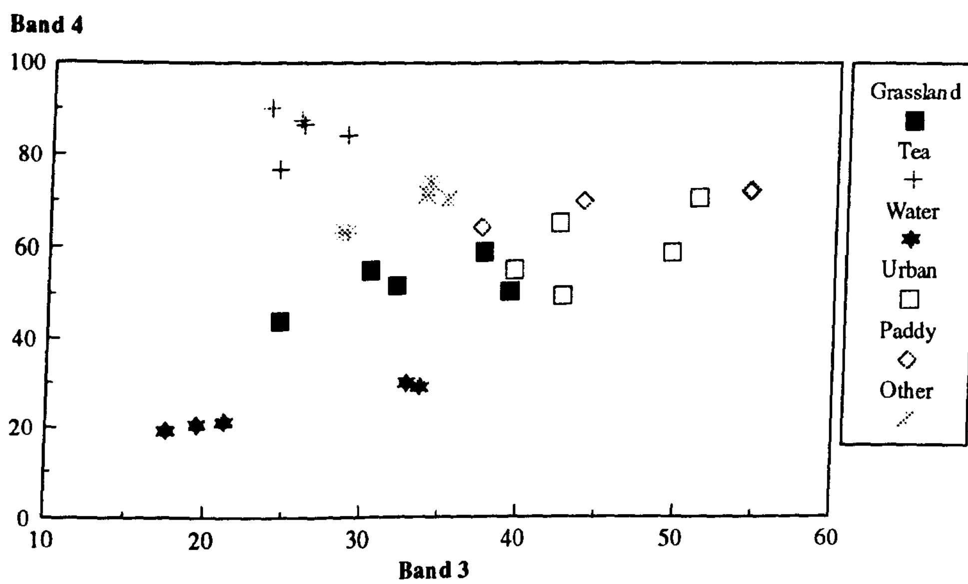


Figure 5.3(b) Scatterplot of Mean Reflectance in IRS Bands 3 & 4 for Non-forest Land Uses

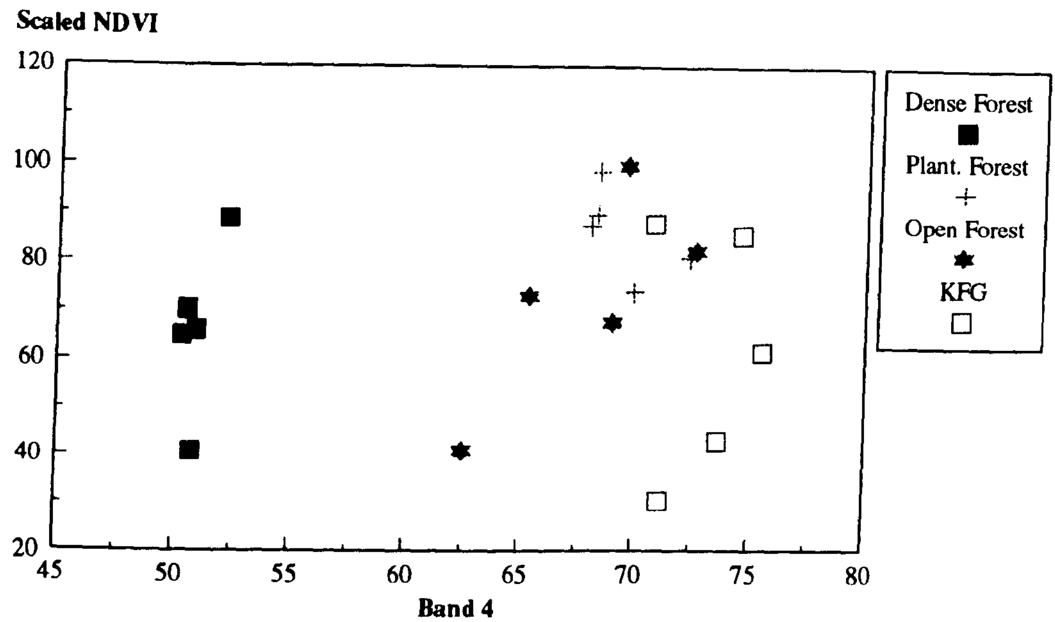


Figure 5.3(c) Scatterplot of NDVI vs Mean Reflectance in Band 4 for Forest Cover Types

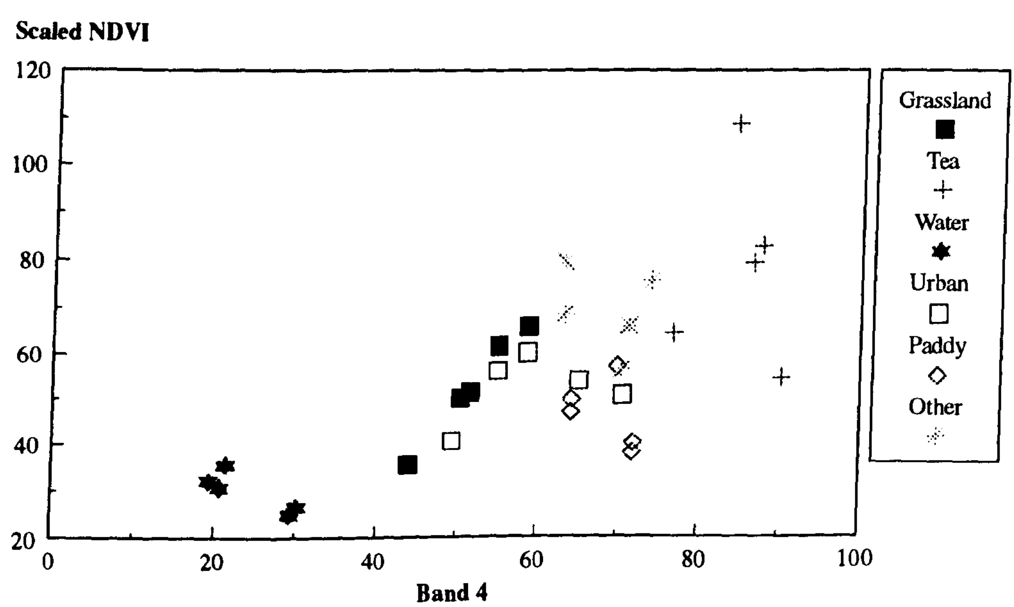


Figure 5.3(d) Scatterplot of NDVI vs Mean Reflectance in Band 4 for Non-forest Land Uses

A statistical measure of distance in multi-spectral space between two or more signatures known as signature divergence was used to evaluate the class signatures. The Jeffries-Matusita Distance, a divergence measure in ERDAS, calculates the actual divergence in a range of possible values 0-1414 (ERDAS Field Guide, 1991). Total separability occurs at the upper boundary while total confusion occurs at the lower boundary. The calculated JM distances of 10 class signatures for the band 1,3 and 4 combination are listed in Appendix D-5(a). The two band JM distances which show where the problems of separation may occur are given in Appendix D-5(b).

Signatures for paddy and urban classes were less divergent. Further, open forest and tea areas were spectrally confused. Frequency distributions of these classes were bi-modal. The polygons containing the training data of these classes were identified and adjusted by running sequential clustering (ISODATA) to derive spectrally divergent, uni-modal class signatures.

5.5.7 Digital Classification Algorithm and Results

The classification algorithm (MAXCLAS) compares image pixel values with the classifier training signatures and assigns classes according to the Maximum Likelihood decision rule (ERDAS Field Guide, 1991). The Maximum Likelihood algorithm strictly assumes that the histograms of signature data are normally distributed (Swain & Davis, 1978). In this study, a priori probabilities derived from direct expansion estimates (see Table 5.8) were introduced to the Maximum Likelihood classifier in order to produce an area-weighted classification for UMCA.

Plate 5.9 shows the area weighted classification of UMCA. The classified image has a noisy appearance (Richards, 1986) due to the presence of many isolated pixels or small groups of pixels where classification is different from most of the neighbours. Since the classification results were to be reclassified according to the hydrological parameter definitions discussed in Chapter 4, image smoothing was not attempted at this stage. A comparison of the area estimates from digital classification with the direct expansion estimates are presented in Table 5.10. A summary of digital image processing methodology is given in Figure 5.4.

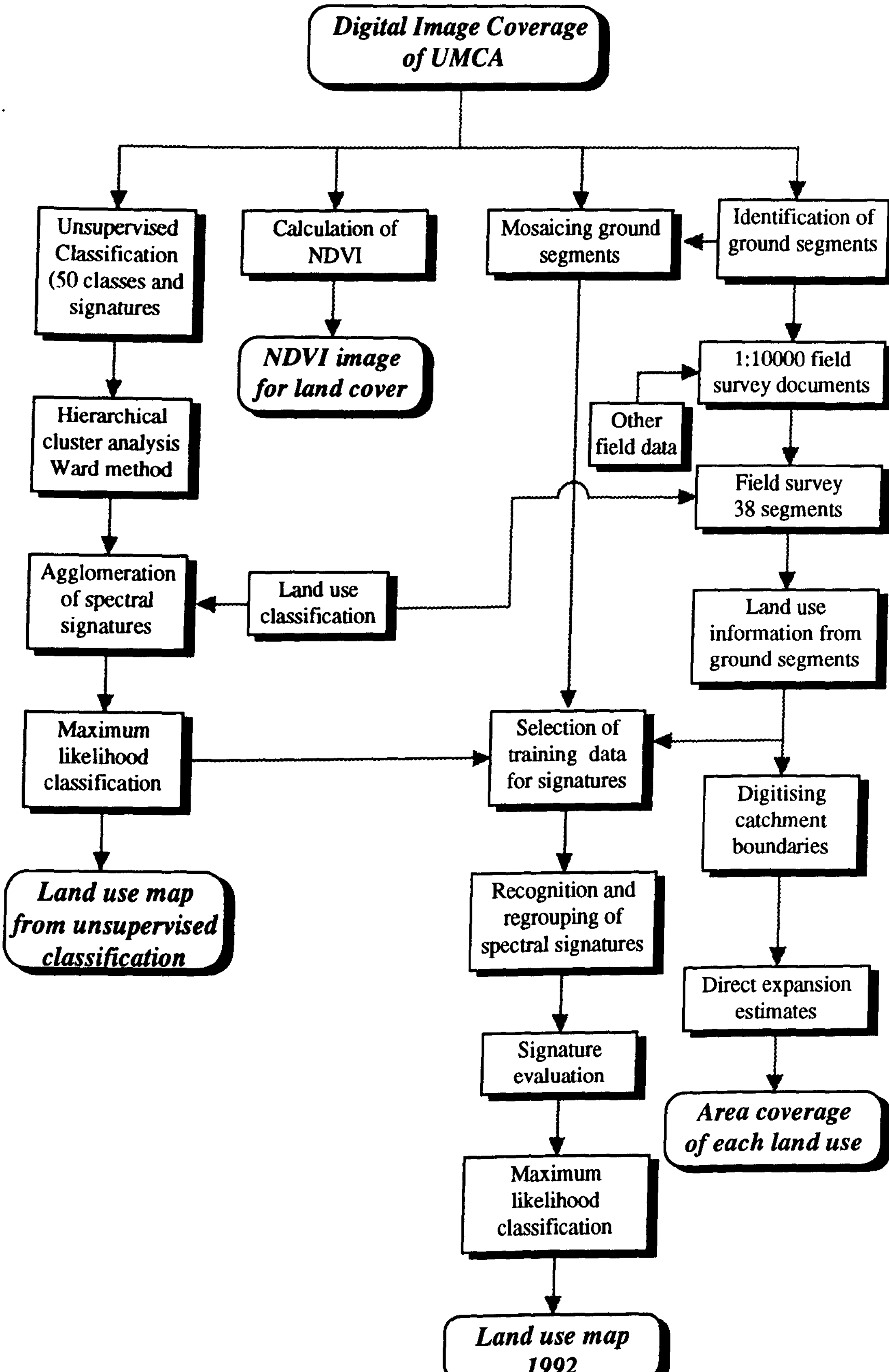


Figure 5.4 Paradigm of Digital Image Processing

Table 5.10 Comparison of Digital Classification Estimates with Direct Expansion Estimates

Land use	Digital classification estimates (km^2)[a]	Direct expansion estimates (km^2)[b]	Percentage Difference between estimates (km^2)*
Dense Forest	201.18	293.16	45.72
Grass	679.82	509.81	25.00
Tea	355.86	473.62	33.09
Water	24.74	150.79	509.49
Plant. Forest	123.62	79.67	35.55
Open Forest	48.97	163.49	233.85
Urban	252.66	231.34	8.43
Paddy	98.16	141.00	43.64
Other	588.1	472.89	19.59
KFG	750.17	608.3	18.91
Total	3124.08	3124.08	

* percentage difference between two estimates = $\left|\frac{(a-b)}{a} * 100\right|$

5.5.8 NDVI for Land Cover Assessment

A number of vegetation indices have been suggested to assist in the efforts of interpreting remotely sensed data for vegetation in the optical and infrared wavelength region (Qi et al., 1994; Crippen, 1990; Clevers, 1989; Jackson, 1983; Richardson & Weigand, 1977; Rouse et al., 1973; Jordan, 1969). The NDVI is the most extensively used vegetation index for land cover characterisation and monitoring (Guyot & Gu, 1994). It is also one of the most popular vegetation indices and makes no assumption about the distribution of data (Curran, 1992). It is sensitive primarily to the amount of photosynthetically active biomass in a vegetation canopy and is found to be correlated with percentage cover, above ground biomass, productivity and Leaf Area Index (LAI) (Tucker et al., 1984; Tucker, 1979).

The hydrological model discussed in Chapter 4 requires continuous updating of land use or land cover data for parameter definitions. An attempt was made to explore the possibility of using NDVI derived land cover as an alternative to supervised classification derived land use, for quick assessment of land cover.

NDVI calculated from radiometrically normalised red and infra red reflectance values were stretched over the full dynamic range (0-255) in 8 bits using gain of 280 and offset of 0.24. An unsupervised clustering algorithm was applied over the NDVI image to produce four major cover classes as shown in Plate 5.10. The statistical distribution of each cover cluster was verified to be of an uni-modal distribution.

5.6 Assessment of Classification Accuracy

5.6.1 Confusion Matrix for Land Use Identification

Remotely sensed data have been and are likely to continue to be a major source of data for many GIS (Curran, 1982; Townshend, & Justice, 1981). The performance of GIS is mainly influenced by the quality or the accuracy of input data. With thematic classifications derived from remotely sensed data, the evaluation of quality is typically based on the assessment of classification accuracy (Foody, 1988).

Accuracy assessment of images and maps derived from remotely sensed data has been the focus for several studies. Errors in images and map data can occur during the stages of pre-processing or in the classification procedure (Story & Congalton, 1986). Further, errors can also arise in the techniques of sampling (Hay, 1979), in calculating accuracy (Benson & De Gloria, 1985; Congalton & Mead; 1983), and in comparing classification results (Ginevan, 1979; Hord & Brooner, 1976).

The classification accuracy has traditionally been expressed by the overall accuracy percentage computed from a confusion matrix or contingency table (Fitzgerald & Lees, 1994). The confusion matrix shown in Table 5.11 was compiled from the area weighted supervised classification. The reference data for the ten land use classes were obtained from the ground survey data covering almost all the ground segments in order to avoid the influence of spatial variability upon accuracy in the assessment (Foody, 1988). The proportion of randomly selected ground data used for accuracy assessment was 13% of the total ground data and this also included some polygons used to train the classifier.

The confusion matrix in Table 5.11 shows that the overall map accuracy is 60.73 percent while the highest producer and user accuracy are 98 percent and 85 percent respectively. The land use classes of dense natural forest and water have contributed positively for the overall mapping accuracy. However, the spectral confusion among classes of urban, grassland, paddy and other crops has negatively influenced the accuracy.

Table 5.11 Accuracy Assessment of the Supervised Classification

Land use	D. Forest	Grass	Tea	Water	P. Forest	O. Forest	Urban	Paddy	Other	KFG	Total	Producer*
D. Forest	936	241			52	15	3			25	1268	73.50
Grass	16	783	14		72	10	296	108	180	365	1844	42.46
Tea	2	49	996		28	119	18	8	89	810	2119	47.00
Water				307				7			314	97.77
P. Forest	80	93	44		291	26			2	59	595	48.91
O. Forest	54	16	63		52	371	2			182	740	50.14
Urban		193					366	28	77	13	677	54.06
Paddy		112	1				347	361	165	43	1029	35.08
Other		78	53		6		68	44	645	331	1225	52.65
KFG	4	299	358		58	17	44	29	382	1612	2803	57.51
Total	1088	1864	1529	307	559	558	1144	585	1540	3440	12614	
User#	85.66	42.01	65.14	100.00	52.06	66.49	31.99	61.71	41.88	46.86		60.73
MAI~	79.12	83.03	54.61	98.87	50.43	57.16	40.20	44.73	46.65	51.64		

* Producer Accuracy # User Accuracy ~ Mean Accuracy Index

5.6.2 Classification Accuracy for Hydrological Parameter Definitions

In the case of hydrological modelling, hydrological parameters were identified for only 4 broad classes of land use as discussed in Chapter 4. The reclassification process was adopted by combining hydrologically similar land uses. This improved the accuracy of classification avoiding spectral confusion up to a certain limit. Table 5.12 shows the distribution of accuracy of the 4 broad class group classification using the same set of reference data as in Table 5.11.

Table 5.12 Accuracy Assessment of Reclassified Land Use

Land use	Forest	Grass	Tea	Plant. Forest	Total	Producer*
Forest	3212	1016	421	162	48.11	66.76
Grass	778	4165	68	78	5089	81.84
Tea	931	164	996	28	2119	47.00
Plant. Forest	165	95	44	291	595	48.91
Total	5086	5440	1529	559	12614	
User **	63.15	76.56	65.14	52.06		68.69
MAI***	64.91	79.11	54.61	50.43		

* Producer Accuracy ** User Accuracy *** Mean Accuracy Index

The overall accuracy has shown an improvement due to reclassification from 60.73 percent to 68.69 percent. Further tests were required to compare the values and test whether they are significantly different. However, adequacy of overall accuracy measure has been questioned and shown to be giving misleading and contradictory results (Fitzgerland & Lees, 1994).

5.6.3 Calculation of Kappa Statistics

In view of the lack of general applicability of overall accuracy assessment, investigators in remote sensing had been searching for a single value to adequately represent the accuracy of thematic classifications (Rosenfield & Fitzpatrick-Lins, 1986). Originally developed by Cohen (1960) as quoted by Congalton (1991), the Kappa statistic has been utilised for accuracy assessment in an increasing number of studies (Fitzgerald &

Lees, 1994; Congalton et al., 1991; Rosenfield & Fitzpatrick-Lins, 1986). The Kappa statistic considers overall accuracy and individual category accuracy as a means of agreement between classification and verification. The Kappa statistic based on maximum likelihood theory has been shown to be a statistically more sophisticated measure of classifier agreement and gives better interclass discrimination than the overall accuracy (Fitzgerald & Lees, 1994).

Theory

Cohen (1960) originally developed the Kappa statistic (Hudson & Ramm, 1987) as shown in Eq. 5.14.

$$\hat{K}(Kappa) = \frac{N\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r} X_{i+}X_{+i}}{N^2 - \sum_{i=1}^{r} X_{I+}X_{+i}} \qquad \text{(Eq. 5.14)}$$

where + represents summation over the index.

The required pixel counts for the calculation of Kappa was obtained from the confusion matrix (Table 5.11).

The computation oriented form of the Eq. 5.14 is given in Eq. 5.15.

$$\hat{K} = \frac{\theta_1 - \theta_2}{(1 - \theta_{2)}} \qquad \text{(Eq. 5.15)}$$

where $\theta_1 = \sum X_{ii} / N$

$$\theta_2 = \sum_{i=1}^{r} X_{i+}X_{+i} / N$$

N = total number of counts and

X_{ii} = number of counts in iith cell of the confusion matrix.

For approximately large sample, variance of Kappa is computed as shown in Eq. 5.16.

$$V(K)=\frac{1}{N}\left[\frac{\theta_1(1-\theta_1)}{(1-\theta_2)^2}+\frac{2(1-\theta_1)(2\theta_1\theta_2-\theta_3)}{(1-\theta_2)^3}+\frac{(1-\theta_1)^2(\theta_4-4\theta_2)^2}{(1-\theta_2)^4}\right] \quad \text{(Eq.5.16)}$$

where $\theta_1=\sum_{i=1}^{r} X_{ii}/N$,

$$\theta_2=\sum_{i=1}^{r} X_{i+}X_{+i}/N^2,$$

$$\theta_3=\sum_{i=1}^{r} X_{ii}(X_{i+}+X_{+i})/N^2 \text{ and}$$

$$\theta_4=\sum_{\substack{i=1\\j=1}}^{r} X_{ij}(X_{j+}+X_{+i})^2/N^3.$$

Calculated Statistics

The Kappa statistic calculated from the results of the land use classification with 10 classes was 0.4534 with a variance of 0.00056 while the hydrological parameter oriented reclassification resulted a Kappa value of 0.5181 with a variance of 0.00008. Landis & Koch (1987) have defined the agreement criteria for Kappa. The agreement is poor when $K<0.4$, good when $0.4<K<0.75$ and excellent when $K>0.75$. According to this agreement measure, both classifications denote a good agreement.

5.7 Concluding Remarks

5.7.1 Discussion

Remote Sensing Approach

The usefulness of remotely sensed data in general, and digital classification in particular, for the land use as an input into hydrological modelling, was evident in this study. However, the compatibility of the digital results and the capability of direct conversion of these results into spatially distributed parameters indicate that the integration of digital data with the hydrological model for the representation of the spatial dimension is promising. Further, the IRS data was found to be the cheapest option given the need for high resolution multi-spectral data, yet the quality of the data is comparable with any other data set from other land resource satellite systems. In this approach, however, the direct application of IRS multi-spectral data for land use identification should not be viewed in terms of the exact quantification of each land use category.

Catchment Delineation

The delineation of the catchment boundary was based upon visual analysis of the contour information on the maps at 1:50000 and 1:63,360 scale. Application of a Digital Elevation Model (DEM) would improve the accuracy of catchment boundary identification. The DEM would also provide a better representation for fog interception derived as a function of elevation as discussed in Chapter 4.

Global Positioning System

GPS was found to be compulsory equipment for the success of field data collection in UMCA. Available maps were mostly outdated and contained some misleading or false information even in the major road network. An externally mounted GPS antenna provided for the continuous update of location information with an error margin of a few meters when compared with known locations.

Systematic Field Documentation

The well organised field documentation methodology (Taylor & Eva, 1992) coupled with accurate GPS location data helped to save time spent in the field. Further, the high quality graphics output of ground segments (FCC) of the image data from a Tektronix thermal wax printer were easy to interpret in the field. The interpretation of a ground segment required less time compared to the time spent finding and confirming the exact ground segment location.

Ground Data Sampling

There were obvious discrepancies between the direct expansion estimates and the supervised classification results suggesting possible spectral confusions although the class signatures were properly tested by JM distance and viewing scatterplots. These deviations were prominent, especially in the less frequent land use categories such as water and open forest. This indicates the need to achieve a higher sampling fraction for ground data collection.

Field Problems

Significant problems were encountered during image classification due to spectral confusion caused by small land holdings, diversified cropping systems, heterogeneity of crop growth stages and the time lag between the date of image acquisition and field survey.

Single Data Supervised Classification

For the supervised classification, a selected sample of radiometric values which have been identified as being representative to each spectral class of land use was used for training data to extrapolate the classification for the entire UMCA. The supervised classification technique operates upon the assumption that images are formed by spectrally uniform and separable classes. In reality, the radiometric classes recorded by the sensor are not homogenous nor are they in all cases unambiguously separable.

Information classes are typically not discrete and the recorded digital value of a spectral class is an average of the reflectance of multiple objects contained within the class. An attempt was made to make variability within each class less than the interclass variability.

Hydrological Modelling and Image Classification

The reason for the initial selection of high resolution imagery for the land use identification was that the model relies heavily on the land use for most of its parameter definitions. However, a conflict in terms of resolution between classification results and the other data was clearly evident. The spatial distribution of rainfall was largely determined by the interpolation function. Land use was derived from reclassification of supervised classification results into four broad classes in view of the hydrological importance. Hence, the need to derive high resolution land use data became less important. Further, the classification scheme developed for land use was not capable of identifying different canopy densities within each land use category although the hydrological importance of different land uses was considered in formulating the classification scheme.

Image Resolution and Land Use Identification

Reasonable estimation of land use could be achieved even with 1 km. NOAA AVHRR data. NDVI or other vegetation indices which are related to canopy density could be easily calculated without a high degree of user inputs to represent the spatial domain of hydrological cover characteristics. Canopy density on the ground seen from space and derived as vegetation indices is the factor which determines the rainfall impact over the catchment and hence, it is well suited to determine the hydrological characteristics of the area in place of the land use identified through a classification scheme. High resolution data on land use is of little importance from the hydrological point of view when they are not accompanied with canopy density characteristics and other data with a similar resolution strength.

The usefulness and applicability of AVHRR is further highlighted by the need for multi-temporal data sets for identifying dynamic and diverse land cover. Further, single date image classification is vulnerable to the spectral ambiguities in certain land uses at different periods of the year, thus requiring time series of image data for representative parameter identification.

5.7.2 Conclusions

1. A properly organised field data collection programme supported with a complete set of field documentation is a prerequisite for a successful supervised image classification.

2. The need for a process of contemporary ground information collection is emphasised, especially when the environment is very dynamic and diverse.

3. The use of GPS information in the field needs to be encouraged, especially in view of the lack of reliable ancillary data for location information.

4. Low cost IRS satellite data is highly recommended in place of other high resolution satellite data.

5. The application of vegetation indices from NOAA AVHRR data may be more useful for parameter definitions in the hydrological modelling in view of its multi-temporal coverage.

6. The possibility of using multi temporal land use or cover data over different periods of the year needs to be explored.

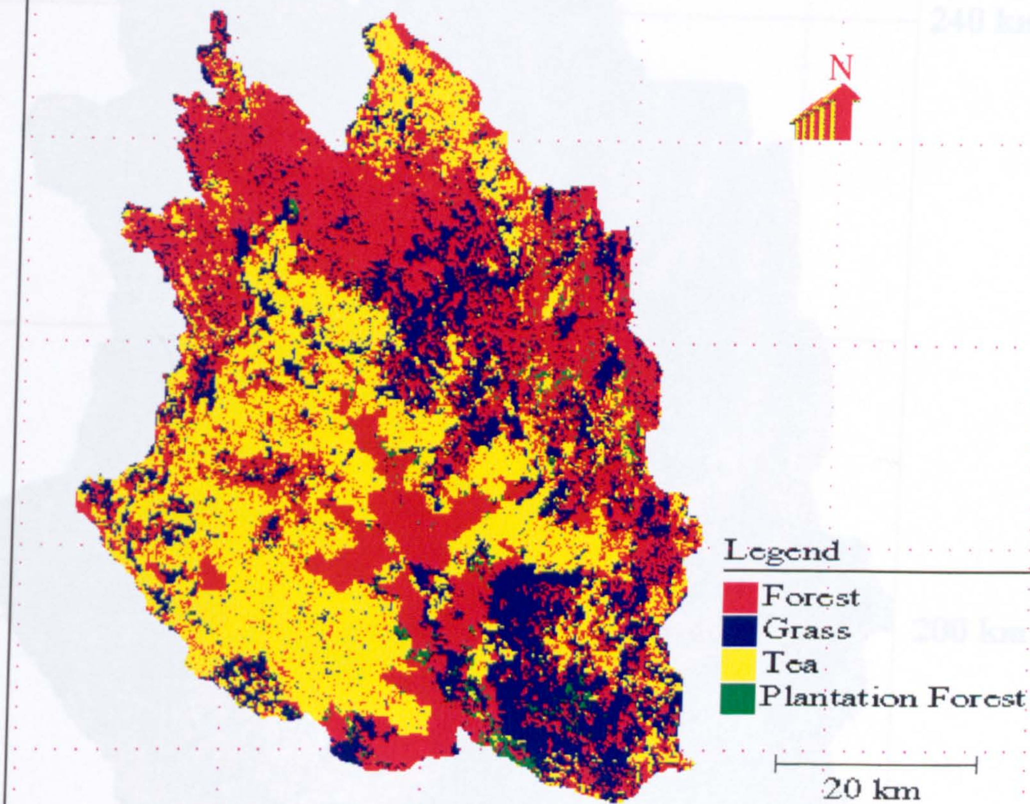


Plate 5.1 Reclassified Land Use Map of 1956

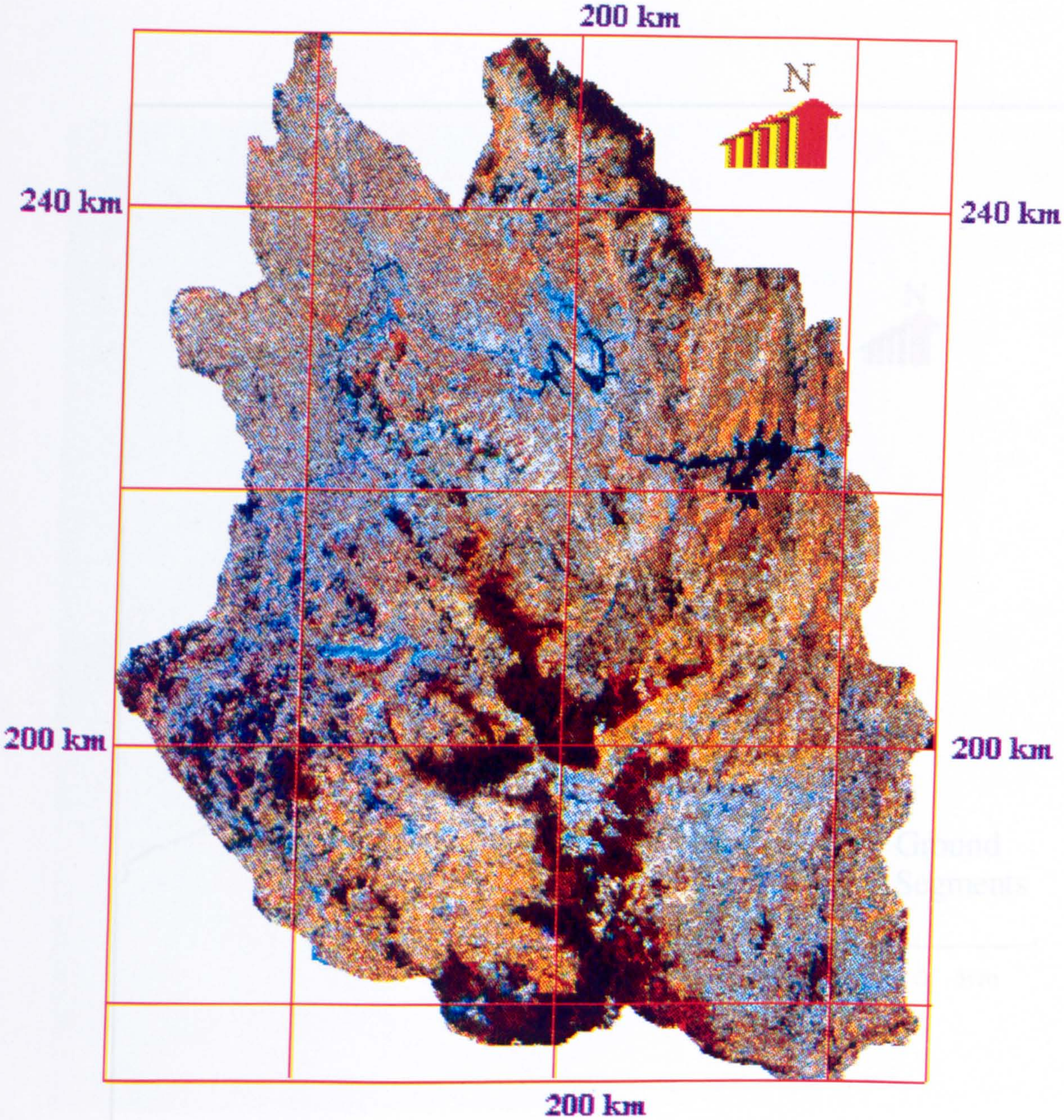


Plate 5.2 False Colour Composite (4,3,1) of UMCA

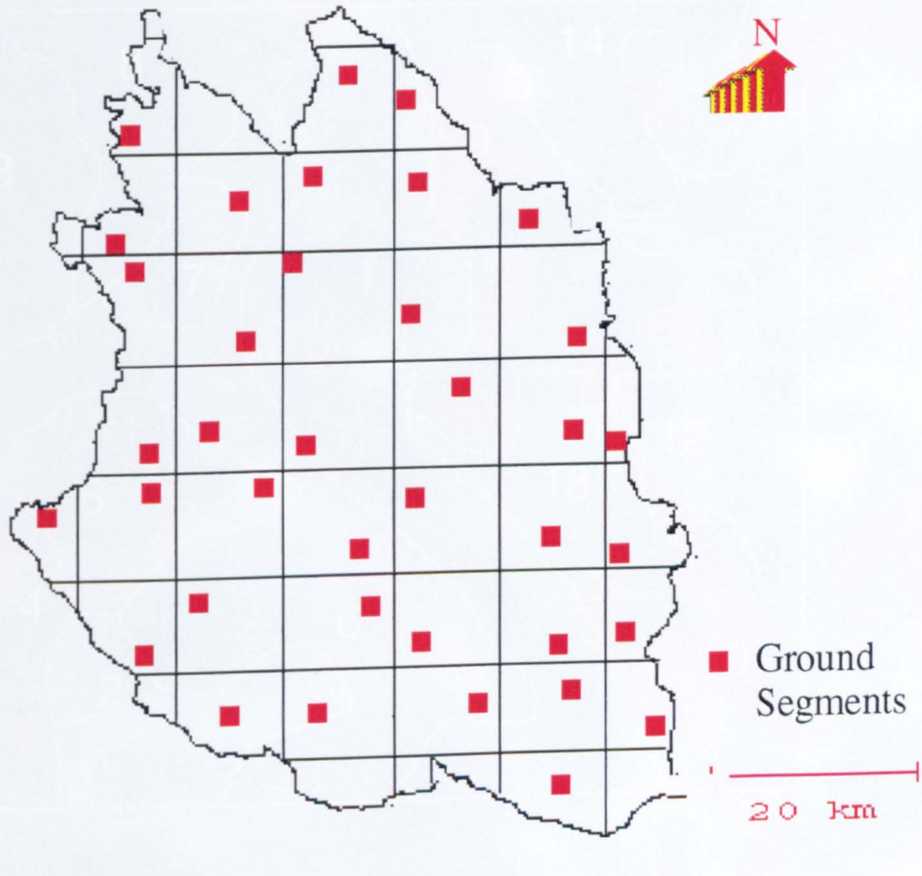
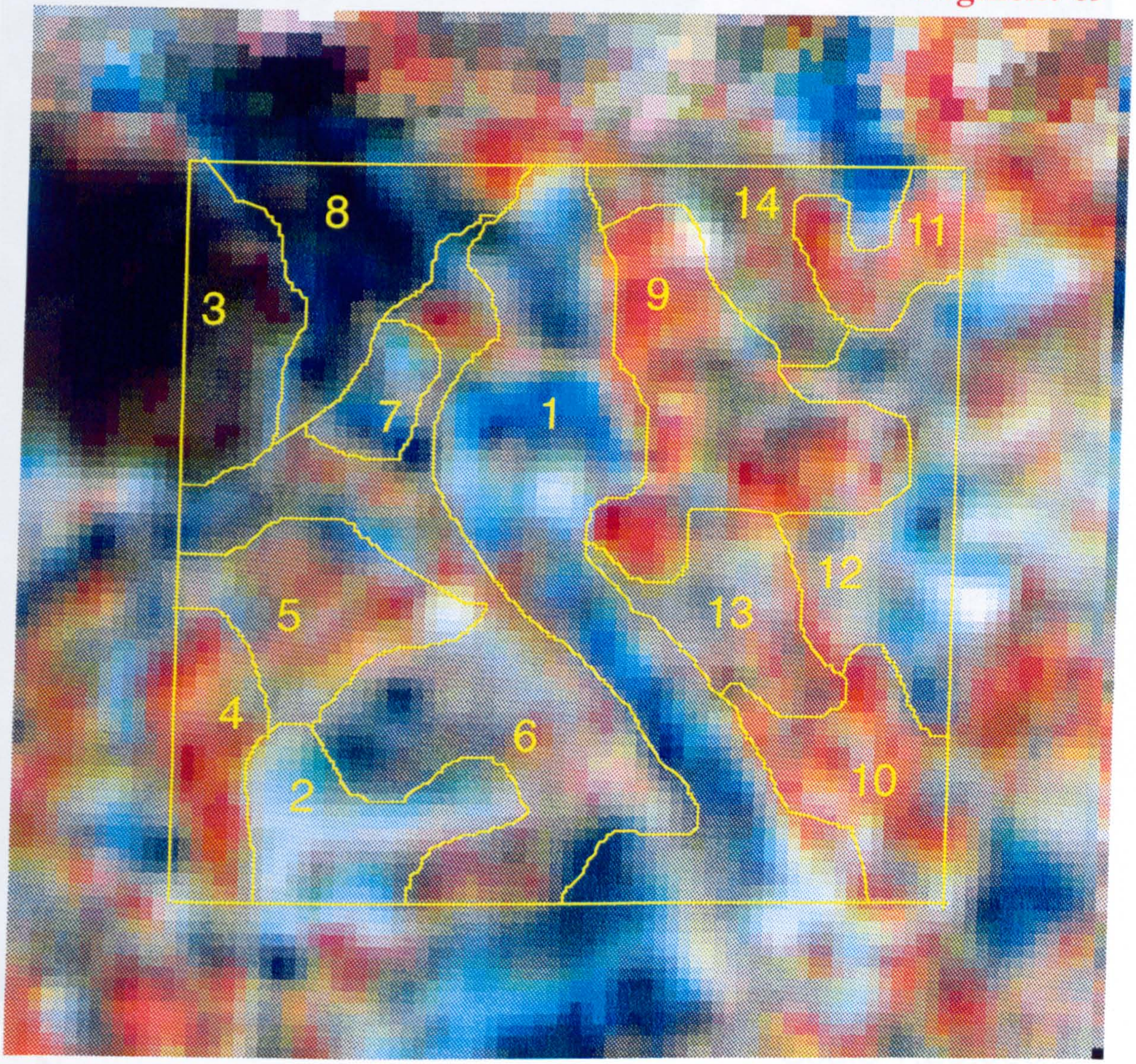


Plate 5.3 Location of Ground Segments

Segment 09



N

Scale 1:10,000

Plate 5.4 A Typical Ground Segment (1 km x 1 km) Used for Field Data Collection

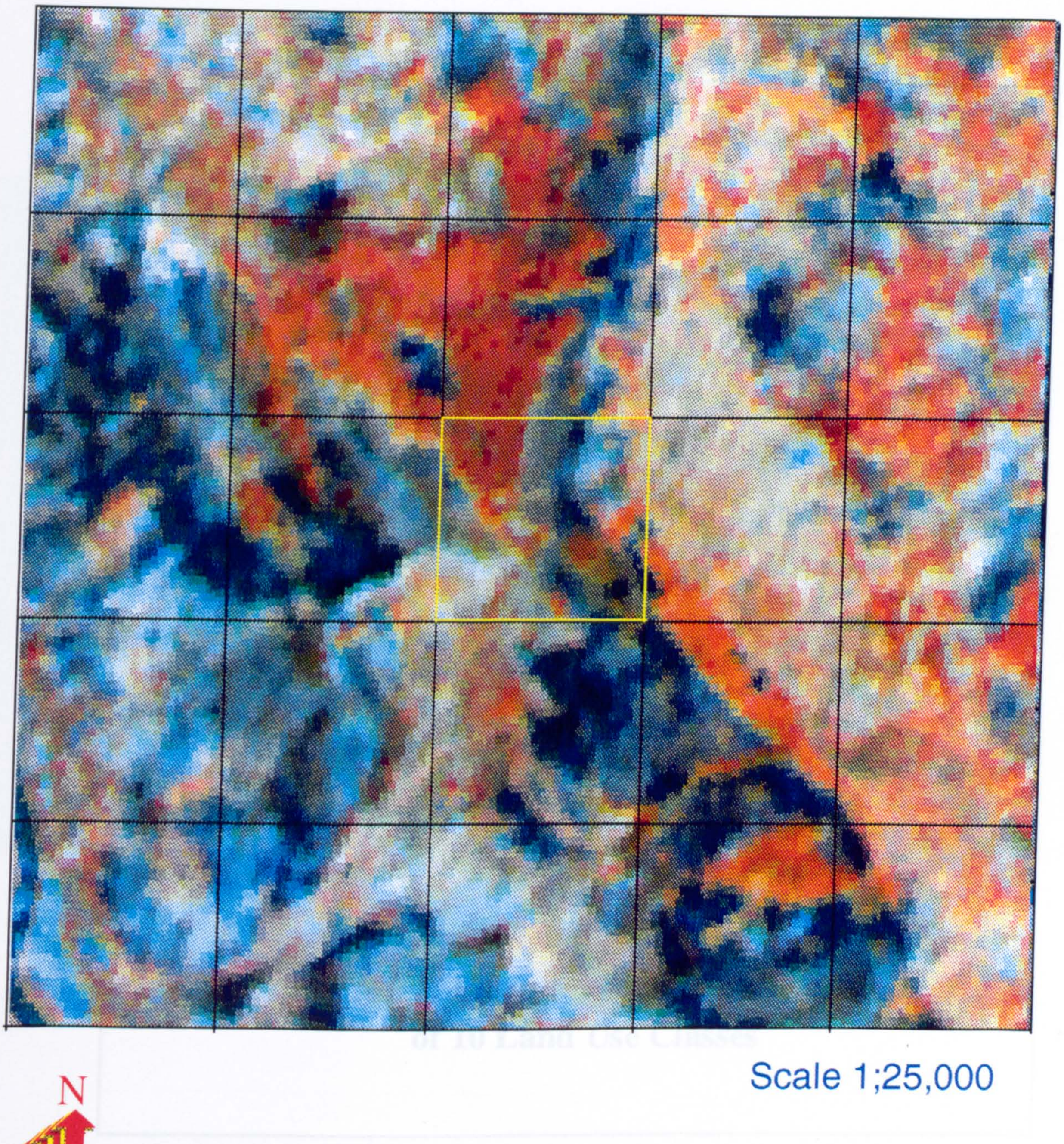


Plate 5.5 An Extract of FCC (4,3,1) of 5 km x 5 km Used for Field Navigation

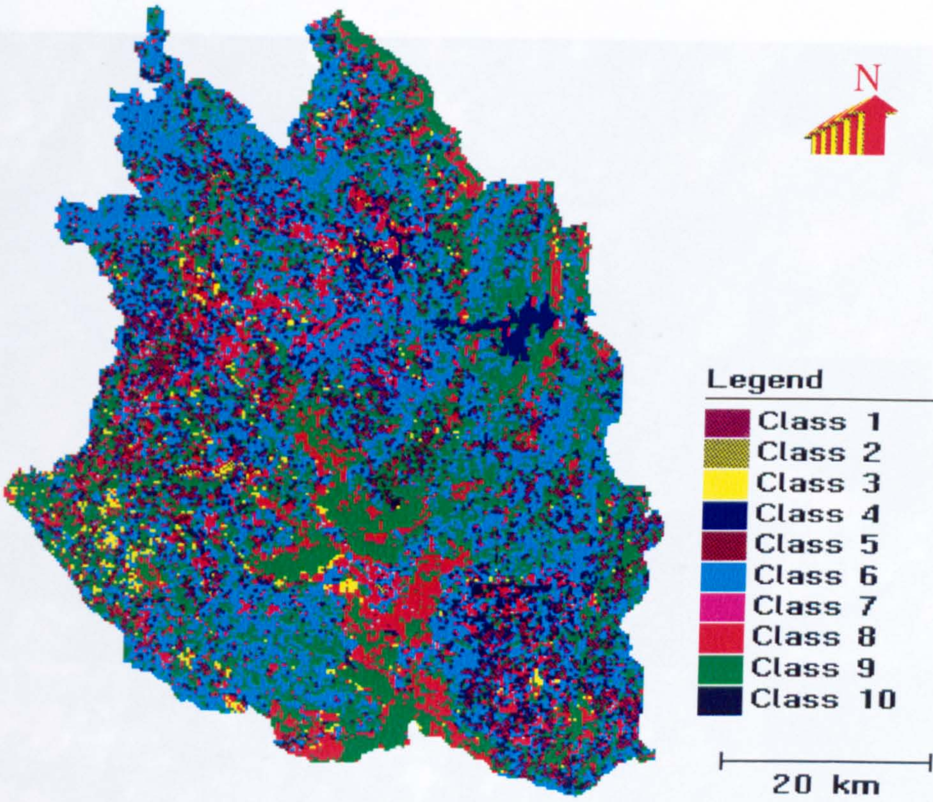


Plate 5.6 Unsupervised Classfication of 10 Land Use Classes

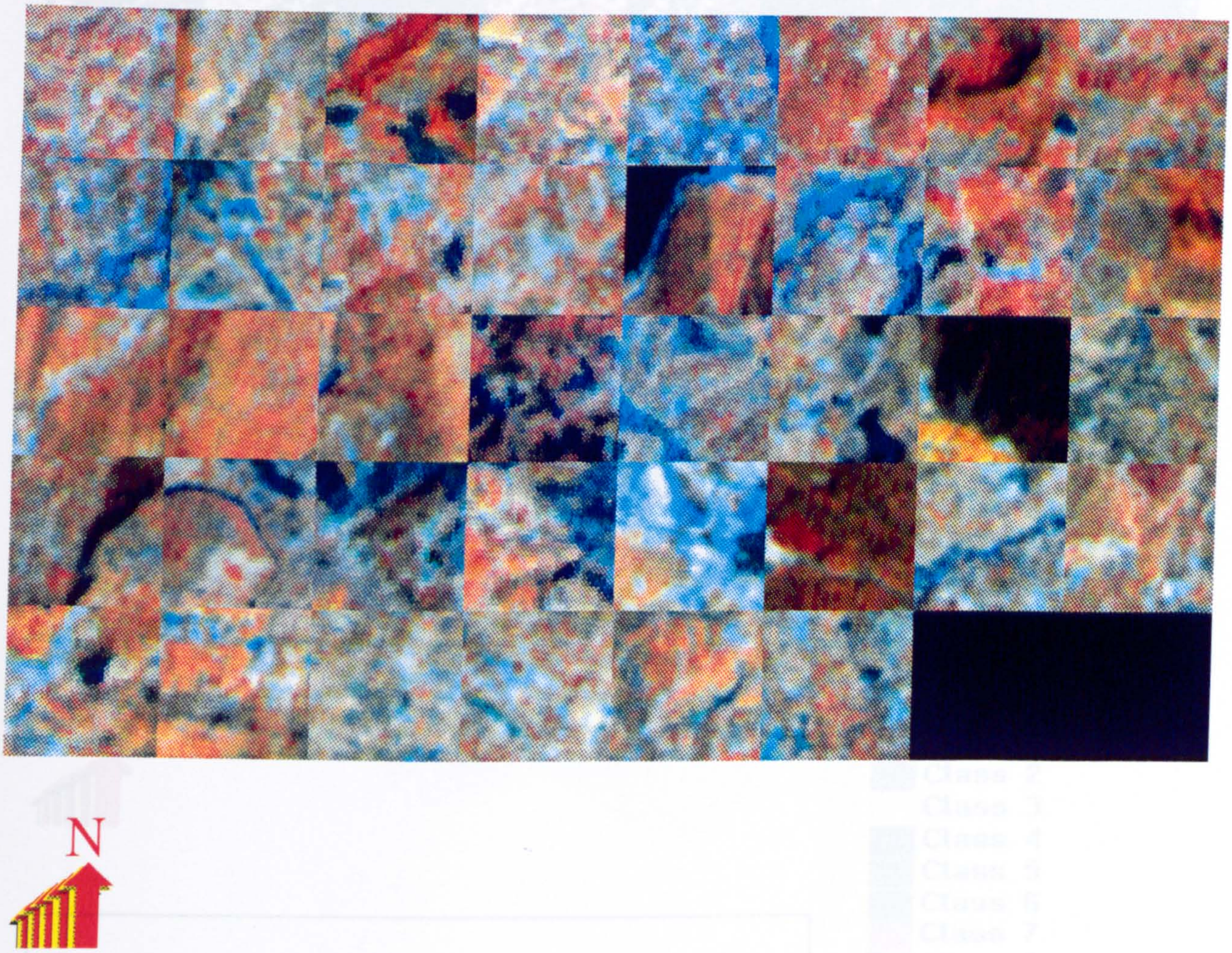
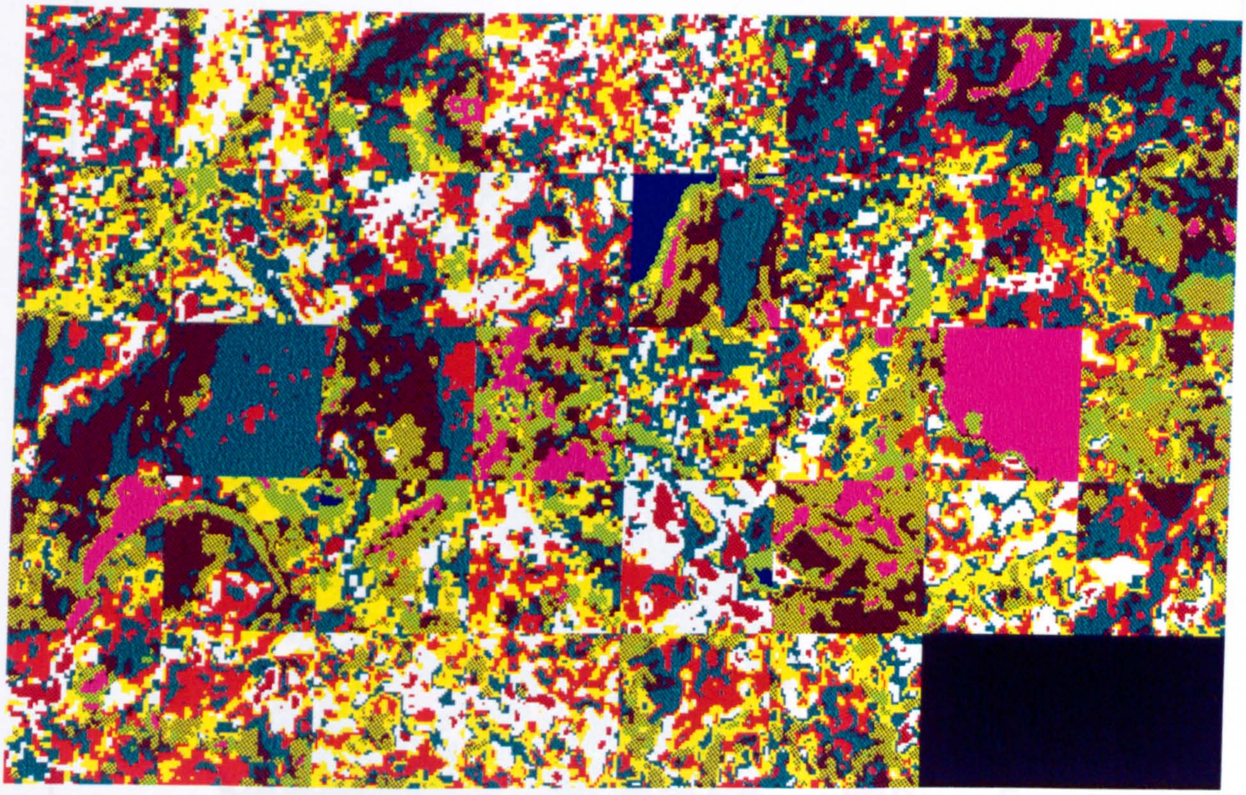


Plate 5.7 Quilted Image of FCC (4,3,1) with 38 Ground Segments



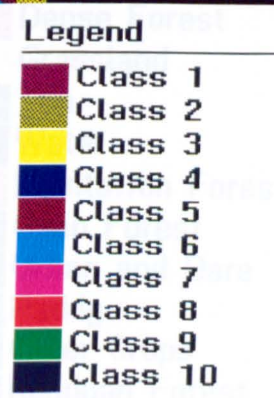


Plate 5.8 Quilted Image of Unsupervised Classfication

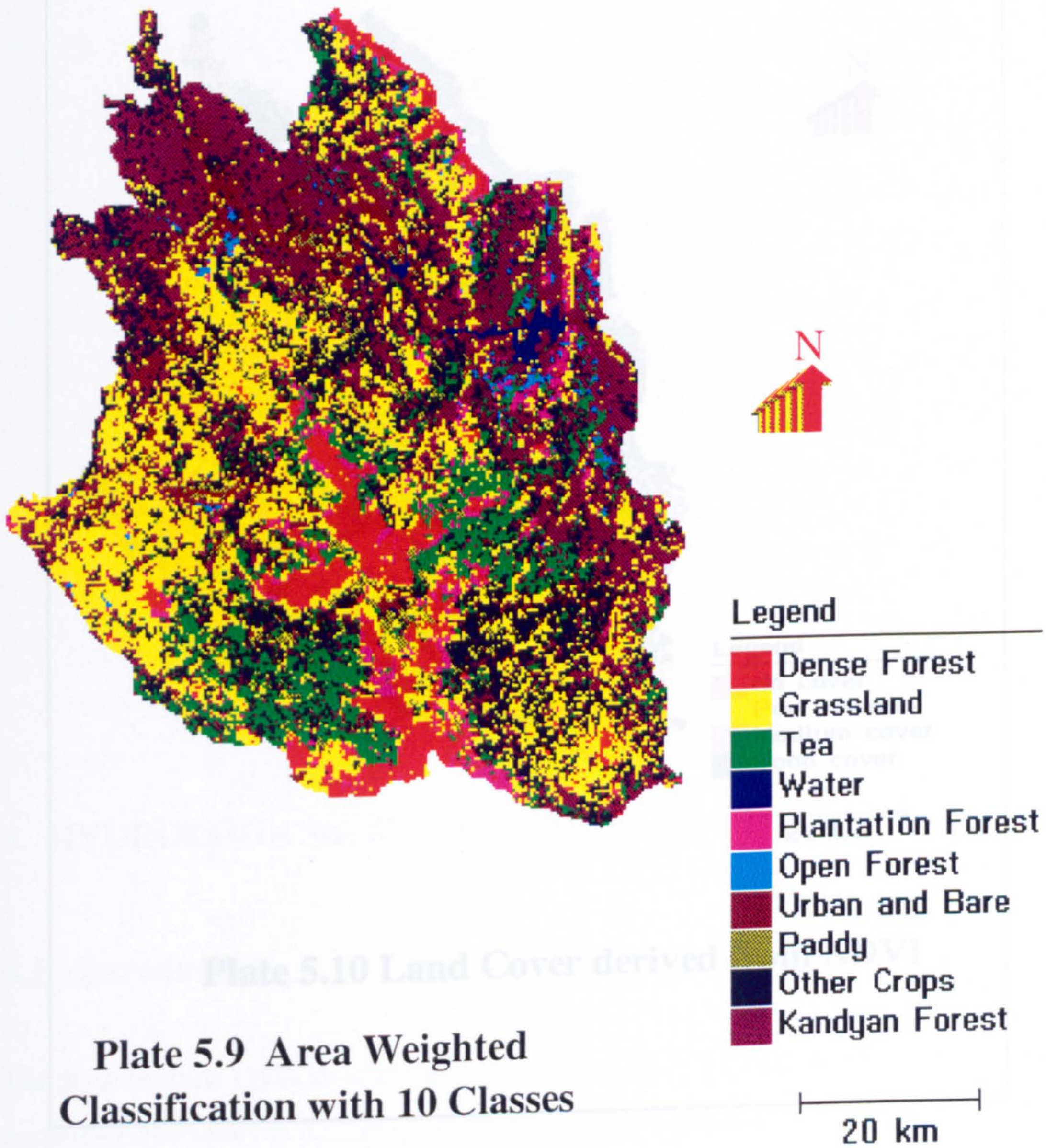


Plate 5.9 Area Weighted Classification with 10 Classes

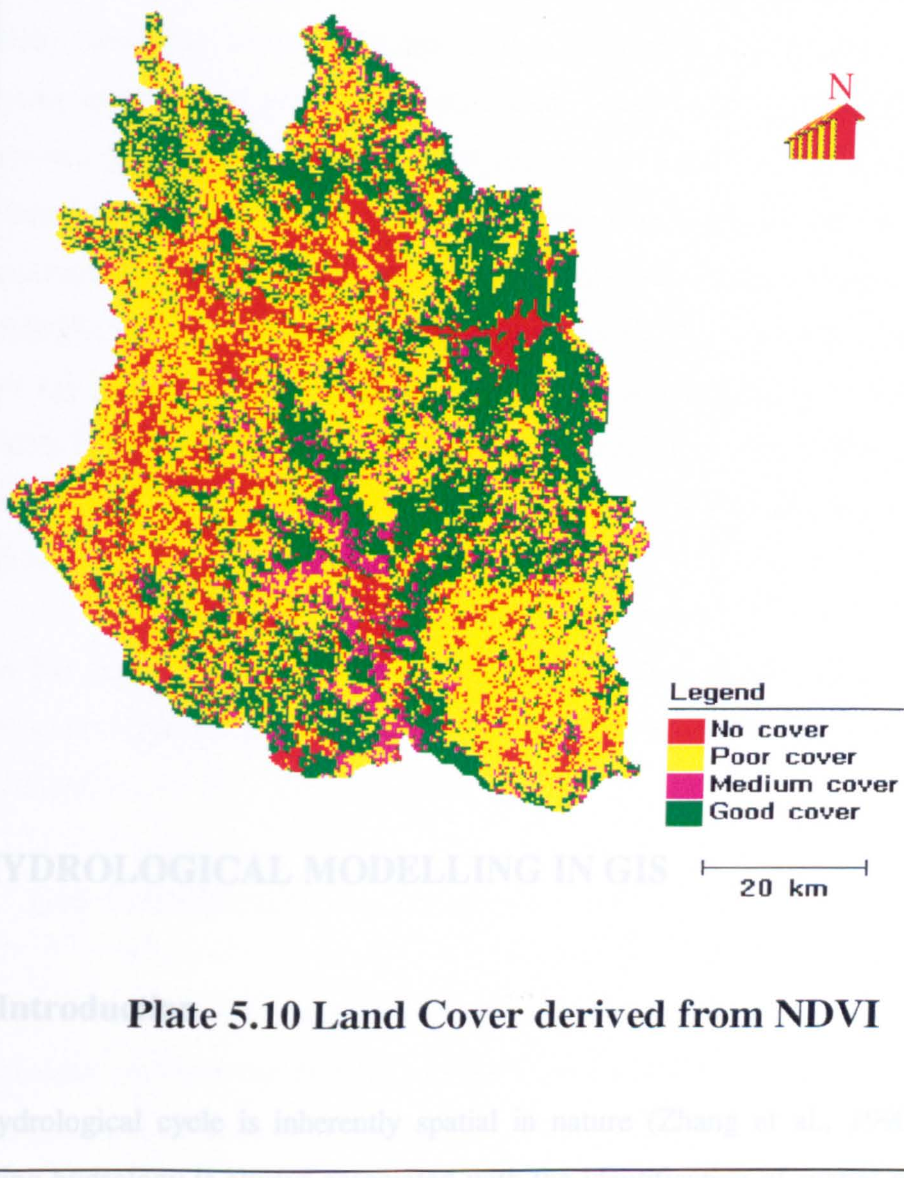


Plate 5.10 Land Cover derived from NDVI

Chapter 6

6. HYDROLOGICAL MODELLING IN GIS

6.1 Introduction

The hydrological cycle is inherently spatial in nature (Zhang et al., 1990). Hence, modelling hydrology is always associated with the identification of spatial relationships (Gardener et al., 1989) and spatial representation of hydrological parameters (Maidment, 1993). Despite the importance of spatial relationships and distribution, the spatial characteristics of land such as land use, soil, topography are often lumped into average parameters representative of the entire watershed (Gardener et al., 1989).

Distributed parameter hydrological models attempt to quantify the spatial variability of hydrologically important parameters and facilitate the analysis of rainfall and runoff processes at any desired location of the watershed. However, these models demand great quantities of input data with exact geographical references for location. Distributed hydrological modelling efforts are generally hampered by the limitations of the available data and processing facilities for the model inputs (Johnson, 1989). Recently developed methods for digital data capture, image processing, interactive computer graphics and geographical information system software provide the tools to incorporate greater spatial and temporal details into rainfall runoff models. Further, distributed hydrological models are inherently map based and provide a productive area for application of GIS techniques (Johnson, 1989) in the domain of digital cartography. Accordingly, it is understood that the integration of GIS with hydrological modelling plays a key role in designing, calibrating, modifying and comparing hydrological model structures (Zhang et al., 1990). However, it is noted that a successful application of GIS technology in hydrological modelling requires careful planning and extensive data manipulation.

Within this conceptual background, this chapter deals with the efforts made in the process of developing a temporally and spatially distributed hydrological model in a GIS environment.

6.1.1 GIS Functionality - A Summary

Geographical information is becoming increasingly important in nature conservation and environmental management as pressures grow on natural resources and with greater concern for sustainable use of resources. Further, geographic information is also becoming more easily managed and used with the advent of GIS (Aspinall, 1995).

A number of definitions of what exactly GIS is, have been proffered (Schoolmaster & Marr, 1992; Star & Ester, 1990; Zhang et al., 1990; Arnoff, 1989; Parker, 1988, Tomilson, 1987; Burrough, 1986). The most widely used definition of GIS is technological. However, in essence, GIS can be viewed as an enhanced information system that aids decision making by referencing data to spatial or geographic co-ordinates.

A GIS consists of a set of computer tools for collection, storing, retrieving, transforming, and displaying spatial data about geographical objects and non spatial attributes of these objects (Burrough, 1986). The strength of GIS lies in its capability of comprising means of encoding and converting geographically or spatially referenced data, a variety of methods for manipulating, overlaying, sorting the data stored in the database and the capacity of retrieving and displaying the information through a variety of media (Zhang et al., 1990).

6.1.2 Modelling Capabilities of GIS

In conceptual terms, GIS seems well suited to address modelling issues that require large, complex databases and are associated with dynamic environments including multi-scale processes, and heterogeneous landscape domains (Maidment, 1993). GIS can also help address data integration issues associated with multi-scale data from ground based and remote sensing sources. GIS could potentially support exploratory analysis of complex spatial patterns and environmental processes. GIS also provides an opportunity for innovative thematic mapping and error analysis, compatible with the required spatial resolutions.

The ease of data access and the ability to develop flexible methods for quantification of spatial attributes over discrete areas make GIS an integral tool for modelling (Battaglin et al., 1993). GIS serves as a link between data and models simplifying the often tedious process of model parameterisation thus enabling the modeller to investigate questions of scale of data for modelling results (Leavesley & Stannard, 1990).

6.1.3 Basic Components of GIS

Geographical information systems have three main components namely; computer hardware, application software modules and a proper organisational context (Burrough, 1986).

Three types of computer platforms are used to run GIS software. In chronological order of development, they include mainframes, personal micro computers (PCs) and recently, workstations (Tsihrintzis et al., 1996). Data capture and drafting devices including digitising tables, raster scanners, desk plotters to flatbed, optical hard drafting devices, disk and tape storage units and Visual Display Units (VDU) are also included in GIS hardware (Carrara, 1992).

The hardware for this study includes a PC with Pentium processor, 32 Mb RAM and 2 Gb twin hard disks and a 16 inch colour display, a high resolution raster scanner, an A0 size digitising table and a Tektronix thermal wax colour printer.

Since the first GIS software was developed in Canada (Tomlinson, 1987), more than 120 different GIS software systems have been developed and are in existence (Tsihrintzis et al., 1996). Irrespective of the types of software, the main modules for a GIS are considered to be data input & verification, data storage & management, data processing & analysis, data output & display and GIS user interaction (Carrara, 1992). Some of the GIS software are run only on dedicated hardware while others are virtually machine independent.

In this study, the software used for hydrological modelling was mainly from SPANS GIS Ver. 5.3 (1993) and Ver. 5.4 (1995) running in Operating System 2 (OS/2) environment. SPANS GIS is a product of Canadian origin and managed by Intera Tydac Technologies Inc., Canada. GIS facilities available in ERDAS image processing system and IDRISI GIS operating in DOS environment were also used for data conversion and formatting.

In addition to the hardware and software components, a successful application of GIS requires the interaction between system components and skilled users (Burrough, 1986).

6.2 Overview of Hydrological Modelling in GIS

Geographic information has been used in hydrologic modelling for many years (Tarboton, 1992) although the conceptual development of application strategies of GIS for hydrological modelling is relatively new. In view of the hydrological modelling, it is noted that prediction of surface runoff is one of the most useful hydrological capabilities of a GIS system (De Vantier & Feldman, 1993). The GIS based methods of estimating runoff tend to be advantageous if: study areas are large or numerous, runoff is modelled repetitively, alternative land use or cover scenarios are explored or if the data already comprise of an existing database (Stube & Johnson, 1990).

GIS and hydrological modelling are found to be complementary in most of the aspects. GIS applications could benefit from the modelling capabilities of hydrological models and hydrological models could benefit from the spatial analysis and display capabilities of GIS (Walsh, 1993). Combining these two results in more powerful tools for hydrological planning, assessment and management.

Maidment (1993) identified several levels of hydrological modelling in association with GIS namely; hydrological assessment, hydrological parameter determination, hydrological modelling inside GIS and linking GIS and hydrological models. According to Ross and Tara (1992), the role of GIS functionality in hydrological modelling is to perform complex map analysis and spatial analysis to derive data for hydrological models, provide a linkage mechanism between models with different spatial representations, convert digital landforms of different projections and scales to a standardised format (georeferencing) and post simulation graphics output display and spatial analysis for evaluating hydrological simulation results. GIS has proved to be enhancing the modelling efforts due to increased accuracy and minimisation of human error and time (Smith et al., 1992).

Interfacing GIS with sophisticated hydrological models (Zhang, 1990) is currently an active area of research. Interfacing processes can take place either within the GIS, as stand-alone interfacing programmes or as front-end processing which forms a part of the hydrological modelling system (Vassilous et al., 1996).

Smith & Brilly (1992) and Johnson (1989) have produced a comprehensive summary reviewing the hydrological modelling work related to GIS. Bitters et al. (1991) and Wu & Chen (1992) have discussed novel approaches for hydrological modelling in GIS.

It is evident in the literature that the use of hydrological modelling with GIS was mostly restricted to making GIS as input data provider and an output display and mapping device (Muzik, 1988; Vieux et al., 1988; White, 1988; Hill et al., 1987; Silfer et al., 1987). Though spatial statistical functions have been introduced to include comprehensive analytical capabilities, predictive and prescriptive modelling efforts are yet at the beginning (Batty & Xie, 1994). The modelling efforts described in this chapter were dedicated to make use of the available statistical and modelling capabilities within the GIS to demonstrate the potential of spatial and temporal scale hydrological modelling in a GIS environment.

6.2.1 Spatial Domain of GIS in Hydrological Modelling

Lumped hydrological models have been widely used to simulate the rainfall runoff process of a watershed since Sherman (1932) as quoted by Wang & Chen (1996) proposed the unit hydrograph concept. However, a major shortcoming of the lumped hydrological model is its disregard of the spatial variability of hydrological parameters and subsequently, the spatial distribution of the rainfall excess over the watershed (Wang & Chen, 1996).

Because of this limitation of lumped models, efforts have been made towards distributed parameter hydrological modelling (Jolley & Wheater, 1996; Wang & Chen, 1996; Van de Nes & Hendriks, 1971 as quoted by De Vantier & Feldman: 1993; Bravo et al., 1970 as quoted by De Vantier & Feldman: 1993; Ragan & Kosicki, 1993; Tarboton, 1992; Vieux & Westervelt, 1992; Boyd, 1978; Mein et al., 1974).

The spatial data management and analytical tools offered by GIS along with all the other functionality on a suitable software platform provide an excellent environment for distributed hydrological modelling. The integration of GIS with distributed parameter hydrological models plays an important role in designing, calibrating, modifying and comparing these models. Successful application of GIS technology in hydrological modelling requires careful planning and extensive data manipulation (Zhang et al., 1990). Three main tasks identified in most hydrological models are the spatial database construction, the integration of spatial model layers and the interfacing GIS and model.

Spatial data transformation capabilities of GIS are an important functionality for creating and managing a spatial hydrological database system. The work involves changes in the media from paper maps to digital encoding. Transformations are required for tabular data when represented graphically on a reference system. There are also modifications when vector geometry is transformed to grid cells and vice versa (Laurini & Thompson, 1992).

The spatial relational data model which is a spatial platform of data representation in GIS was extremely efficient in processing vast quantities of data on individual layer of information for hydrological modelling. However, the most crucial limits are the differences in the spatial data models and in the way spatial relationships are handled in GIS and in hydrological models (Maidment, 1993). Hence, attention must be focused on the representation of the spatial domain in GIS for hydrological modelling and it is a key area where considerable constraints hamper the efforts for the successful integration of GIS and hydrological modelling.

Delineation of hydrologically homogenous areas required for distributed parameter watershed modelling is one of the most common approaches of GIS in hydrological modelling due to its ability to extract, overlay and delineate land characteristics (Vieux et al., 1988). This is achieved by means of hydrologic response units (Stube & Johnson, 1990), grid based sampling (Jolley & Wheater, 1996; Johnson, 1989) or subcatchment delineation at different spatial resolutions (Jones & Nelson, 1992).

6.2.2 Concept of Time in GIS

Many hydrological analyses are time varying and mostly so for surface water flow. Maidment (1993) emphasised that GIS really does not lend itself to time-varying studies because there is no explicit representation of time in GIS data structures. Hence, it is not possible to readily model the evolution through time of spatial variations in a phenomenon with GIS and such variations are often needed in hydrology.

GIS were not originally envisioned as a time series database tool (De Vantier & Feldman, 1993). Hence, they are not optimally suited for handling time varying data. Although recent hydrological modelling efforts have reinforced the emphasis on temporal dynamics (Spence et al., 1995; Putman, 1992; Calkins, 1984), in most of the studies, the role of GIS was to perform the spatial data referencing and analytical functions while the traditional hydrologic codes performed the time dependent hydrological simulations (Ross & Tara, 1993). In order to realise the full potential of GIS in hydrological modelling, it requires a 3-D GIS with seamless integration of the time dimension.

The continuous development of a conceptual framework for spatiotemporal modelling confirms that the goal of fully functional temporal GIS is close to realisation. Reviewing the research trends towards a temporal GIS, Langran (1993) defined five technical requirements for the development of a temporal GIS namely; a conceptual model of spatial change, treatment methodology for non-spatial attributes, data processing logistics, a spatiotemporal data access method and efficient algorithm to operate on the spatiotemporal data.

However, it was found that provisions are made within the existing GIS software for time varying modelling facilities at discrete temporal resolutions through iterative procedures. The time dimension could be implicitly incorporated into the existing GIS modelling algorithm in order to employ time variant modelling while maintaining the spatial distribution parameters intact. Such methodology should be developed after giving careful consideration to the time variant parameters in the model. In this attempt, attention should be focused on the limitations of data representation within the software architecture. The characteristics of the software platform such as format of data representation in the software (vector or raster), data storage and retrieval mechanisms, data base structure, operating environment as the key factors contributing for the nature of temporal coverage in GIS. Nevertheless, it is noted that there is no universal solution for temporal modelling in existing GIS.

6.2.3 Software Platform and Characteristics

At the beginning of the study, an extensive search was carried out to compare the relative advantages and the processing capabilities offered by different commercially available GIS software in terms of spatiotemporal hydrological modelling. It was envisaged that the UMCA hydrological model required large quantities of data derived from different map layers and attribute tables. In view of this, a GIS based on raster data format was found to be more storage efficient than that of a vector based GIS (Zhang et al., 1990). According to Stube & Johnson (1990), this was the reason for the first application of GIS in hydrological modelling using grid cell or raster storage of information. Further, processing speed of a raster based GIS is higher than that of a vector based system (Zhang et al., 1990) and this also played a determinant role due to extensive spatial processing required for the daily resolution of the UMCA temporal hydrological model.

Furthermore, the classification results of image processing were a major source of information for parameter determination in the hydrological model. Direct and composite integration facilities of raster GIS with the remotely sensed data (Hinton, 1996) placed added benefits to establish raster based software selection ahead of a vector based system.

Accordingly, the raster based SPANS GIS was the best choice. In addition to the benefits gained from raster data structure, the unique quad tree design of SPANS GIS offers efficient storage avoiding data redundancy. The quadtree hierarchical data structuring based on tessellated discretisation of space recognises variable spatial resolution, and provides a basis for efficient spatial access and referencing (Laurini & Thompson, 1992).

Based on the six basic generic forms defined by Goodchild (1987) for a comprehensive GIS with spatial analysis and modelling tools, Openshaw (1996) concluded that no current products come close to the ideal GIS. In SPANS, however, there is a rudimentary framework which allows a range of spatial analysis encoding functions to be built in.

6.3 Data Representation in GIS

6.3.1 Rain Gauging Locations

Khun & Parker (1992) suggested that actual estimation of the spatial distribution of precipitation in mountainous areas was critically important in calibrating distributed parameter hydrological models. In order to have a more realistic rainfall coverage for modelling, it was decided to obtain data from all the available stations in UMCA as detailed in chapter 2.

6.3.2 Precipitation Data Formats

The GIS software, SPANS required precipitation data to be in an ASCII file (.TBA) so that these files could be directly imported to binary format (.TBB) recognised by SPANS algorithms. The location of the rain gauges was obtained from the GPS data as described in Chapter 2. The rainfall data files were prepared in such a way that each file contains daily data in each column for a particular month and for all the gauging stations recorded in each row. There were 360 individual data files to cover the 30 year period. All the data files were converted to binary files (.TBB) using SPANS GIS table conversion utilities.

6.3.3 Rainfall Interpolation Functions

Conversion of discrete point data a into spatially continuous data format has long been investigated (Whitten, 1975; Davis, 1973). The use of different interpolation techniques to generate a spatial rainfall surface has been attempted by Tarboton (1991). If only point rainfall data are available at sites of rain gauges, it is a standard hydrological procedure to determine the area assignment associated with each gauge (Johnson, 1989). The selection of interpolation method needs to be carried out considering the type of data, density of control points and scope of the application (Carrara, 1986).

In view of the hydrological modelling in SPANS GIS, spatial interpolation was mandatory on the point estimates. However, in general, there is no correlation of rainfall with elevation or inter-station distance as a whole for the UMCA according to the results of the rainfall regime analysis discussed in Chapter 2.

However, the analysis of rainfall cross correlation between adjacent stations as described in chapter 2 showed high correlation which justifies linear interpolation locally. The spatial correlation coefficients found in adjacent stations were always above 0.7 on the monthly scale and above 0.4 on the daily scale.

6.3.4 Thiessen Polygon Based Interpolation

Proximal interpolation in the form of Thiessen polygons is the simplest and quickest point oriented interpolation technique offered by SPANS GIS. In this method, the catchment area is divided into polygons by lines that are equidistant between pairs of adjacent stations. It assumes that each gauge is representative of its portion of the catchment. The advantage is that it takes account of gauge distribution and does not require rainfall data. Thus, the spatial shape of areas stays the same for the entire set of time series data.

The high rain gauging density and high spatial correlation found in the monthly and daily rainfall time series of adjacent stations in UMCA provided a reasonably accurate interpolation background for spatial rainfall distribution based on Thiessen polygons. However, it does not yield a smooth variation in spatial rainfall due to its approach of drawing up abrupt boundaries to delineate uniform areas. The configuration of the Thiessen polygon map for gauging locations of UMCA is shown in Plate 6.1.

6.3.5 Surface Interpolation

SPANS functionality includes surface interpolation techniques commonly known as contouring in its data transformation utility. The process of contour interpolation involves in forming a Triangulated Irregular Network (TIN). TIN is a patchwork of triangles produced from a collection of irregularly spaced points and connected by lines

(De Vantier & Feldman, 1993). TINs have become a common tool for computer modelling of terrain features and surface mapping using GIS (Jones & Nelson, 1992). In this method, the TIN structure was constrained to pass through the daily data of gauging locations.

The TIN was constructed with the vertices at the rain gauging locations using the rainfall values at the gauges to describe the surface value. The rainfall for each quad cell was then linearly interpolated within the triangle. In this process, the contour interval and the number of discrete classes generated was controlled via a pre-defined classification scheme. The contour conversion algorithm also allows the option of generating a new classification scheme depending on the quantiles defined interactively by the user. The nature of contour surface developed by the algorithm was totally dependent on the thresholds of the classification scheme. Thus, two classification schemes were designed and introduced for months of monsoons and inter-monsoons separately because the rainfall values of these two periods are obviously different.

There are two basic methods available for surface interpolation in SPANS data transform utility, namely linear and non-linear interpolation. Both methods were attempted in order to derive comparable results.

Linear interpolation was made to occur within each triangle of the TIN structure resulting in triangular flat planes. The advantage of linear interpolation is that the values of the interpolated surface were bounded by the minimum and maximum values of the anchor points of each triangle which represents the actual daily observations. However, the disadvantage lies on the interpolated surface being not continuous (see Plate 6.2) and thus suggesting that the agreement of the interpolation with the actual distribution is very remote.

In contrast, non-linear interpolation occurs along a surface fitted through a neighbouring triangle of TIN resulting in a smooth continuous surface. The disadvantage being the interpolated values are not necessarily bounded by the values at the triangle (SPANS GIS User Manuals; Ver. 5.3, 1993) and hence, it can give totally unrealistic values even for the gauging locations at the triangle where the measured values are available. The typical examples of surface interpolation including both linear and non-linear options for a set of daily data are shown in Plate 6.2 and 6.3 respectively.

6.3.6 Potential Mapping

Potential mapping allows interpolation to be made in such a way that the interpolation surface represents the best fit plane for the given set of data. In this approach, the derived surface is not constrained to pass through the data points. The potential mapping algorithm also makes provisions to define statistical functions for interpolation. Further, each point location could be assigned a relative weighting factor which may reflect the degree of reliability of the point data set.

In the correlation analysis discussed in chapter 2, the existence of high daily and monthly correlation was established between pairs of rain gauges located even at a distance of 10 km.. Accordingly, in the potential mapping, the allowable interpolation radius was chosen to be 10 km.. The thresholding of interpolation radius led to have non-interpolated regions in the North and North Western parts of the UMCA due to poor representation of gauging locations in that region. The results of the potential mapping illustration is shown in Plate 6.4. For the Plates 6.2 through 6.4, a seasonal data set was used to clearly illustrate the effects of interpolation method.

6.3.7 Selection of Rainfall Interpolation Methods

The approach based on interpolation algorithms for rainfall data representation in GIS is summarised in Figure 6.1. According to the discussion made in the preceding sections, each method has its own strengths and weaknesses. However, all the four methods have an advantage in common that they can be directly incorporated into the modelling framework with a very little adjustments. The comparison of the numerical results of these methods in terms of deviations from the mean interpolated values and variability is discussed in chapter 7.

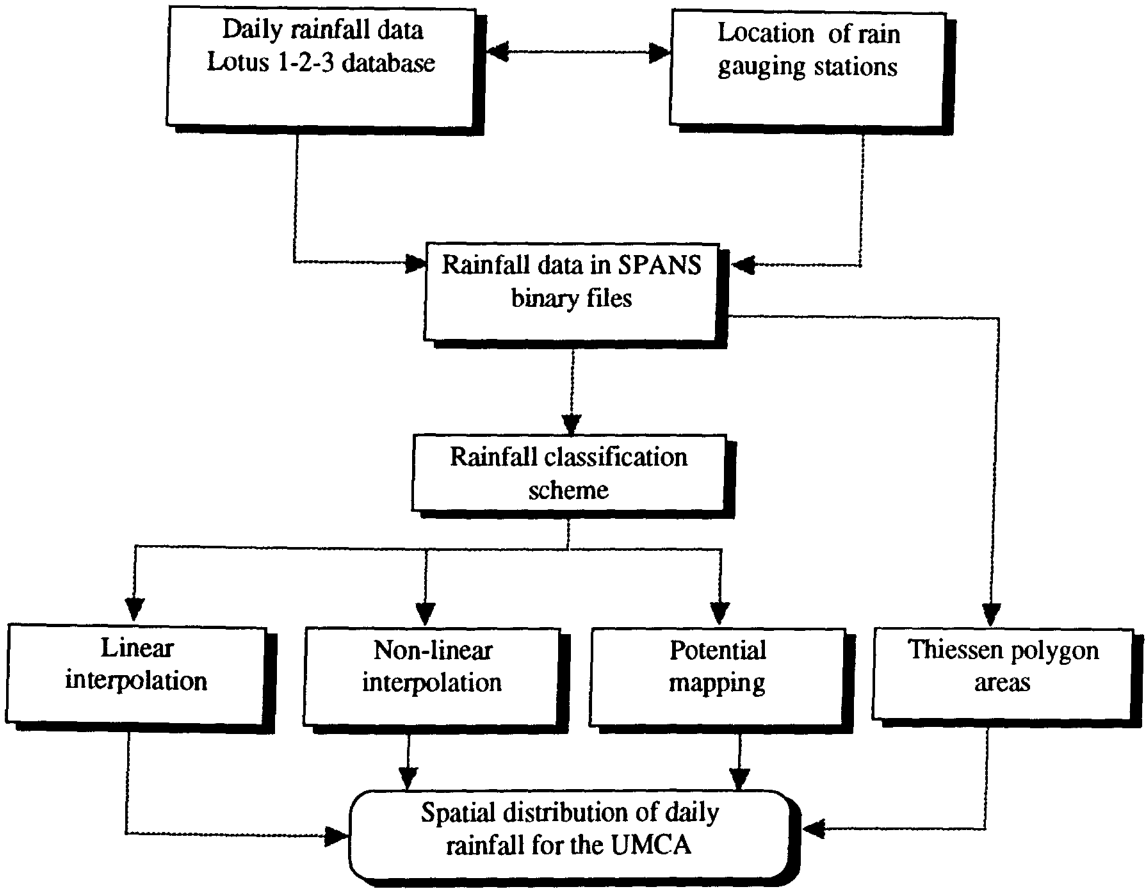


Figure 6.1 Rainfall Interpolation Process in SPANS GIS

Thiessen polygon method does not change its boundaries according to rainfall data. Hence, it is computationally efficient compared to other three methods discussed in the preceding sections because all the other methods require interpolation algorithm to produce the rainfall surface for each set of daily data for the entire length of modelling. Because of this advantage, Thiessen polygon method was adopted for the initial modelling task described in subsequent sections. The numerical results of these methods in terms of the variability and the deviations from the mean interpolated values are compared and assessed in chapter 7.

6.3.8 Evaporation Data and Distribution

Evaporation data analysis in Chapter 4 indicated that the spatial variation of evaporation in UMCA was less significant compared to the temporal variations within a year. Further, the number of evaporation gauging stations was not sufficient to attempt any meaningful approach of interpolation. Furthermore, the actual evapotranspiration was determined by the land use and soil moisture status and these parameters were well segregated spatially in the model. Accordingly, the decision was made to rely on a single open water evaporation value (1408 mm) for the entire UMCA. However, this value was temporally divided into average monthly rates depending on the recorded evaporation demand as discussed in chapter 4.

6.3.9 Land Use and Associated Data Definitions

The potential for using digital remotely sensed data as a primary source of information for GIS has received considerable attention in recent years (Hinton, 1996; Wilkinson, 1996; De Vantier & Feldman, 1993). An effective integration of remote sensing and GIS tools can decrease the costs of gathering resource information, reduce the time required to capture and process information and increase the details of the information (Green, 1992).

In this study, supervised classification of IRS LISS II imagery was the main information source for land use derived parameters. The NDVI based vegetative measurements for land cover was also tried out as an alternative.

As discussed in chapter 5, the ten broad land use categories identified in supervised classification were reclassified to four land uses for hydrological parameters covering the period after 1976. The historical land use information derived from a 1956 digital land use map (Plate 5.1) was used as the basis for model parameters from 1964 to 1976.

6.4 Quadtree Resolution

The coverage of UMCA in SPANS is 3124 sq. km.. The highest resolution of data available was for the land use from IRS imagery and it is around 40 m. The study area in SPANS was set up in such a way that at quad level 13, it supports the resolution of 32 m. However, it was noted that the time to run the model was increasing exponentially with the increasing quad level. Basically, it is not only impractical to run the model at 32 m quad level because of time constraints but also it is not justifiable because of the underlying accuracy of spatial representation of other data and the underlying simplifications in the model. Accordingly, it was decided to carry out trials at different quadtree resolutions and to choose a reasonable lower quad level for further model performance. The resolution for various quad levels are given in the Table 6.1.

Table 6.1 Quad Levels and Corresponding Ground Resolution

Quad Level	Data Resolution
5	8.28 km
7	2.07 km
9	518 m
11	129 m
13	32 m

6.4.1 Effect of Quadtree Resolution on Land Use Identity

The identification of four major classes of land use at different quadtree resolutions of the 1956 land use map were tried out within the extent of the derived quad level 13 catchment boundary. The results showing area coverage are tabulated in Table 6.2(a) through Table 6.2(d). In this analysis, quadtree resolution 5 was omitted because of its very coarse appearance in the output.

Table 6.2(a) Sensitivity of Quadtree Resolutions - Quad Level 07 (1956 Land Use)

Class Legend	Area %	Cumm %	Area (km^2)	Error %*
1	43.88	43.88	1370.79	+3.49
2	23.26	67.14	726.77	-11.19
3	32.59	99.73	1018.19	+10.78
4	0.27	100.00	8.32	-86.62
Class total	100.00		3124.08	39.05**

* Composite Error Percentage in comparison with Quad Level 13 map

** Area Weighted Root Mean Square (RMS) Error

Table 6.2(b) Sensitivity of Quadtree Resolutions - Quad Level 09 (1956 Land Use)

Class Legend	Area %	Cumm %	Area (km^2)	Error %*
1	42.31	42.31	1321.95	-0.188
2	24.09	66.41	752.69	-8.029
3	32.67	99.08	1020.77	+11.066
4	0.92	100.00	28.66	-53.92
Class Total	100.00		3124.08	33.25**

* Composite Error Percentage in comparison with Quad Level 13 map

** Area Weighted Root Mean Square (RMS) Error

Table 6.2(c) Sensitivity of Quadtree Resolutions - Quad Level 11 (1956 Land Use)

Class Legend	Area %	Cumm %	Area (km^2)	Error %*
1	41.89	41.89	1308.75	-1.184
2	25.31	67.20	790.68	-3.384
3	31.16	98.36	973.36	+5.908
4	1.64	100.00	51.29	-17.540
Class Total	100.00		3124.08	17.44**

* Composite Error Percentage in comparison with Quad Level 13 map

** Area Weighted Root Mean Square (RMS) Error

Table 6.2(d) Sensitivity of Quadtree Resolutions - Quad Level 13 (1956 Land)

Class Legend	Area %	Cumm %	Area (km^2)
1	42.39	42.39	1324.44
2	26.20	68.59	818.38
3	29.42	98.01	919.06
4	1.99	100.00	62.20
Class Total	100.00		3124.08

6.4.2 Effect of Quadtree Resolution on Subcatchment Coverage

Thirty-three subcatchments of the UMCA were delineated so that modelling results could be used to predict runoff at the outlet of each subcatchment. This is very useful for hydrologic and hydraulic designing of structures as stream flow records are not available at subcatchment level for the entire UMCA. The only available flow data were from subcatchments in Talawakele, Kotmale (Morape), Rantembe, Randenigala, Victoria, Peradeniya, Gampola, Welimada and Watawala.

Since the model predictions were intended to scale down to subcatchment level, the sensitivity of subcatchment boundary delineation was carried out at the selected quad levels. The Plate 6.5 shows the subcatchments at different quad resolutions. The results of the sensitivity analysis are summarised in Table 6.3.

Table 6.3 Sensitivity of Subcatchment Delineation for Quad Resolutions

Class	Quad 07		Quad 09		Quad 11		Quad 13
	Area (km2)	Error %*	Area (km2)	Error %*	Area (km2)	Error %*	Area (km2)
1	228.08	+5.84	215.74	+0.12	215.41	-0.04	*215.49*
2	167.84	+6.39	157.94	+0.11	157.67	-0.06	*157.76*
3	34.44	+6.40	32.56	+0.59	32.46	+0.28	*32.37*
4	123.13	-0.32	122.85	-0.55	123.60	+0.06	*123.53*
5	27.65	-18.12	33.72	-0.15	33.77	-0.00	*33.77*
6	175.10	+1.51	172.39	-0.06	172.46	-0.02	*172.50*
7	75.31	-0.34	75.67	+0.13	75.44	-0.17	*75.57*
8	4.31	+33.85	3.54	+9.94	3.19	-0.93	*3.22*
9	111.93	-7.07	118.66	-1.48	120.69	+0.21	*120.44*
10	70.63	+1.70	70.27	+1.18	69.28	-0.25	*69.45*
11	23.76	-14.90	27.82	-0.36	27.87	-0.18	*27.92*
12	26.73	+19.92	22.18	-0.49	22.21	-0.36	*22.29*
13	60.76	-7.98	65.97	-0.09	66.01	-0.03	*66.03*
14	176.51	+0.45	175.70	-0.01	175.70	-0.01	*175.72*
15	64.58	-3.40	67.27	+0.63	66.85	-0.00	*66.85*
16	77.49	+3.76	74.26	-0.56	74.67	-0.01	*74.68*
17	103.62	-0.28	103.67	-0.23	104.24	+0.32	*103.91*
18	34.44	-19.89	43.32	+0.77	43.03	+0.09	*42.99*
19	47.36	+11.96	41.98	-0.76	42.21	-0.21	*42.30*
20	30.14	-16.56	35.79	-0.91	36.09	-0.08	*36.12*
21	55.97	-8.22	61.35	+0.61	60.98	-0.00	*60.98*
22	159.29	+3.68	152.83	-0.52	153.67	+0.03	*153.63*
23	150.68	-1.59	153.37	+0.16	153.17	+0.03	*153.12*
24	73.19	-2.91	76.42	+1.38	75.34	-0.05	*75.38*
25	265.27	+1.73	261.71	+0.37	260.50	-0.10	*260.75*
26	64.58	+17.59	54.62	-0.55	54.82	-0.18	*54.92*
27	120.54	-0.45	120.27	-0.68	121.44	+0.29	*121.09*
28	107.63	-4.38	112.74	+0.16	112.56	-0.00	*112.56*
29	127.11	-0.28	127.01	-0.35	127.55	+0.07	*127.46*
30	47.36	-5.15	50.66	+1.46	49.91	-0.04	*49.93*
31	181.04	-0.82	182.55	+0.01	182.55	+0.01	*182.54*
32	68.88	-3.65	71.57	+0.11	71.49	-0.00	*71.49*
33	38.75	+3.80	37.67	+0.91	37.27	-0.16	*37.33*
Total	3124.08	2.76**	3124.08	0.31**	3124.08	0.07**	*3124.08*

* Composite Error Percentage in comparison with Quad Level 13 map

** Area Weighted Root Mean Square (RMS) Error

6.4.3 Selection of Quad Level

The selection of the best quad level was based on the accuracy of area representation (Table 6.2 and Table 6.3), storage requirements and computational time in terms of speed of map production and display (Table 6.4). Considering the assumptions made in the process of interpolation and the generalisation of land use for four major classes, the error of area representation even at quad level 07 is not outstanding. However, with increasing quad level, the requirements of data storage and computational time become a constraint for successful running of the model. Within this background, all the data analysis were carried out and the model predictions were based on the map coverage of quad level 07. The computational time given in Table 6.4 is for a PC with 100 MHz Pentium processor and may vary with the available hardware set-up.

Table 6.4 Comparison of Storage Requirement at Different Quad Levels

Quad Level	Land Use Map 1956 (bytes)	Sub Basin Map (bytes)	Computational Time (min/year)*
07	781	405	126
09	4,121	2,237	298
11	117,249	10,737	748
13	1,412,237	45,669	1780

* computational time is based on the Thiessen polygon interpolation for modelling and for running the model for a period of one year.

6.5 Assessment of Alternative Modelling Methods

The main issue involved in the modelling approach was to decide on the mechanism of integrating the hydrological model with GIS to derive the catchment response for different land use scenarios. Several different methodologies, developed using SPANS spatial analysis and modelling functionality were attempted before opting for the best approach.

6.5.1 Integrating Turbo C++ with SPANS

In this approach, the hydrological model was totally run in Turbo C++ under the DOS environment for each rain gauging station up to the desired run length to derive daily flow data series for each land use type. There was no spatial identification coupled with C programming. Hence, initially, SPANS GIS was used to measure the spatial limits of each land use in each of the Thiessen polygon areas. Whenever another point area interpolation technique was used spatial limits of each rainfall range were recalculated for each analysis.

A Lotus 1-2-3 database handled through the macro command language was the interface between C programme (see Appendix C) and SPANS GIS. The interface is capable of transferring the model output into SPANS GIS at regulated time intervals (monthly) so that model output can be visualised upon a spatial platform. The spatial referencing process was carried out through the centroids of each polygon, created upon the unique condition definition of all the available polygons. A summary of the SPANS GIS modelling process interfaced with C programme is shown in Figure 6.2.

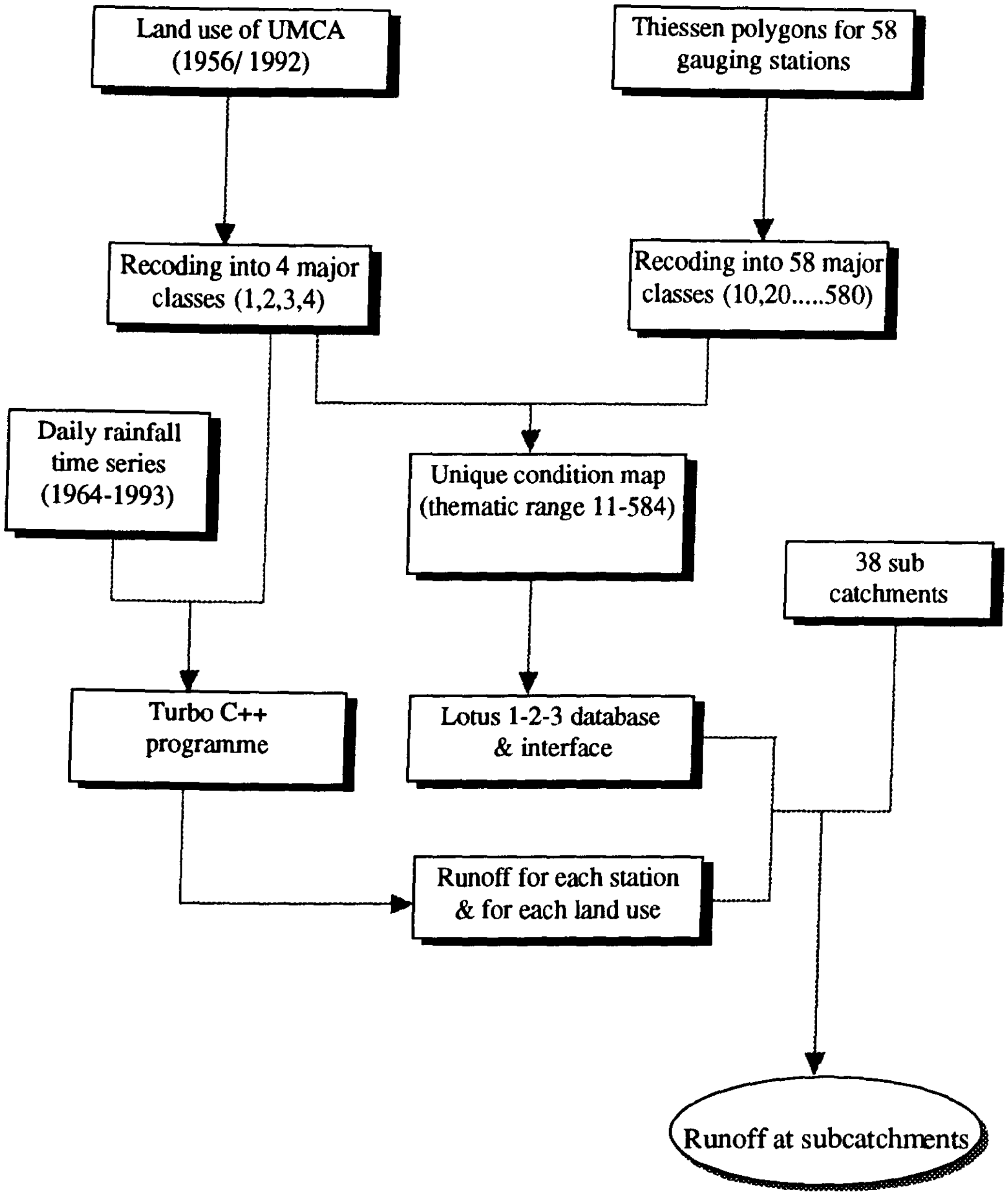


Figure 6.2 Methodology for SPANS GIS Interface with C++ Programming

The main advantage of this approach was that the methodology was simple and straightforward. The same methodology can be applied elsewhere with a different set of data and also for a different type of model. Interfacing was not a complicated task and the processes can be automated using macro language facilities in Lotus 1-2-3.

However, the strong SPANS GIS capabilities in general, and modelling facilities in particular, were totally ignored in this approach. The utility of SPANS GIS was restricted to simple analytical tasks and to provide a display and data transfer device. The cost incurred on SPANS GIS cannot be justified for such a utility. Moreover, a continuous spatial simulation model based on "what if ?" questions cannot be run successfully through the interface because of polygons being bounded to a single unique condition set up in spatial coverage and hence, it limits the scope of the modelling exercise.

The study area was characterised by small land parcels, heterogeneity and diversity of land use types which produced several land use polygons within each spatial rainfall unit. This led to produce a large number of sequences for spatial references within the Lotus 1-2-3 database. The number of unique polygons was theoretically equal to the number of gauging stations multiplied by the number of land use classes. The large number of centroids with complex polygonal structure and associated data increased the computer processing time considerably. This also made confusions in cross referencing geographical locations due to the lack of facilities for a complete automation of the interface.

6.5.2 Coupling REXX Procedures with SPANS GIS

SPANS GIS operates in the IBM OS/2 system environment. The OS/2 environment introduces an advanced programming language called REXX procedures. There is an explicit provision to run a time series model through REXX procedures in OS/2 environment. However, spatial referencing is lacking in this methodology. The modelling language is very straightforward and does not differ much from Turbo C++ except for the command key words. SPANS GIS was again used as the data provider and the display device. The advantages and disadvantages of this approach were similar to those discussed in section 6.5.1.. Further, interfacing was not a difficult operation as both REXX procedures and SPANS GIS run in OS/2 environment.

6.5.3 Spatial Modelling within SPANS GIS

In developing a spatiotemporal model completely within GIS, relationships required to be established among the hydrological parameters were carefully considered. It was also viewed in the light of possible future improvements required to be incorporated, in terms of spatially distributed information. The choice had to be made from four major types of modelling functionality offered by SPANS GIS namely table modelling, point modelling, aggregation modelling and map modelling.

6.5.4 Selection of modelling functionality

In selecting the modelling function in SPANS GIS, the main criteria was the capability of direct spatial data processing. Map aggregation performs statistical functions but is deprived of some basic functions for spatial analysis. Point modelling functions require all the polygons represented by grid centroids. Because of the large number of polygons found in thematic maps and the fact that this number varies with each modelling step, point modelling was also not seen as a viable option.

The fast processing capability and its ability to handle continuous variables as opposed to integers were the positive points scored by table modelling in the selection process. However, it was an inherent weakness in table modelling that the interactive table editing capability was not available. This led to accumulation of columns of data in the tables at the each step of the table modelling process resulting in a large volume of unwanted data in the system. Spatial segregation for different subcatchment resolutions was also a complex and tedious process in table modelling because it identifies only a point reference for each spatial unit. Further, table modelling functionality does not run the model on a real spatial scale. In comparison, map modelling scored the highest in most of the criteria used for the selection.

6.5.5 Introduction to Map Modelling

SPANS GIS map modelling provides the capability of linking spatially distributed numerical parameters with tabulated data and imported attribute data in binary form. Both spatially distributed and tabulated data can be run through various mathematical and statistical expressions to derive associated information. Accuracy of spatial data representation depends on the quad resolution selected for the analysis.

6.5.6 Map Modelling Functionality

The result of the map modelling is a thematic map. The generated map is displayed on the display device and stored in the system as well. The thematic details shown on the resultant map can be manipulated by means of a pre-defined classification scheme. All the mathematical computations are required to be combined in an equation file, using the SPANS GIS modelling language. In addition to SPANS menu driven commands for map modelling, command mode equivalent functions are also available and convenient to use for iterations. SPANS map modelling also provides an opportunity to change the model parameters interactively by the user while proceeding with the computations.

6.5.7 Data Input for Map Modelling

Daily rainfall data required a strict format to be able to be used in map modelling. The format of the binary file of rainfall data is shown in Appendix E-1(a).

The parameters for land use were also introduced into the modelling equation in a binary tabular format as shown in Appendix E-1(b). Map modelling equations read the tabular data and find the spatial reference for the parameters from the defined land use map. Whenever horizontal precipitation was required to be accounted for precipitation input, the corresponding elevations of the gauging locations were also procured from a table.

6.5.8 Model Structure for Map Modelling

A series of equations were formulated using map modelling language codes of SPANS GIS. Each sub model of the UMCA hydrological model, as described in chapter 4, was represented in a set of equations and additional equations were required to increment the file pointer along the columns of the data tables for daily rainfall.

In the case of Thiessen polygons, representative areas for each gauging station are directly identified from the morton numbers of the gauging locations. Morton numbers are hexa-decimal numbers used for spatial referencing in SPANS GIS. For a particular day, the hydrological model reads the relevant column of the rainfall data and calculate the fog interception according to the season. The total precipitation is then assigned to the corresponding Thiessen polygons. Based on sub models, it calculates the spatial distribution of interception and evaporation losses according to the hydrological parameters assigned for each land use. It also takes into account the spatial variation of antecedent moisture and the soil moisture stress. Finally, the model calculates the daily runoff and changes in soil moisture regime through the water balance equations and updates spatial coverage for cumulative runoff, soil moisture and cumulative interception and evaporation, stored in thematic maps. The updated map of soil moisture provides antecedent moisture status for the water balance calculations of the following day.

The entire model structure was setup to run on actual numerical values of each quad cell of thematic coverage. The equations used in the map modelling and a description of each modelling step are given in Appendix E-2. A generic representation of the spatial hydrological model structure is shown in Figure 6.3.

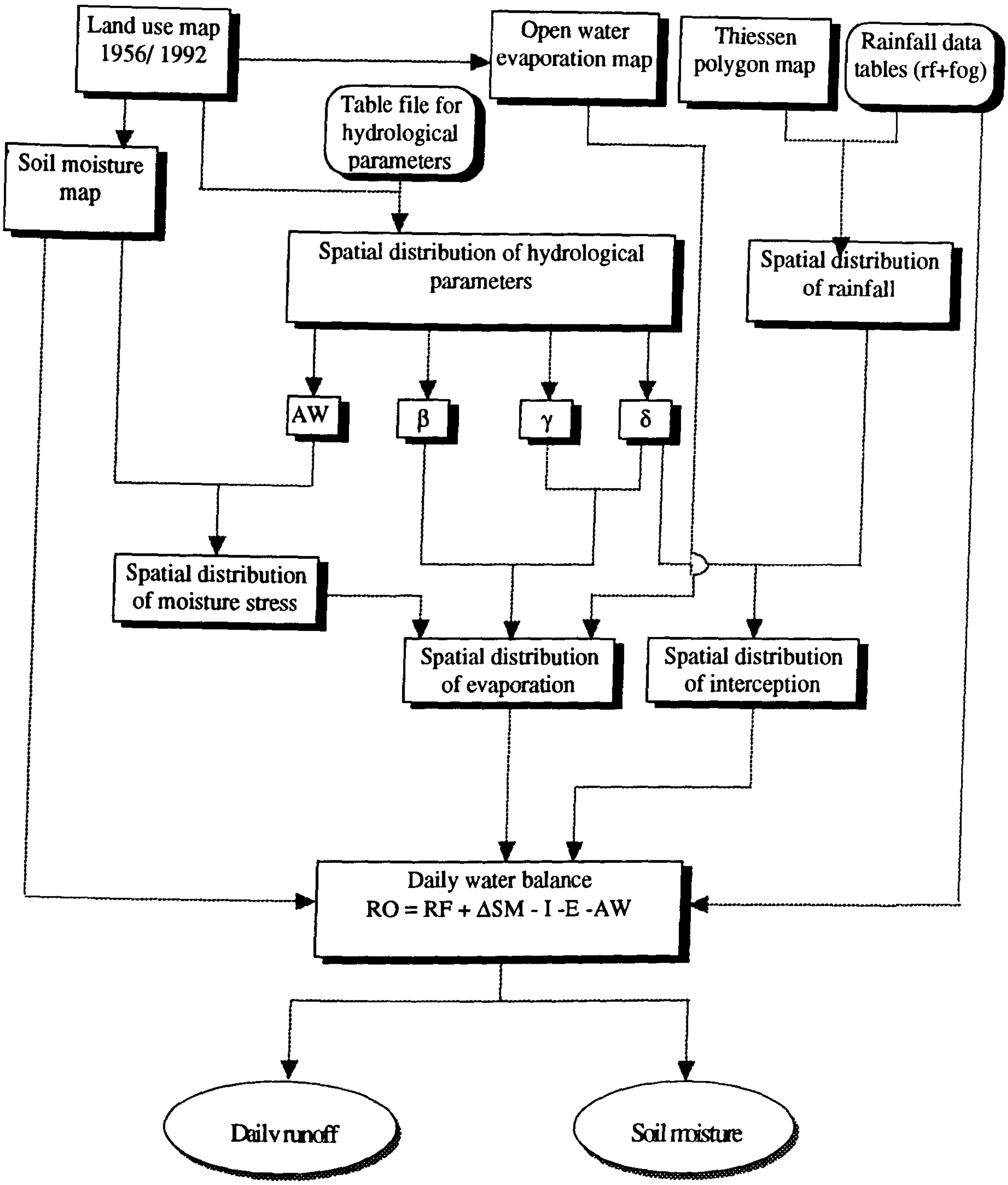


Figure 6.3 Spatial Hydrological Model Structure in SPANS Map Modelling

6.5.9 Processing Challenges in Map Modelling

There were several limitations to modelling UMCA hydrology in SPANS map modelling. Table 6.5 summarises these limitations and the approaches adopted to overcome the limitations.

Table 6.5 Limitations of SPANS Map Modelling and Adopted Solutions

Limitations	Approaches adopted to overcome limitations
Decimal data are not recognised for thematic maps.	Modelling equations were run on actual values at the data scale & output was multiplied by a factor of 10 to include a decimal place in thematic scale.
Number of classes allowed on the thematic scale is 8192 with original SPANS classification scheme. This limited the value of a map with one decimal point to 819.2.	New classification schemes which identify a range from 0 to 100,000 were generated independently for each parameter and introduced into map modelling equations.
Map class value of zero is not permitted in thematic maps because zero is used to define background value.	All the thematic maps were given an initial value of 10 to denote the value 1 with one decimal and set to a minimum threshold of 10. The actual map class was obtained, dividing the calculated values in the model by 10 and subtracting 1 from thematic map value.
Map modelling functions provide only one thematic map as the output.	For each day, a series of modelling equations were used to derive maps for individual parameters.
Maps produced for individual days required a large volume of storage space.	Only two sets of map names were used alternatively so that previous maps were successively overwritten.
There is no mechanism in SPANS to increment the file pointer to read different columns for time series data.	A separate map was defined to denote the column number and it was incremented by one at the end of each day using a map modelling equation.

6.6 Data Output Formats

The distributed modelling approach adopted for the study was capable of estimating daily upstream flow at any desired point of the drainage network. However, the model calibration required flow to be predicted at the flow gauging locations in order to make comparison with the historical flow records. Plate 6.6 shows the locations of principal flow gauging installations in the catchment. Further, provisions were made in the model to estimate composite flow values at the identified 32 subcatchments (Plate 6.5) in UMCA. In addition to the real time series of flow data generated from the model, it provided the display facilities representing the spatial distribution of runoff on thematic maps at any desired time period of interest.

6.7 Spatiotemporality in GIS

A temporal GIS should potentially provide a framework for representing the three basic components of geographic information i.e. location, attribute and time without fixing any of these components (Langran, 1993). Sinton (1978) proposed a framework for geographic data representation which draws a clear distinction between the current and the desirable temporal capabilities in GIS.

In the literature, a great deal of research work is found encompassing philosophical, conceptual and technical aspects of temporality in GIS (Armstrong, 1988; Langran, 1988; Schiel, 1983; Sinton, 1978). In most of the GIS, mapped data fix time. Accordingly, spatial distributions are represented for a specific temporal identity. In another instance, location specific data are presented for continuous or discrete time sequences in GIS. Spatial integration into a point or a uniform representative area is the basis for the limitation in dimensions. In some other cases, the approach of the GIS was to fix neither space nor time but the corresponding attributes. Different GIS offer some temporal capabilities and provide the opportunity to represent the spatiotemporality implicitly. None of these approaches including that of SPAN GIS can be counted as a true background for a spatiotemporal GIS. In short, a truly spatiotemporal GIS is yet to be designed and introduced. However, the dynamism and the development of GIS will not make the above statement valid for an extended period of time.

6.7.1 Temporal Capabilities of SPANS GIS

SPANS GIS menu driven functions can be run using equivalent command mode codes. The advantage is that a series of SPANS functions can be programmed into a batch file recognised as an audit file and run on the command mode. Further, operating system (OS/2) commands also can be run on the command mode. This provides a facility to handle iterative procedures very efficiently.

6.7.2 Spatiotemporal Hydrological Modelling

In order to include the temporal dimension into hydrological modelling, command mode functions were used extensively. The entire methodology depends on the format and thematic details of the input data and map files. Having prepared daily rainfall data in monthly tables with a column of data series for each day, it was possible to use only one set of equations for a month, incrementing the file pointer to read the data in different columns. One equation file was designed for each year incorporating a series of monthly equations.

In addition to the equation files, command files were required to call the relevant equations for map modelling. The command filing system was organised in such a way that each file contains executable files for each month. A typical example of a monthly command file is given in Appendix E-3.

6.7.3 Temporality with REXX Programming

In the temporal modelling, a set of equation files were needed to run for each day up to the run length of 30 years. In the process of automating the entire modelling task, thousands of equations were needed to be created and executed in an orderly manner. Having incorporated complex relationships, especially in the spatial domain, in these modelling equations, the filing up of equations in the system consumed a considerable storage space. This problem was overcome through the use of REXX procedures.

In this approach, the modelling task commenced in OS/2 system, with a REXX command file. The REXX command file opened up an equation file and writes up the required modelling equation for a year. A series of command files were also produced, making one for every month of model run. At the end of each year, it overwrites the set of former equations and command files and writes up for the next year.

6.7.4 Formatting Model Outputs

The REXX procedures were set up so that they produced monthly values of weighted average of spatial distribution of runoff at each subcatchment. They also created maps showing spatial distribution of monthly runoff on the thematic scale according to the user-defined classification scheme. A typical model output showing spatial distribution of runoff for the year 1993 is shown in Plate 6.7. Some of the colours used in Plate 6.7 look similar but are different in true RGB combinations. Cumulative monthly totals of the other hydrological parameters such as evaporation, interception and soil moisture were also calculated whenever required. The summary of temporal modelling is given in Figures 6.4(a) & 6.4(b). A typical illustration of REXX programme codes used is listed in Appendix E-4.

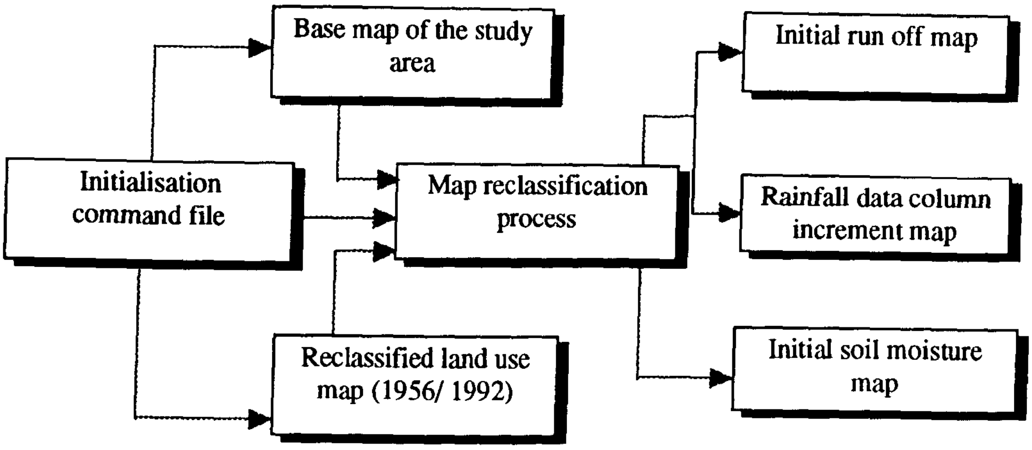


Figure 6.4(a) Block Diagram for System Initialisation Process

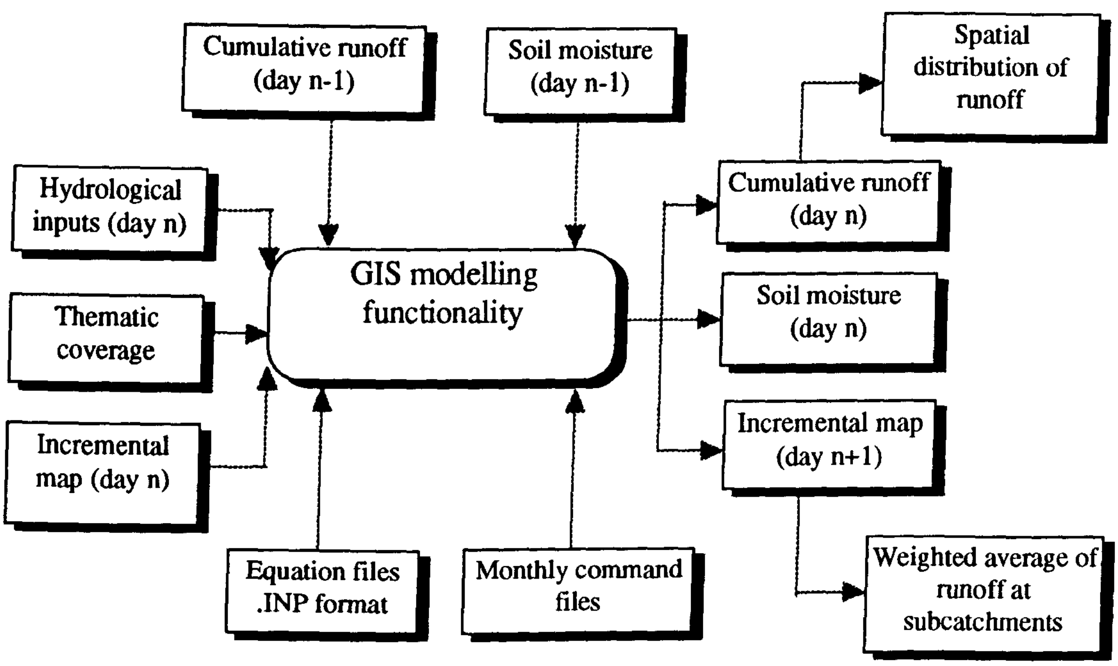


Figure 6.4(b) REXX Programme Set-up for Spatiotemporal modelling

6.7.5 Computational Speed and Efficiency

The type of the micro processor in the PC, complexity of computational processes, thematic details and the quad resolution are the key factors determining the processing speed. The nature of the computational processes and the thematic details are not possible to be compromised for achieving higher processing speed within the available software architecture. However, a higher computational speed and efficiency could be achieved adjusting data and computational resolution and also upgrading the micro processor in the hardware set-up. The model formulation philosophy is such that efficiency of the model performance depends not only on what data are required but how they are organised in the context of geometric space on the topological structure.

6.8 Customised Interactive Temporal Model

Other users of the programme may find a difficulty in understanding and making use of the model because of the complex programming functions used in the spatiotemporal modelling. Hence, a customised application was developed using SPANS GIS menu functions making only the required SPANS functionality for UMCA model available for the user with descriptive customised names for each utility. With the customised version, the UMCA hydrological model can be run and model outputs can be obtained without a deep knowledge of SPANS GIS software functionality.

The initialisation file was modified in such a way that it interactively requests data from the user for the model parameters via the keyboard. Figure 6.4(a) depicts the steps involved in system initialisation process. REXX programming set-up used for customised application is summarised in Figure 6.4(b). Rainfall data can either be used from the existing database or be copied into the system. There is also a provision for the use of existing rainfall and land use maps or to include additional thematic data files. A summary booklet could be produced to provide the information on input file formats, required SPANS GIS commands and the choice of the different output options available to run the UMCA hydrological model in SPANS. This would enable the project team to make use of the model without having to learn SPANS GIS software. However, the development of this is beyond the scope of this study. Further, the use of this customised applications is only applicable to the UMCA hydrological model.

6.9 Discussion and Conclusions

6.9.1 General Applicability of the Modelling Approach

Map modelling was found to be the best approach for spatiotemporal modelling of UMCA hydrology as discussed in section 6.5.4. This selection was totally based on the hydrological processes and data inputs accounted in the UMCA hydrological model. Although the modelling methodology detailed in the foregoing sections is not a universal solution for spatiotemporal modelling in GIS, the working principles can be applied elsewhere for modelling hydrology or any other similar modelling process. The application elsewhere with a different model may require a series of modifications to the working assumptions or probably a totally different approach within the SPANS GIS modelling functionality. The lack of universal applicability is the major weakness in the modelling approach.

6.9.2 Interpolation Options

Thiessen polygon was the most computationally efficient interpolation option because the spatial distribution remains same and only the polygon values change. The problem with Thiessen polygon is the unrealistic spatial distribution to produce uniform rainfall polygons. TIN based on a tessellation model for surface interpolation is a promising method when the rain gauging network is well distributed and gauging locations are available in and around the catchment boundary. TIN based interpolation methods change the spatial distribution which is theoretically better. However, anomalies such as negative values can be introduced when the coverage of gauges is spatially biased and the interpolation is extended beyond the convex hull formed by the outermost points of the TIN structure.

Potential mapping needs to be used with caution. The results are bound by the user-defined interpolation radius. Depending on the threshold radius, some areas of the catchment can remain without an interpolated surface. Potential mapping is particularly useful when the reliability ratings of the gauging data are different. Statistical weighting functions can be introduced for potential mapping so that reliable gauges receive higher interpolation strength over the other points.

6.9.3 Choice of Quad Levels

Selection of a suitable quad resolution for spatiotemporal modelling is an important decision despite the fact that resolution can be changed subsequently. The data files need to be produced at the highest resolution possible leaving the option of any lower quad level for modelling. The changes in spatial dimensionality in general, and from a higher level to a lower level in particular, can cause information loss or reduction and hence, the approach was to retain data as originally encoded and generalise as needed at a later stage. The decision on the quad level should be based on the required accuracy of the modelling output, storage requirements, interpolation and other analytical tools used and the complexity of the data and process representation.

6.9.4 Lack of True Temporality in GIS

The existing GIS identify three dimensions i.e. the two dimensions of location X and Y and the other for attribute data. GIS have originally been designed to use for spatial analysis and modelling with these three dimensions. In the existing GIS software architecture, time is not recognised as a true dimension. Incorporation of true temporality into existing GIS has not so far been possible and that was the reason for implicitly defining temporal dimension in the hydrological modelling as detailed in section 6.7.

6.9.5 Assessment of Software Suitability

SPANS GIS provides efficient algorithms for the calculation of spatially distributed parameters. The modelling language is also very strong having a large number of mathematical and statistical functions and the provisions for user defined equations. The ability to run SPANS functions and operating system commands on the command mode provides an excellent opportunity to convert an atemporal set-up into a temporal mode. At each time step, spatial dimension is fixed instantaneously and at each spatial analysis, time variation is fixed. This avoids conflicts in representing four dimensions at any given time.

6.9.6 Compatibility of SPANS Version 6.0

In addition to the available modelling and command mode functions of SPANS GIS Ver. 5.4, the Ver. 6.0 running in Windows NT environment, provides the capability to run SPANS GIS commands directly in the operating system environment. This helps to automate the entire modelling approach one step ahead so that model can be run without any user input into the SPANS GIS software system.

Plate 6.1 Thiessen Polygon Map of UMCA

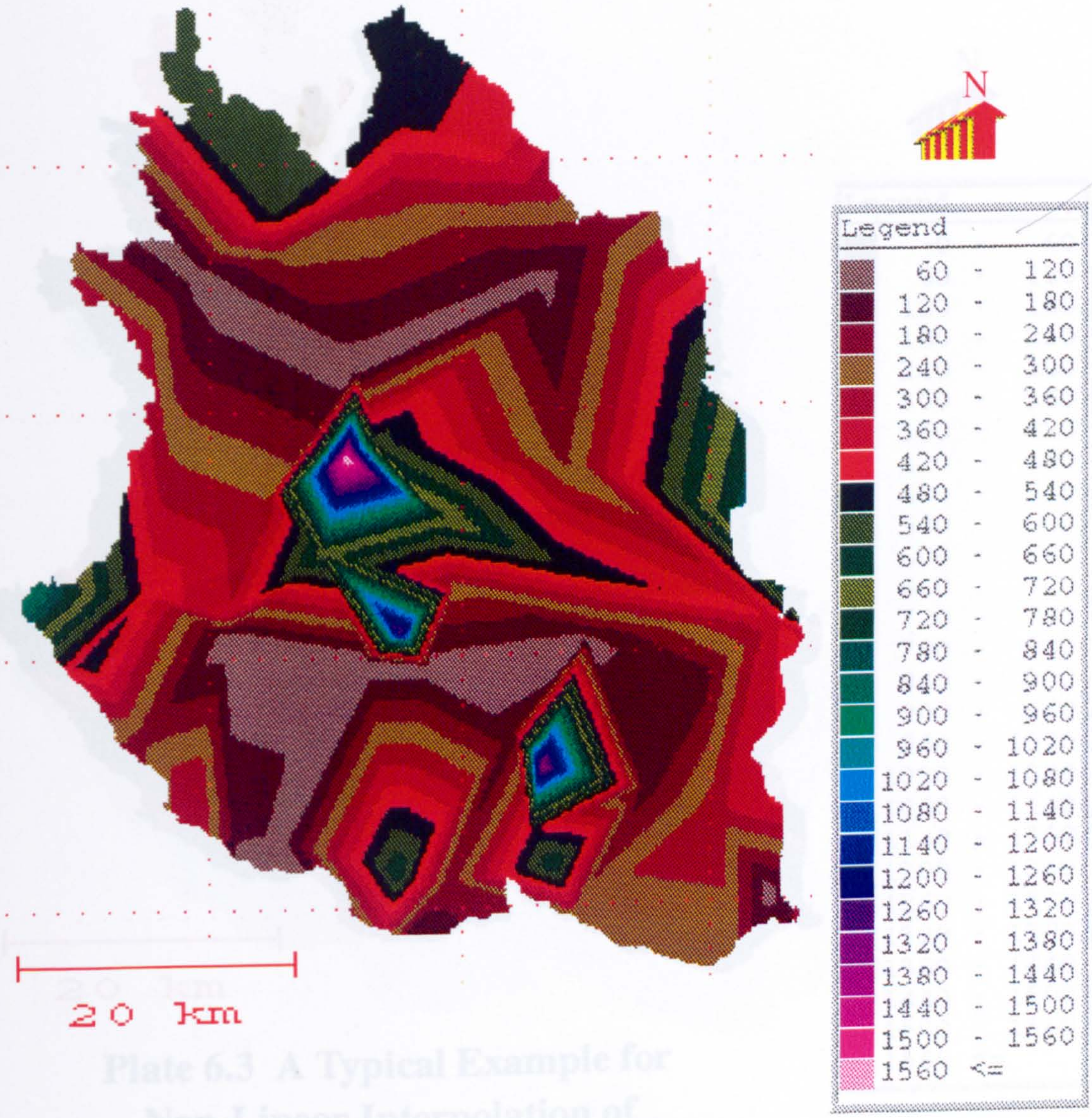


Plate 6.2 A Typical Example for Linear Interpolation of Rainfall for UMCA

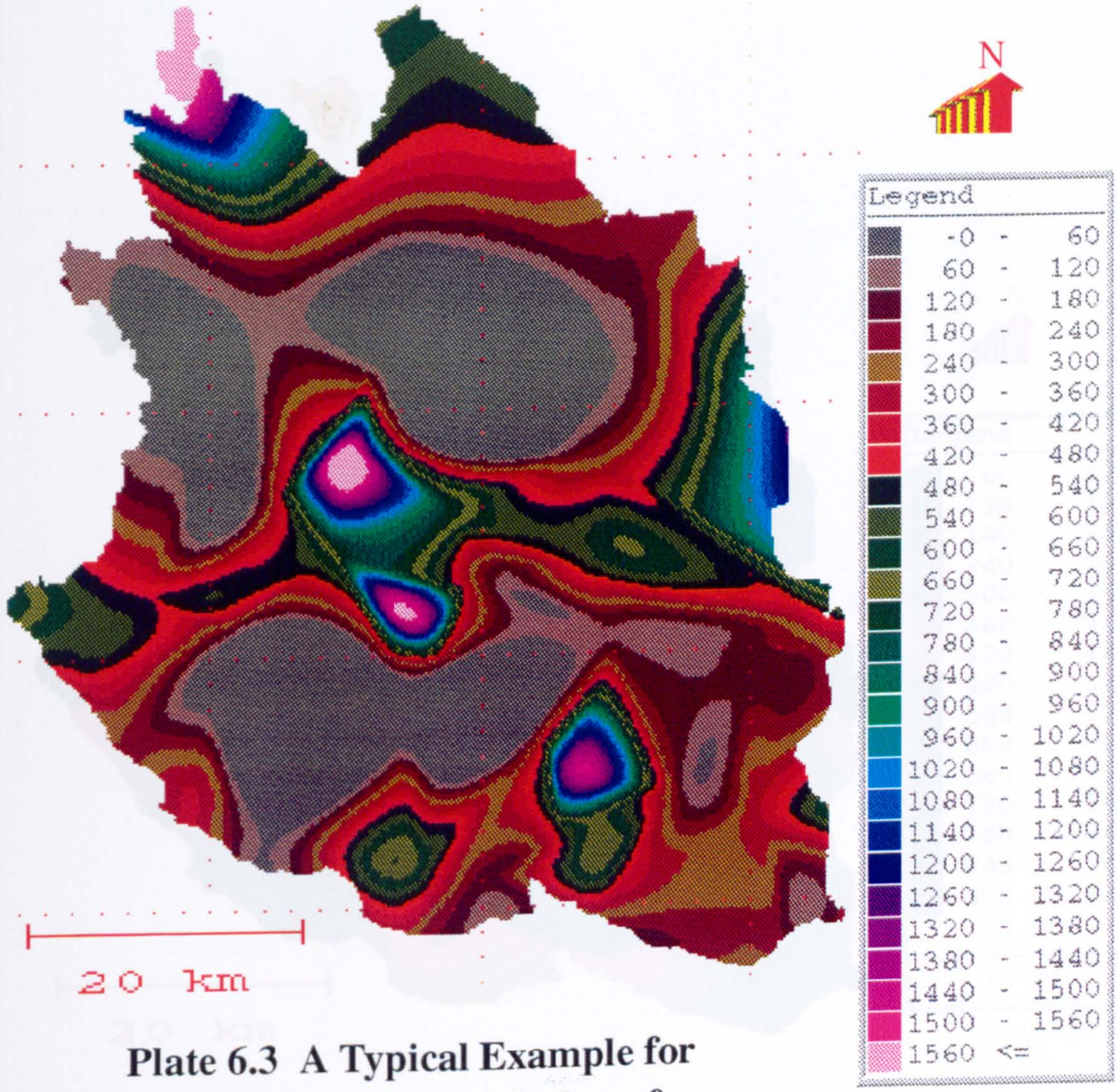


Plate 6.3 A Typical Example for Non-Linear Interpolation of Rainfall for UMCA

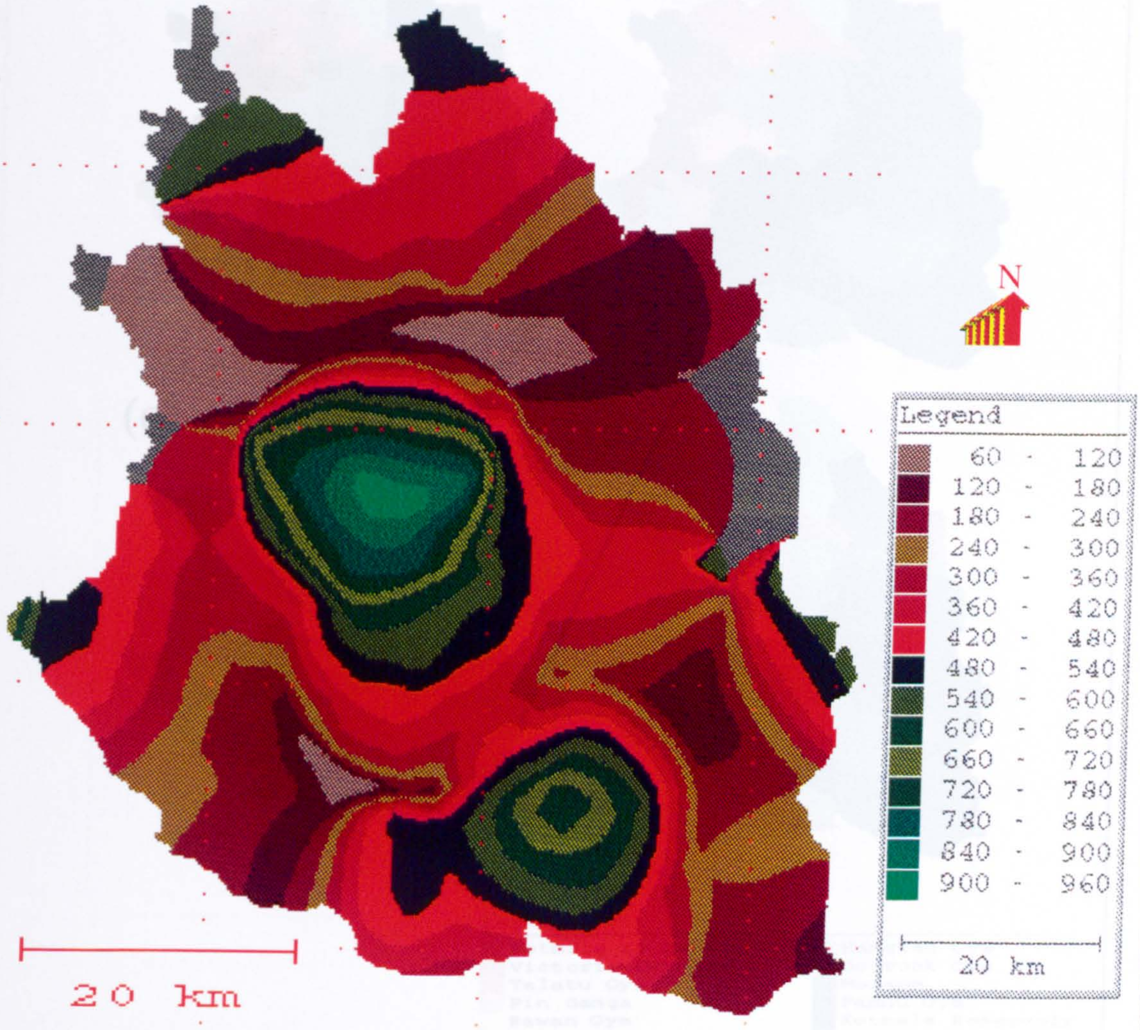


Plate 6.4 Typical Example of Potential Mapping Interpolation of Rainfall for UMCA

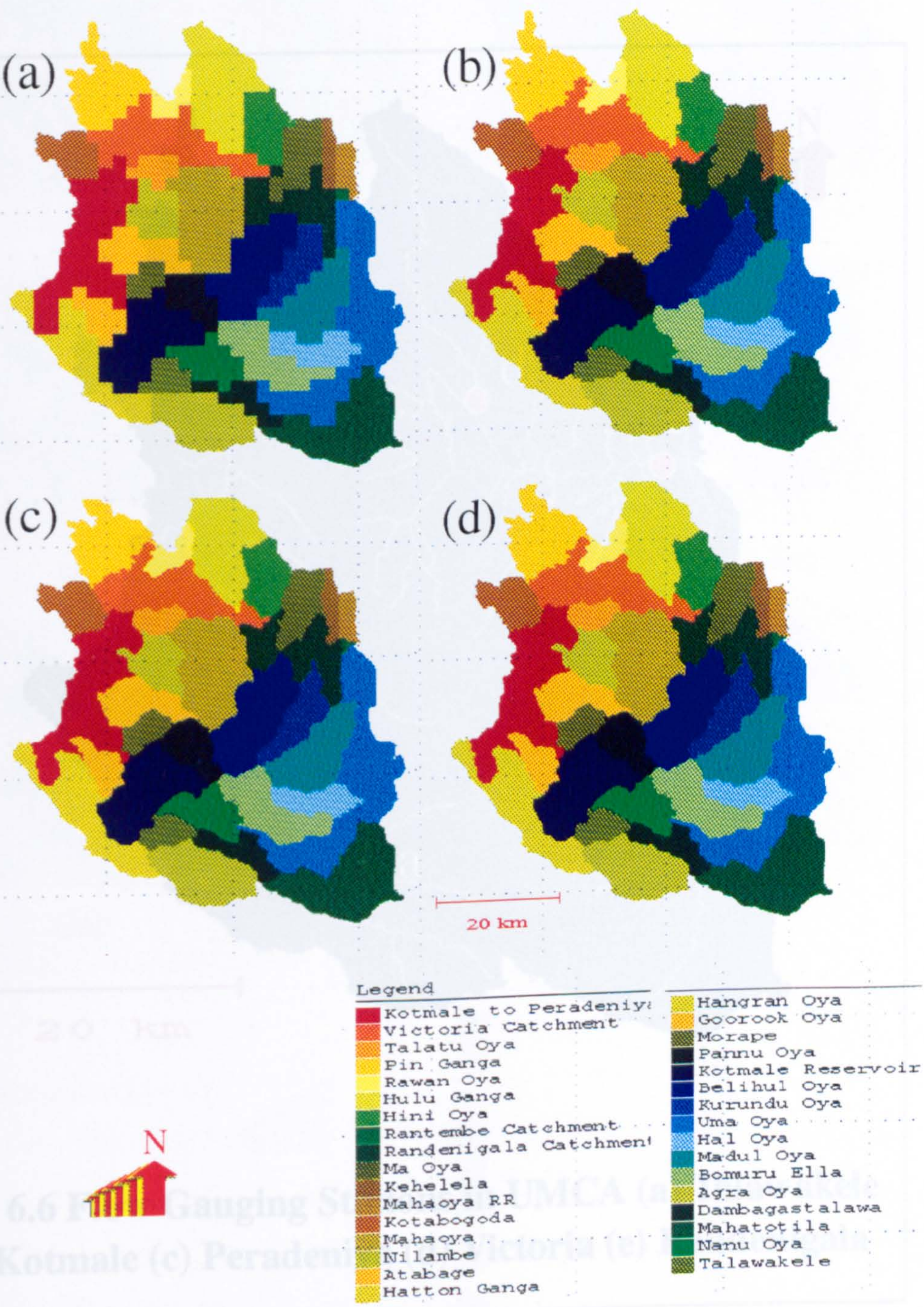


Plate 6.5 UMCA Subcatchments at (a) quad 07 (b) quad 09 (c) quad 11 (d) quad 13

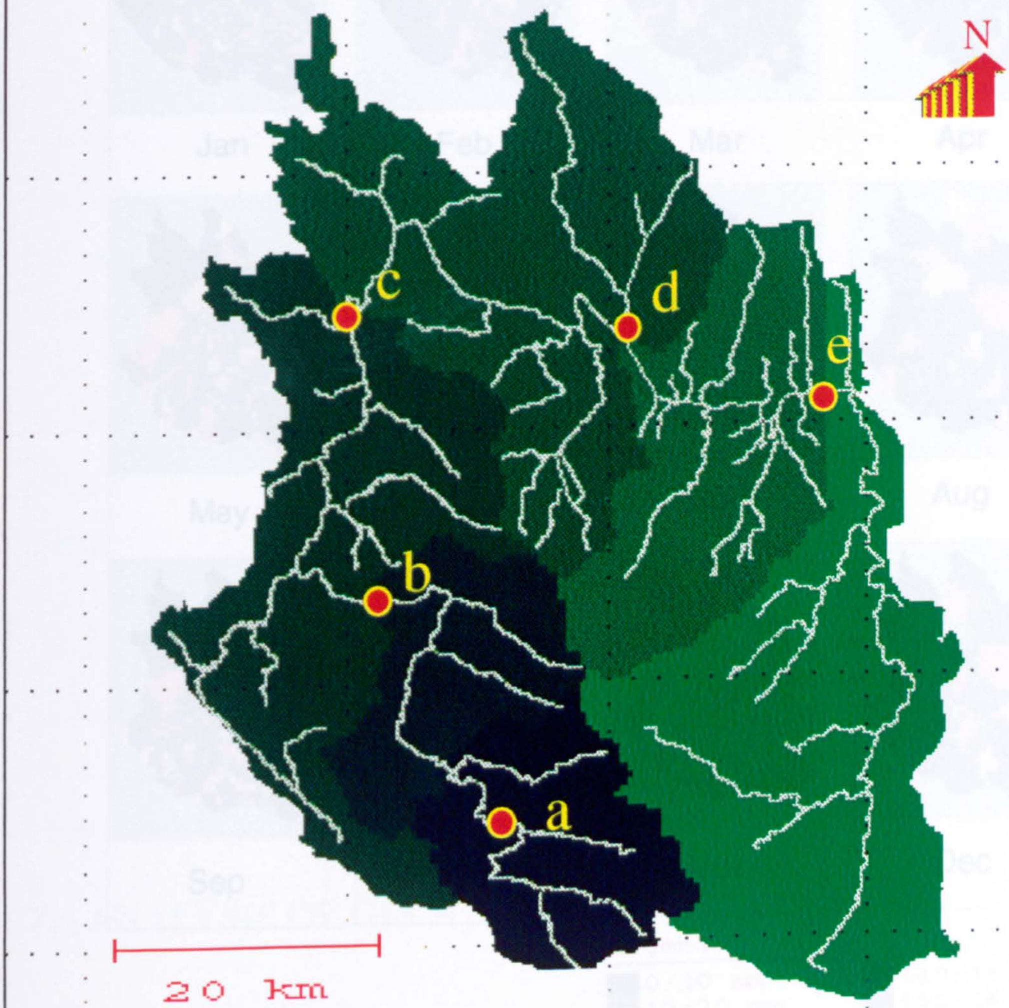


Plate 6.6 Flow Gauging Stations in UMCA (a) Talawakele (b) Kotmale (c) Peradeniya (d) Victoria (e) Randenigala

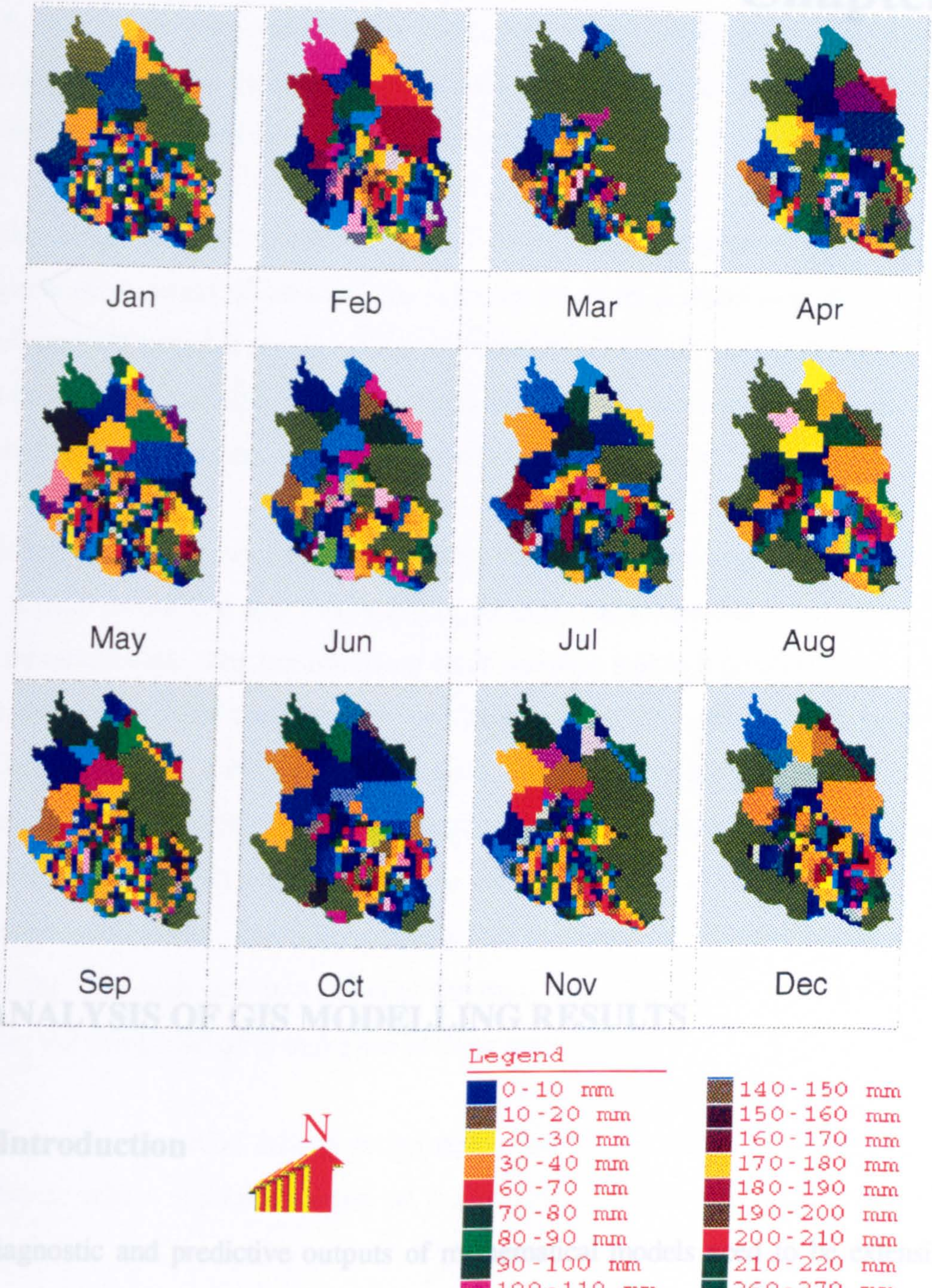


Plate 6.7 Spatiotemporal Model Output of Runoff as a Thematic Time Series - 1993

Chapter 7

7. ANALYSIS OF GIS MODELLING RESULTS

7.1 Introduction

The diagnostic and predictive outputs of mathematical models need to be extensively assessed before making use of them on realistic practical applications. Accordingly, in this chapter, the performance of the spatiotemporal hydrological model, discussed in the foregoing chapters was evaluated in terms of its capability to reproduce stream flow response with respect to the input hydrological data. This can also be viewed as a system verification approach in order to choose the best modelling philosophy, thresholds of model parameters and spatial resolutions for the simulation of catchment response in addition to examining the credibility of the postulated model.

The degree to which a model output conforms to the corresponding observed data can be measured by a variety of goodness-of-fit techniques (Green & Stephenson, 1986). Such techniques may range from subjective, visual methods to purely objective techniques where the goodness-of-fit is measured by means of a statistical function of the differences between simulated and measured values.

Visual comparison of simulated and observed data provides a quick and often comprehensive means of assessing the accuracy of model performance. In this chapter, visual analysis includes the graphical representation of both measured and simulated flow time series, cumulative flow functions and residual mass curve. Statistical analysis is based on the assessment of several statistical parameters.

Sensitivity analysis provides a systematic means of examining the response of a hydrological model in a way that is free of the error variations that exists when dealing with measured data. The freedom from error variation makes it possible to assess more easily the rationality of the model, as well as examining the effect of error in the input (McCuen & Snyder, 1986). In this chapter, the sensitivity analysis was extended to include model sensitivity for hydrological parameter definitions, and temporal and spatial resolutions. All the analysis were carried out with a part of the time series covering several years . It is impractical to run the model for 30 years for all the tests due to the very high run time required for each test. Further, it is not necessary to consider the whole period to make use of these tests.

Finally, error propagation criteria in the spatiotemporal modelling is also identified in this chapter with a special emphasis on the associated errors with the quad tree data structure.

7.2 Verification of the Monthly Water Balance

The model inputs, outputs and net gains are illustrated graphically in Figures 7.1(a) and 7.1(b) for Morape and Talawakele sub catchments in order to verify the mathematically correct differential partitioning of the hydrological inputs. In these figures, symmetry over y=0 axis clearly indicate that the water balance among inputs, losses and soil storage terms are accurately accounted in the model.

7.3 Performance of the Spatiotemporal Hydrological Model

In the context of spatiotemporal hydrological modelling, the basic model structure without fog interception component seems to be the most suitable starting point for simulations in the process of progressive modification of model representation. The model performance was based on daily data at quad level seven. However, model evaluation was carried out on the accumulated monthly time series at the same quad resolution. The initial modelling involved in the period from January 1964 to December 1969, with the identification of land use status from the reclassification of 1956 land use map. The model outputs which consist of individual quad cell values were spatially averaged as a function of height over the identified six sub catchments in UMCA. The available flow data as flow rates (in m^3/sec) were also converted to flow-heights over the sub catchments. However, the subsequent analysis was restricted to five sub catchments due to non-availability of flow data at Rantembe gauging station for the period considered. The area coverage of each sub catchment is listed in Table 7.1.

Table 7.1 Statistical Summary of Hydrological Modelling Results

Sub Catchment	Area Coverage (sq.km)
Talawakele	286.9
Kotmale	249.97
Peradeniya	612.21
Victoria	770.83
Randenigala	446.55

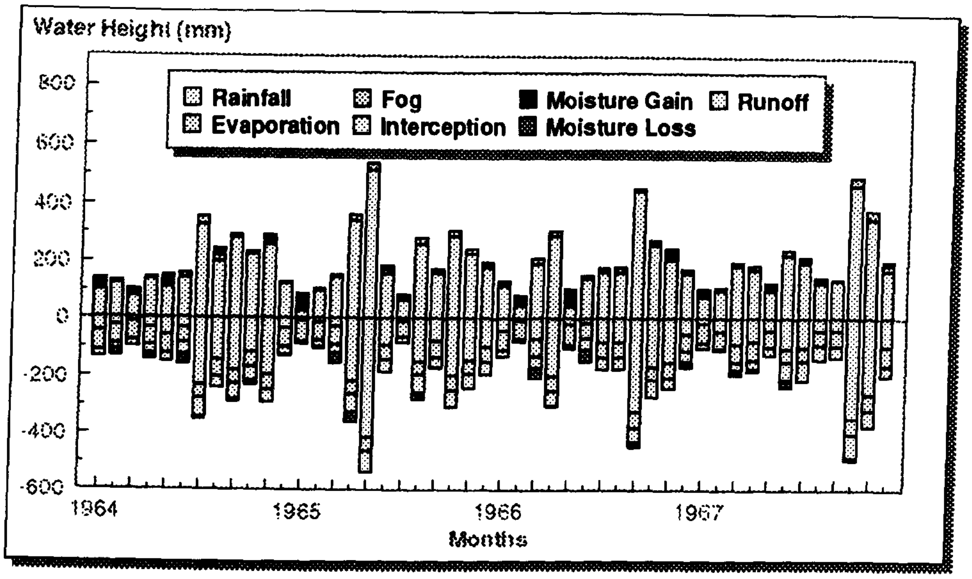


Figure 7.1(a) Water Balance at Talawakele Sub Catchment

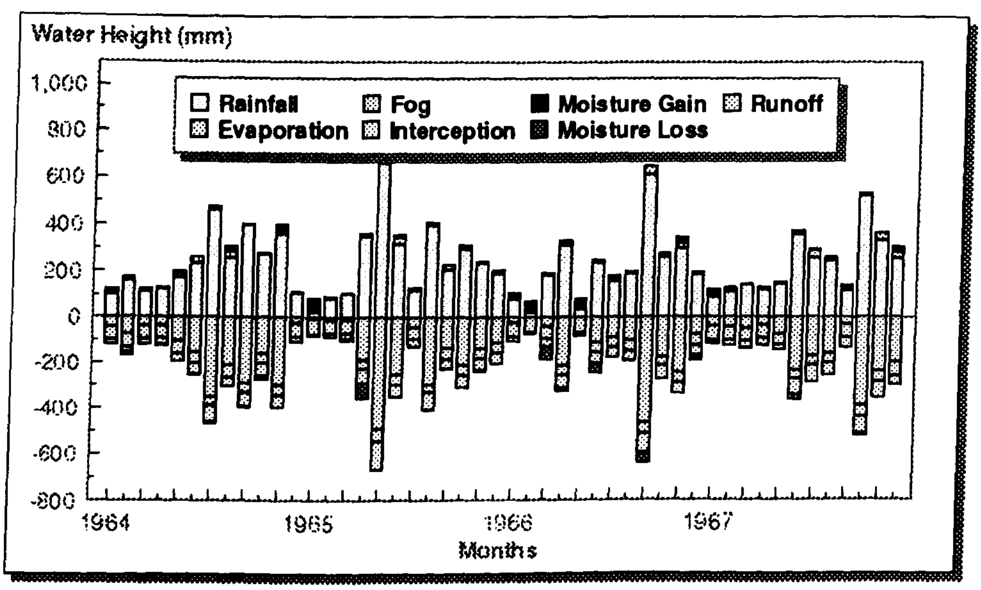


Figure 7.1(b) Water Balance at Kotmale Sub Catchment

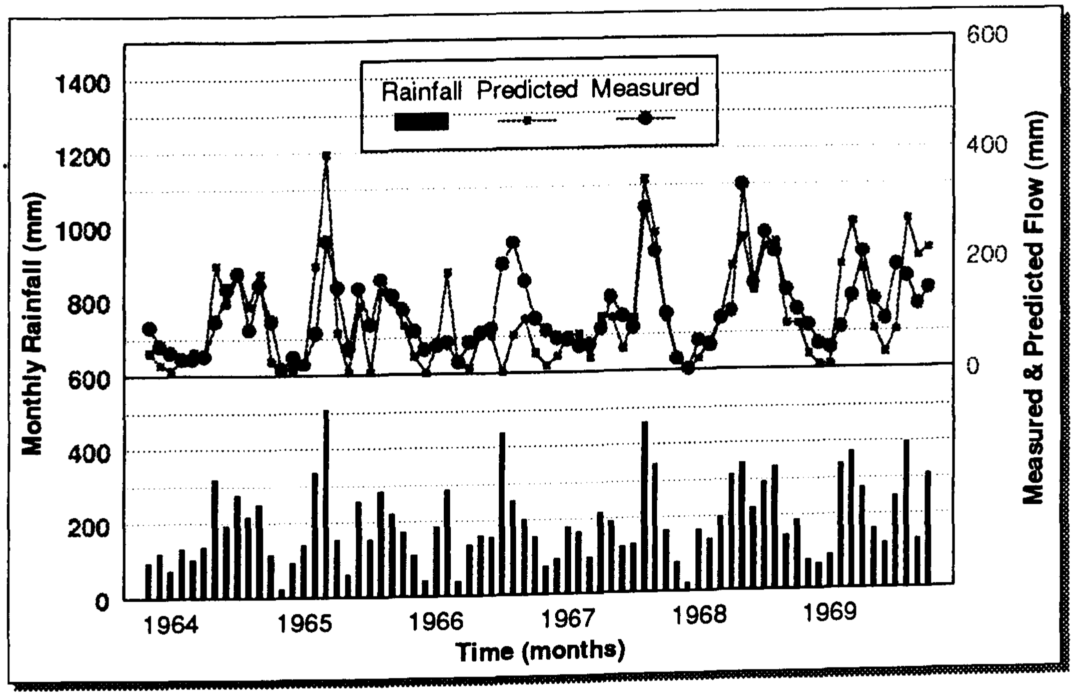


Figure 7.2 (a) Rainfall, Measured and Simulated Flow Time Series for Talawakele

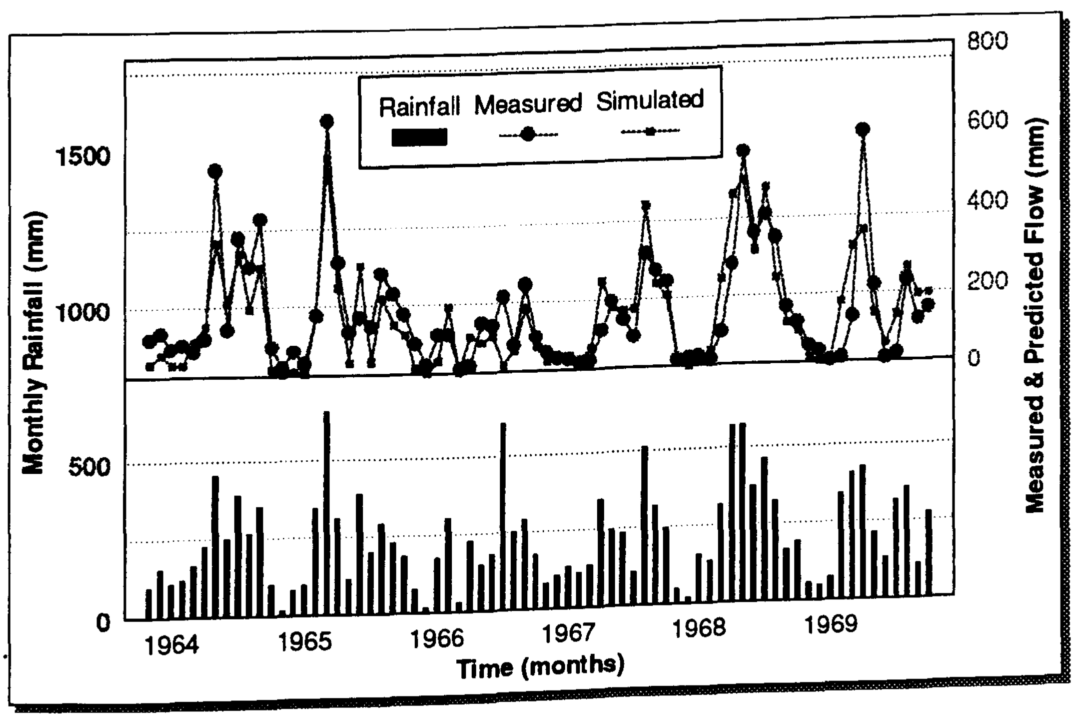


Figure 7.2 (b) Rainfall, Measured and Simulated Flow Time Series for Kotmale

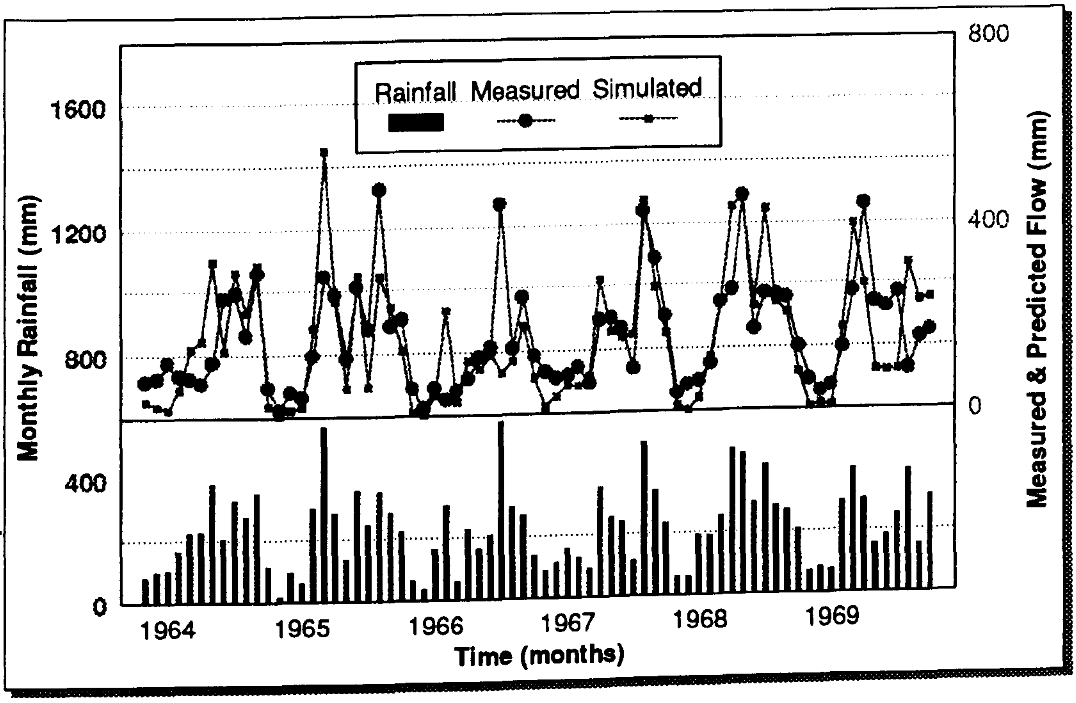


Figure 7.2 (c) Rainfall, Measured and Simulated Flow Time Series for Peradeniya

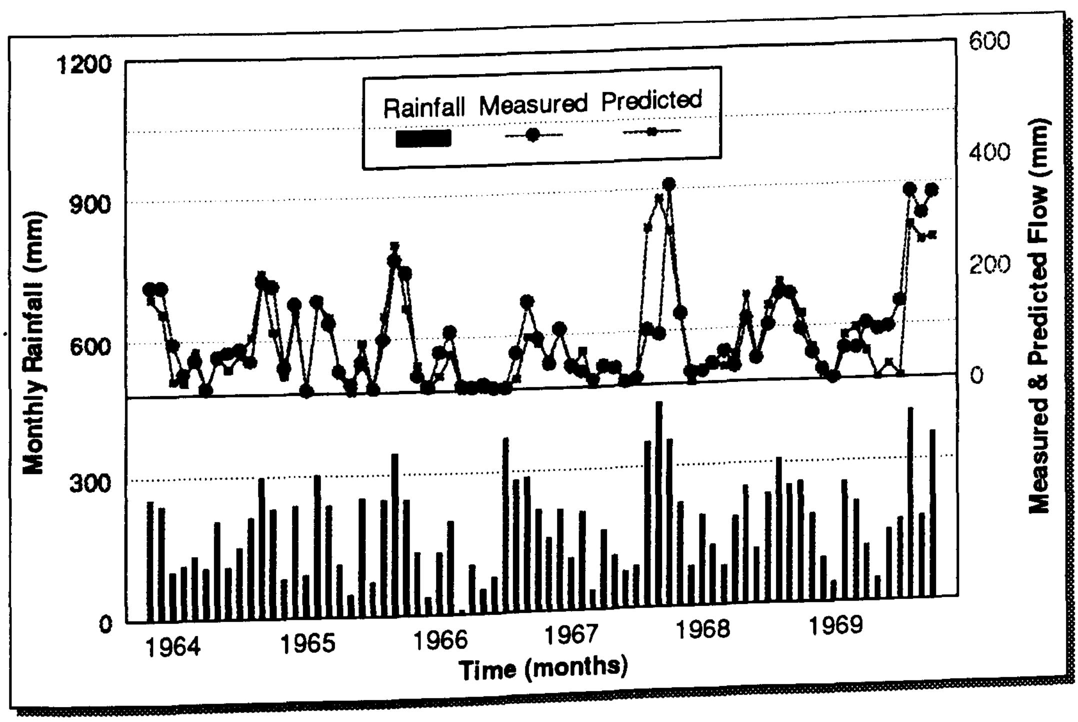


Figure 7.2 (d) Rainfall, Measured and Simulated Flow Time Series for Victoria

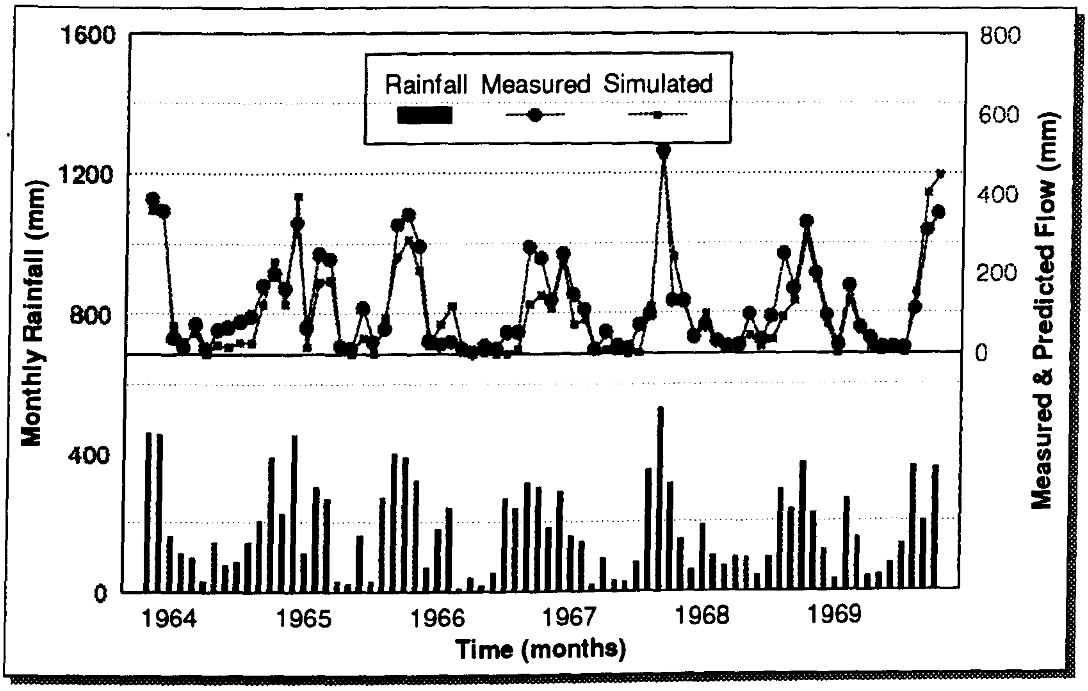


Figure 7.2 (e) Rainfall, Measured and Simulated Flow Time Series for Randenigala

7.3.1 Graphical Verification of Catchment Response

Figures 7.2(a) through 7.2(e) illustrate the temporal distribution of measured and simulated flow at five major sub catchments in UMCA along with the average rainfall of each sub catchment. The catchment rainfall values were computed by spatially averaging the distribution after interpolating by Thiessen polygon method and cumulating over a period of a calendar month in order to be comparable with the flow regimes. Despite the few deviations, the simulated response seems to be clearly associated with the measured data on the graphical format.

A further comparison was attempted by examining the temporally cumulative flow for measured and simulated data as shown in Figures 7.3(a) through 7.3(e). In all the other sub catchments except in Victoria, the cumulative predictions were lower than the observed values. Figure 7.3(a) for Talawakele sub catchment shows a significant deviation of the simulated value from the predicted value in January, 1966. This can probably be due to a change in instrumentation or a possible error in data series.

Furthermore, residual mass curves were also plotted for the measured and simulated flow and are presented in Figures 7.4(a) through 7.4(e). Residual mass curves show the cumulative deviations of the individual values of a series from the mean value. According to the above figures, residuals were always found to be more in the simulated data series suggesting a higher variability status. This indicates that the model parameters are highly responsive for the changes in input data and prone to quick changes in their response. It also indicates that the catchment seems to have a storage effect on the flow regime to yield a lower variability.

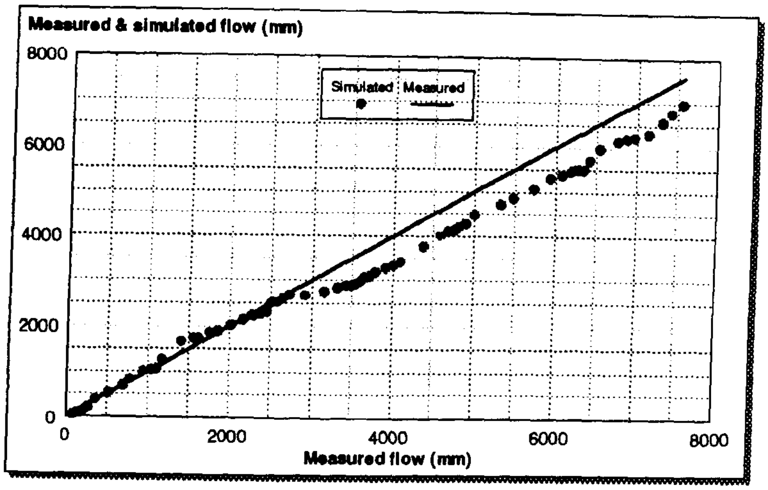


Figure 7.3(a) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ for Talawakele

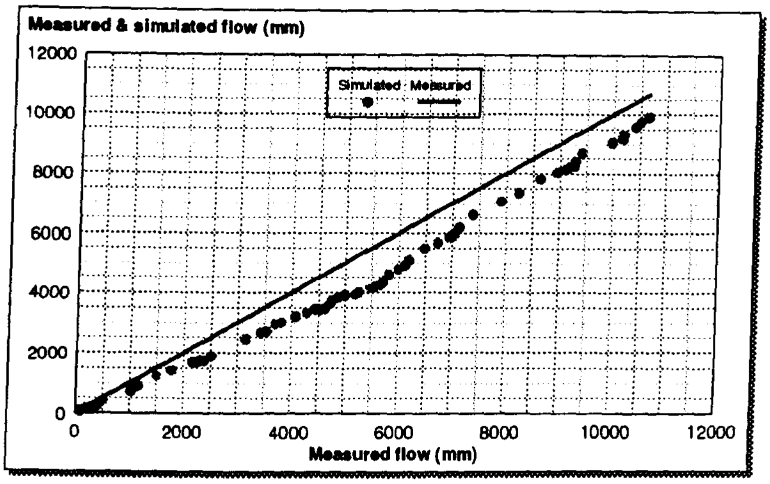


Figure 7.3(b) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ for Kotmale

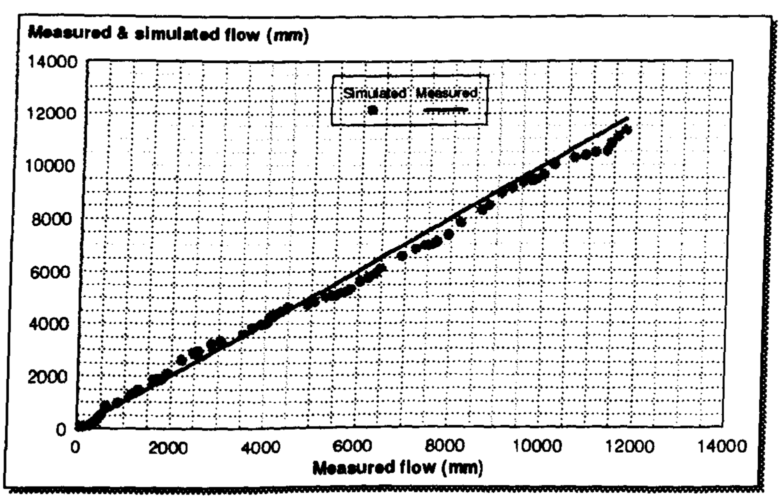


Figure 7.3(c) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ for Peradeniya

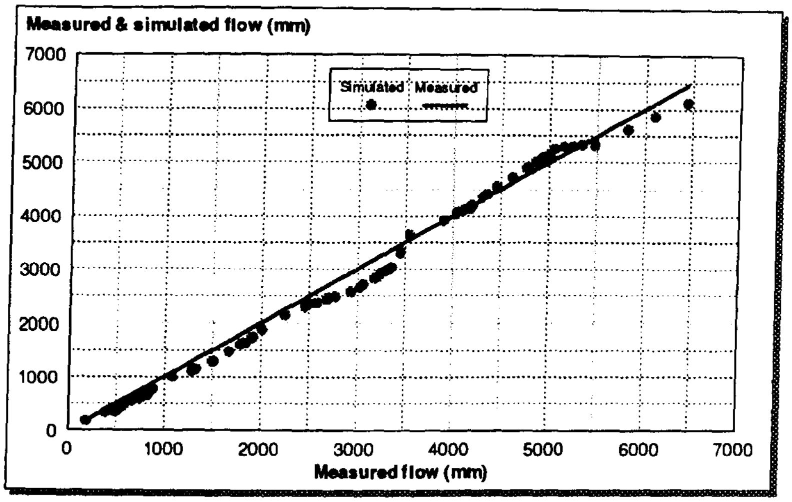


Figure 7.3(d) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ for Victoria

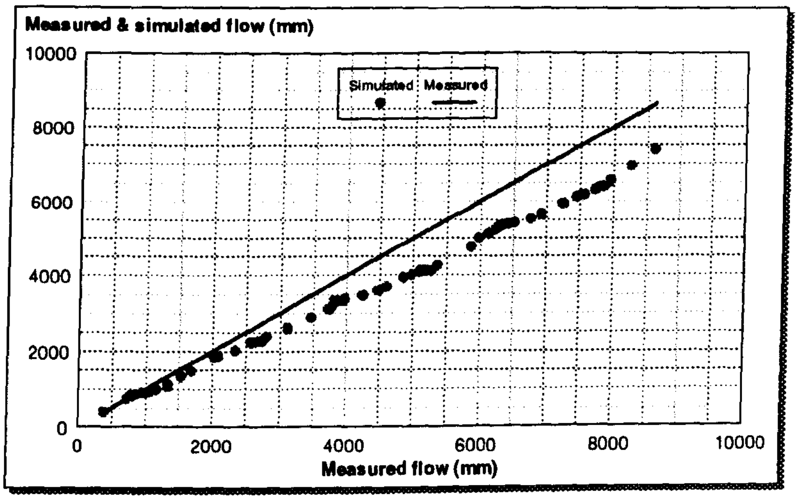


Figure 7.3(e) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ for Randenigala

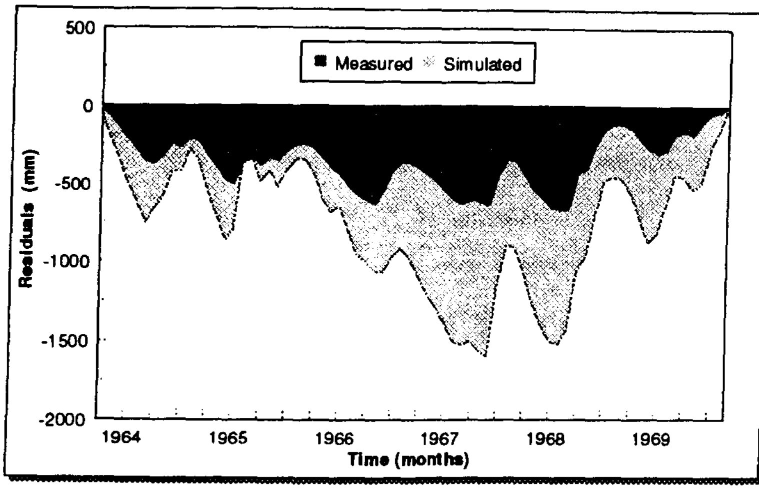


Figure 7.4(a) Residual Mass Curve for Talawakele

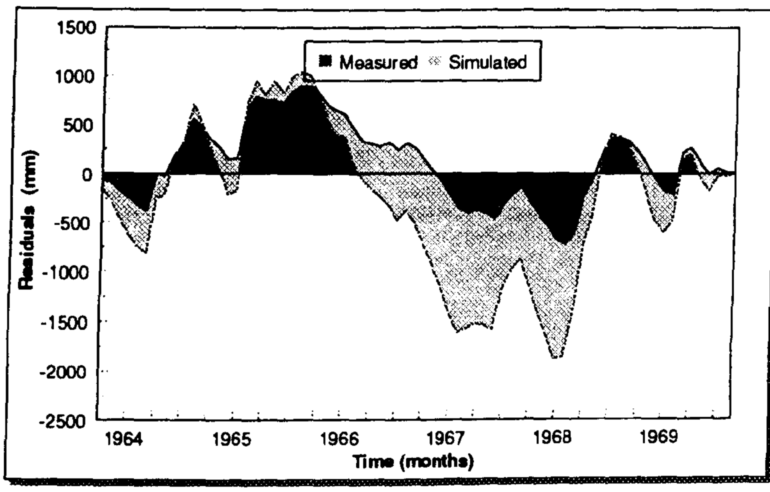


Figure 7.4(b) Residual Mass Curve for Kotmale

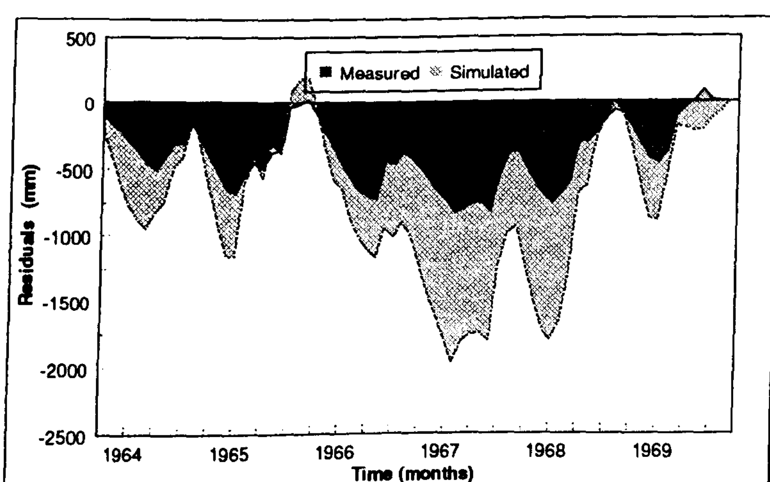


Figure 7.4(c) Residual Mass Curve for Peradeniya

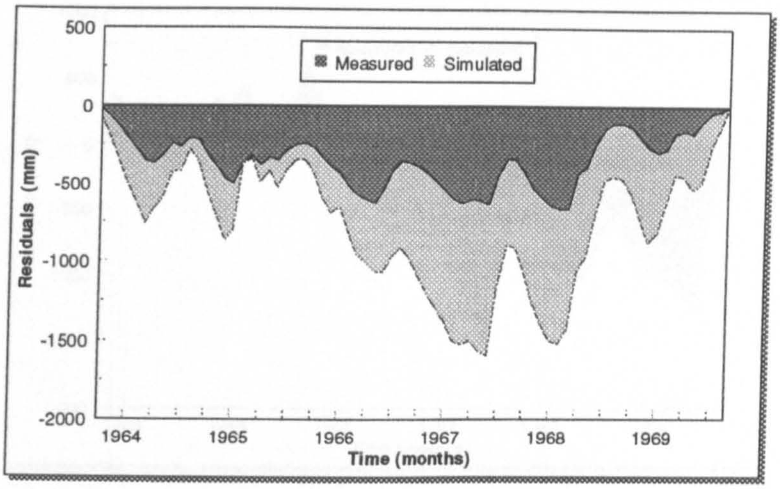


Figure 7.4(a) Residual Mass Curve for Talawakele

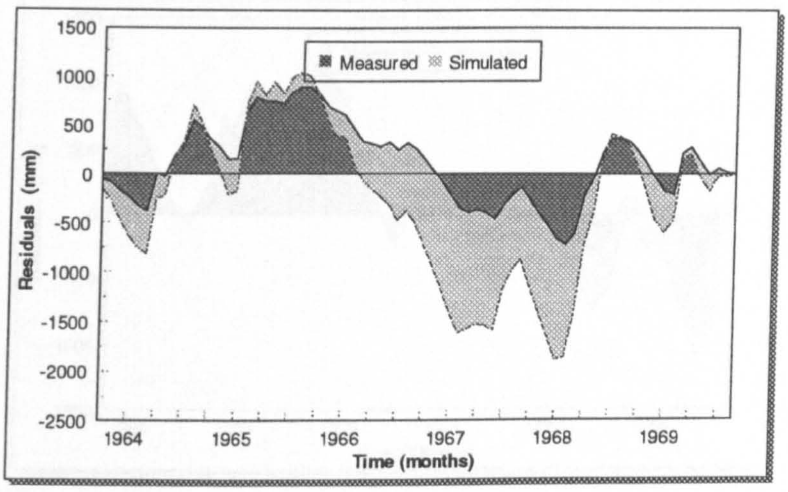


Figure 7.4(b) Residual Mass Curve for Kotmale

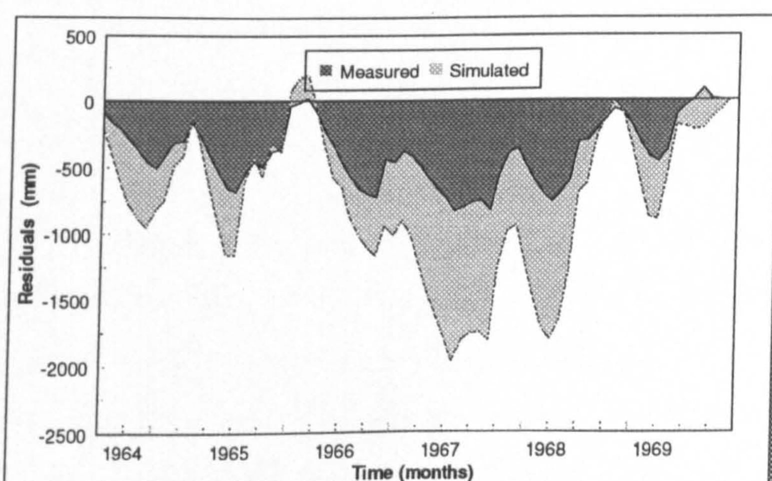


Figure 7.4(c) Residual Mass Curve for Peradeniya

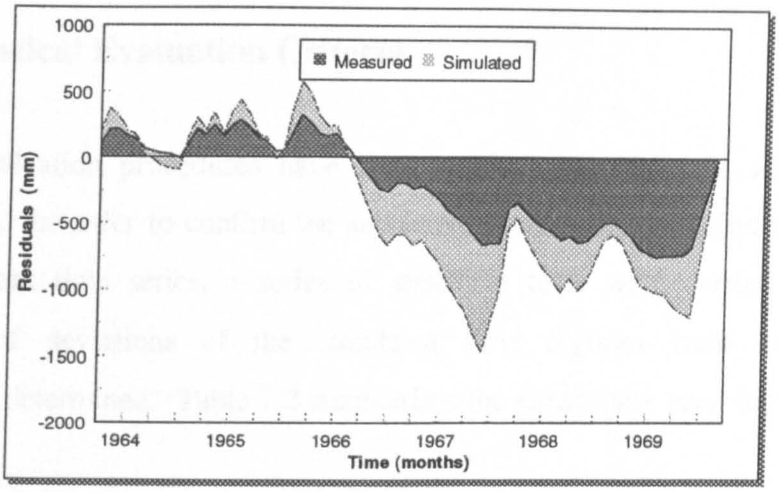


Figure 7.4(d) Residual Mass Curve for Victoria

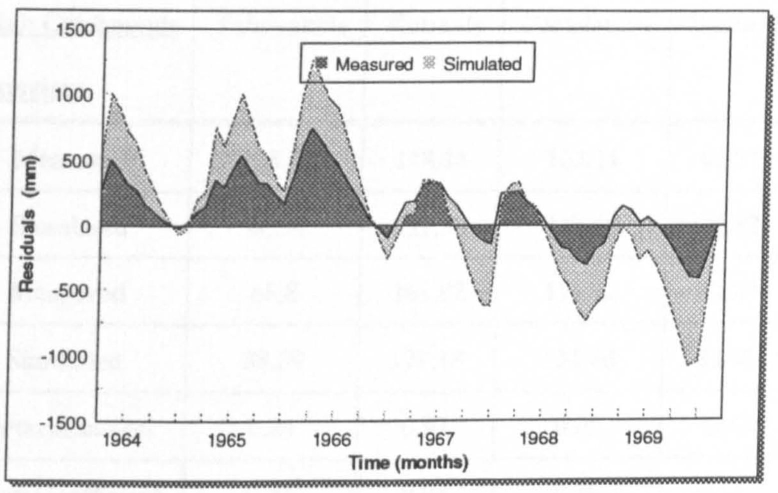


Figure 7.4(e) Residual Mass Curve for Randenigala

7.3.2 Statistical Evaluation Criteria

Statistical evaluation procedures have been regularly employed in assessing model performances. In order to confirm the subjective assessments made on visual displays of the resultant time series, a series of statistical tests were carried out and the distribution of deviations of the simulated flow regimes from actuality were quantitatively determined. Table 7.2 summarises the parameters used for the statistical comparisons.

Table 7.2 Statistical Summary of Hydrological Modelling Results

Sub Catchments / Statistical Parameters		Talawakele	Kotmale	Peradeniya	Victoria	Randenigala
Mean (mm) Runoff	Measured	105.12	148.14	163.11	89.51	119.8
	Simulated	96.94	137.39	156.62	84.82	102.48
STD (mm) Runoff	Measured	68.8	141.82	111.72	83.34	116.42
	Simulated	88.69	129.18	131.88	83.62	119.59
Coefficient of Determination		0.84	0.92	0.83	0.90	0.96
Cross Correlation Coefficient		0.71	0.84	0.69	0.81	0.92
Lag 01 Correlation		0.49	0.23	0.22	0.33	0.46
Coefficient of Efficiency*1		0.15	0.69	0.22	0.62	0.82
Residual Mass Curve Cof.*2		-0.40	-1.20	0.21	0.32	0.35

*1 - see Equation 7.1
*2 - see Equation 7.2

It is apparent that there is a good agreement between the measured mean & the standard deviation and the simulated mean & the standard deviation for all the sub catchments when the entire time series are considered (Table 7.2). However, it is noted that the simulated means are always lower than the measured means for all the cases confirming the findings from the plots of cumulative flow. Further, standard deviation figures seem to be higher for the simulated data with an exception for the Kotmale sub catchment indicating higher variability in the simulated flow series.

The cross correlation coefficients are above 0.69 for all the sub catchments (Table 7.2) confirming a good degree of association between the measured and the simulated values. The calculated lag 01 cross correlation coefficient values never exceed 0.5, thus suggesting a remote chance of a lag effect on flow series.

None of the above statistics identifies the distinction between random and systematic errors (Kachroo & Natale, 1992; Green & Stephenson, 1986; Pitman, 1978; Aitken, 1973). The coefficient of efficiency includes in its statistics the bias of the modelling results. According to Nash & Sutcliffe (1970), the efficiency term is analogous to the coefficient of determination from a linear regression except that it compares the measured values to a 1:1 line of measured equals predicted, rather than to a best fit regression line (Quinton, 1994). The efficiency statistics takes the form as shown in Equation 7.1.

$$E = \left[\sum\left(q_0 - \overline{q_0}\right)^2 - \sum\left(q_0 - q_{est}\right)^2\right] / \sum\left(q_0 - \overline{q_0}\right)^2 \qquad \text{(Eq. 7.1)}$$

where E = coefficient of efficiency of the model,

q_o = measured flow,

q_{est} = simulated flow and

$\overline{q_o}$ = mean of the measured flow.

The formulation includes the $\sum\left(q_o - \overline{q_o}\right)^2$ which represents the initial variation and $\sum\left(q_o - q_{est}\right)^2$ which describes the residual or unexplained variation. It provides a dimensionless measure of model performance, with the value E approaching unity as the difference between observed and predicted values become smaller. A value less than zero indicates that the model predictions would be worse than using the mean of the observed values. Besides Randenigala, all the other sub catchments have recorded coefficient of efficiency values less than 0.7. Further, in all five cases, the efficiency term is always lower than the coefficient of determination (Table 7.2) confirming the deviation or bias in the highly correlated simulated statistics.

Residual mass curve coefficient (Nash & Barsi, 1983; Pitman, 1978; Aitken, 1973; Nash & Sutcliffe, 1970) is a measure of association between measured and simulated flow data and it is sensitive to the systematic errors in the flow sequence. This coefficient is thought to have an important advantage over the other statistics in that it measures the relationship between the sequence of flows and not simply the relationship between individual flow records.

The statistics for residual mass curve coefficient is derived as in Equation 7.2.

$$R = \frac{\sum\left(D_c - \overline{D_c}\right)^2 - \sum\left(D_c - D_{est}\right)^2}{\sum\left(D_c - \overline{D_c}\right)^2} \qquad \text{(Eq. 7.2)}$$

where R = residual mass curve coefficient,

D_c = departure of individual element in the observed residual mass curve from the mean of the observed residual mass curve,

$\overline{D_c}$ = mean of the departures from the mean of the observed residual mass curve and

D_{est} = departure of individual element in the simulated residual mass curve from the mean of the simulated residual mass curve.

The statistics derived here evaluate the residual mass curves (Figures 7.4(a) through 7.4(e)) for systematic errors. It was found that all the residual mass curve coefficient values are below 0.4 (Table 7.2) and negative values are seen for the Talawakele and Kotmale sub catchments. A negative value for the residual mass curve coefficient arises when the residual or unexplained variation between the simulated and the measured residual mass curve exceeds the initial variation of the measured residual mass curve. These statistics also seem to suggest the presence of a systematic error component in the simulated flow data series. Further statistical tests were carried out to determine whether the means of the measured and the simulated flows differ significantly.

It is noted that the monthly rainfall time series exhibit seasonality due to the bi-modal rainfall pattern as discussed in chapter 2. Accordingly, the monthly flow series are also expected to be seasonal. If seasonal data are used, the high inter-month variability will definitely obscure the inherent variability present in the measured and the simulated flow series because it is not possible to account for this variability within the simulated or measured data series. Therefore, the statistical analysis was based on the monthly time series for each month separately.

Further, it was observed from the comparison of flow series that there are considerable annual variations even within the flow series of each month. The objective of the statistical analysis was to determine whether the simulated flow series were significantly different from the corresponding series of the measured flow. The null hypothesis was formulated for the statistical analysis such that the time series of deviation from each corresponding measured and simulated flow values (measured - simulated) are equal to zero rather than taking each monthly series separately and checking for the equality in the mean. This approach of accounting deviation of paired observation avoids the inter-month variability affecting the analysis. Accordingly, alternative hypothesis for the paired comparison was that the deviation is positive indicating the situation of model under-prediction. The test statistics generated using the relationship given in Eq. 7.3 are summarised in Table 7.3. The measured and the simulated flow data series for each sub catchment and the net deviations are listed in Appendix F-1. The use of the individual monthly statistics allows comparison to be made for each month so that it is possible to determine the influence of fog interception if any, on the model performance according to the relationship described in section 4.2.4..

$$\text{T statistic} = \frac{|\bar{d}|}{S_d / \sqrt{n}} \qquad \text{(Eq. 7.3)}$$

where $\bar{d}$ is the mean deviation,

S_d is the standard deviation of the deviations and

n is the sample size.

Table 7.3 Calculated T-test Statistics ($T_{0.90(5)}$=1.48) for the Monthly Time Series of Differences Between Measured and Simulated Flow

Station / Month	Talawakele	Kotmale	Peradeniya	Victoria	Randenigala
Jan	*3.80**	*3.86**	*1.85**	0.13	*3.93**
Feb	*4.77**	*3.61**	*5.88**	*2.42**	0.14
Mar	*1.95**	*1.91**	*3.23**	*1.63**	0.25
Apr	*2.82**	1.35	1.30	0.07	0.14
May	*1.65**	1.30	*1.92**	0.57	*1.86**
Jun	0.43	0.30	0.78	0.53	*2.21**
Jul	0.80	*3.79**	0.17	0.69	*3.68**
Aug	*4.00**	1.36	1.22	0.72	*2.74**
Sep	*2.22**	0.26	0.78	0.85	*5.34**
Oct	0.18	0.66	0.25	0.97	1.03
Nov	0.09	*1.91**	0.10	0.73	1.21
Dec	0.98	*1.95**	1.47	*2.70**	0.31

According to the results shown in Table 7.3, at least for 3 months in all the stations, the model predictions are significantly lower than the measured values. This is very prominent in Talawakele, Kotmale and Randenigala where model predictions are significantly lower for at least 6 months of the year. These months with significant deviations do not exactly correspond with the seasonal behaviour. However, these findings confirm the visual observations made with the cumulative flow and the residual mass curve and suggest the need for improving the model parameters to produce better results.

7.4 Modelling Results with Fog Interception

The statistics of student-t, the coefficient of efficiency and the residual mass curve coefficient discussed in section 7.3.2 suggests the presence of a systematic error while the calculated mean values of the simulated flow data shows significant decrease with respect to those of the measured series. Moisture contribution from fog interception in the cloud forests of the catchment as described in section 4.2.4 was included in the hydrological model in order to compensate this discrepancy in the simulated data. The Table 7.4 presents the statistical summary of the modelling results obtained for the hydrological model described in section 7.3 after the inclusion of fog interception process and Figures 7.5(a) through 7.5(e) illustrate the temporal distribution of the measured and the simulated flow. Further, the temporally cumulative measured and simulated flow after the inclusion of fog interception component are shown in Figures 7.6(a) through 7.6(e).

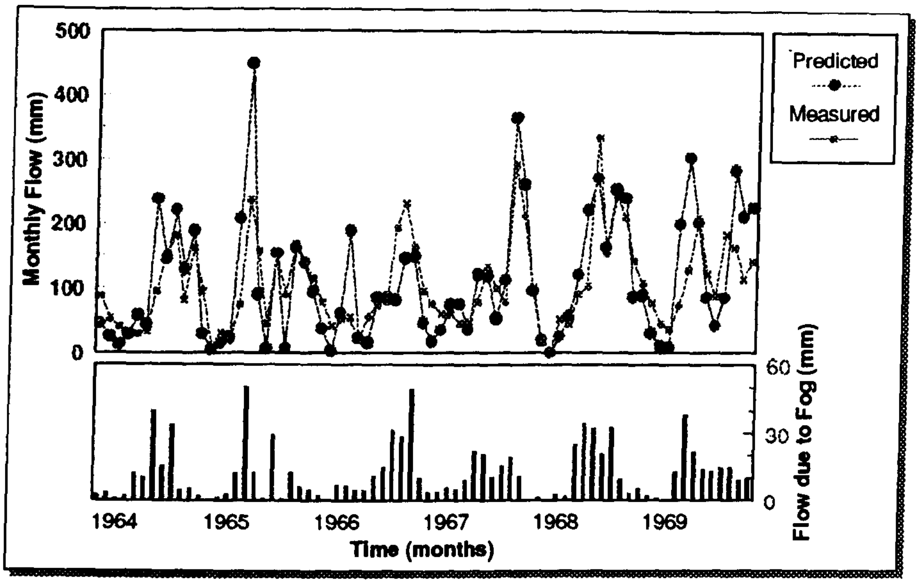


Figure 7.5(a) Simulated (with fog), Measured Flow and Fog Interception for

Talawakele

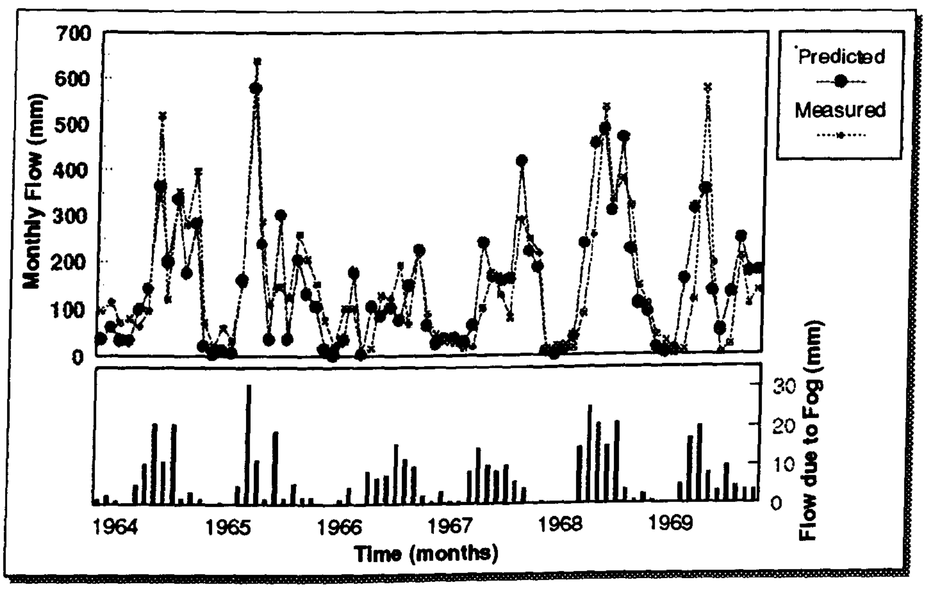


Figure 7.5(b) Simulated (with fog), Measured Flow and Fog Interception for

Kotmale

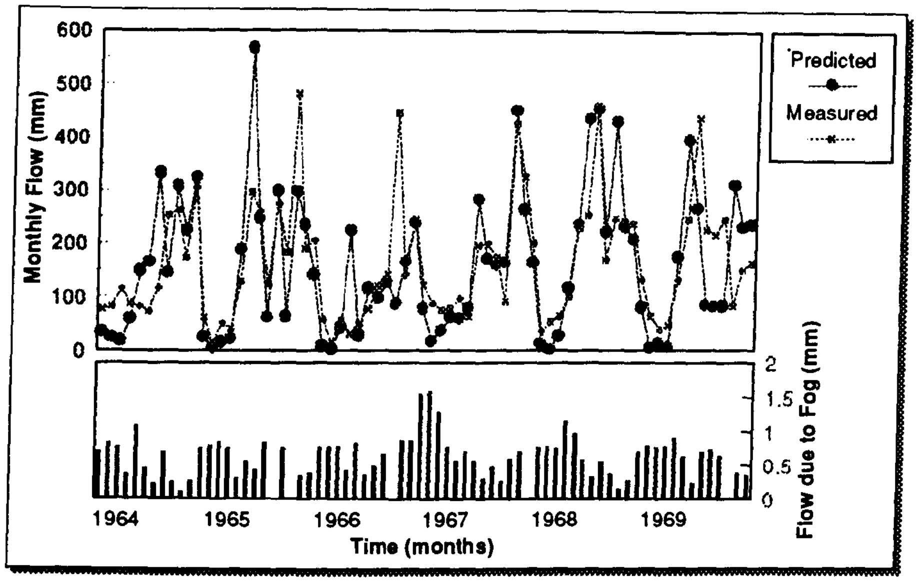


Figure 7.5(c) Simulated (with fog), Measured Flow and Fog Interception for Peradeniya

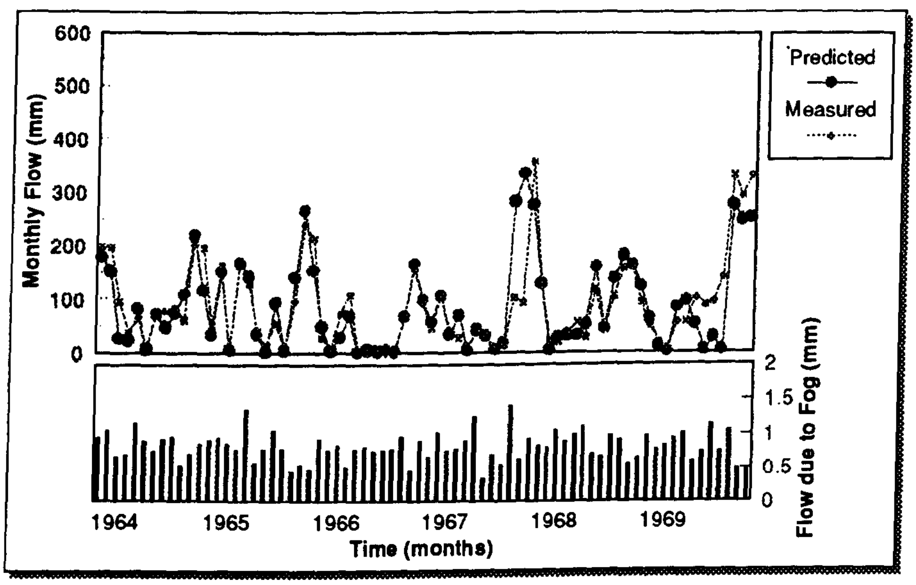


Figure 7.5(d) Simulated (with fog), Measured Flow and Fog Interception for Victoria

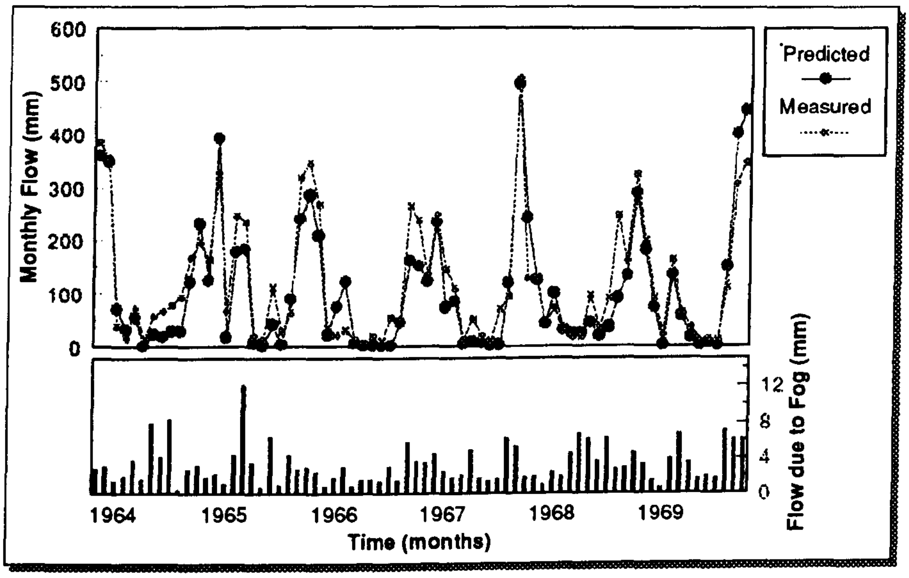


Figure 7.5(e) Simulated (with fog), Measured Flow and Fog Interception for Randenigala

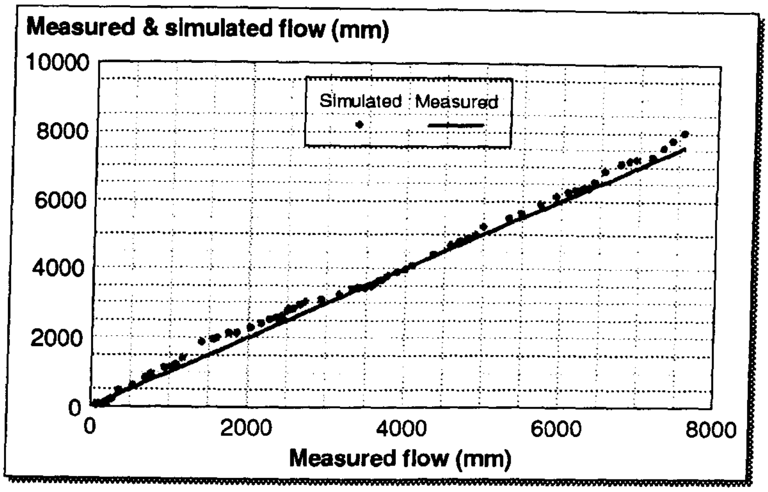


Figure 7.6(a) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ (with fog) for Talawakele

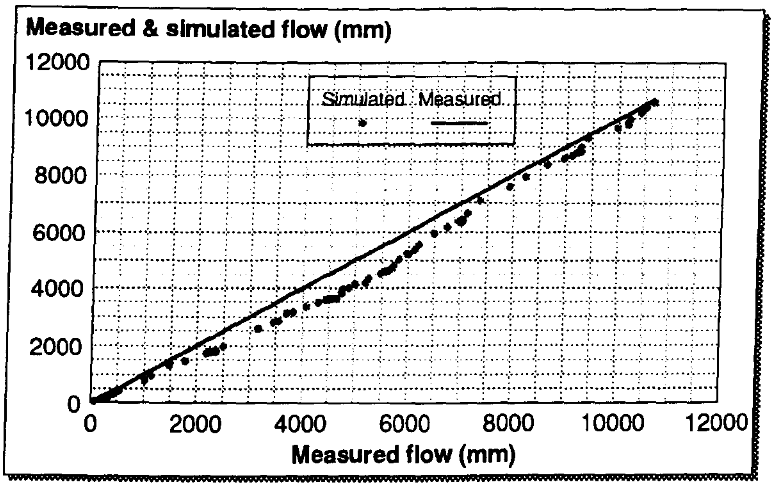


Figure 7.6(b) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ (with fog) for Kotmale

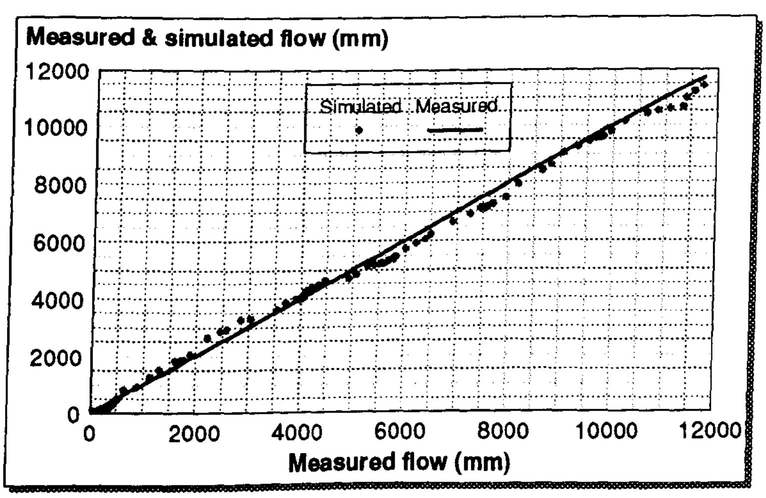


Figure 7.6(c) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ (with fog) for Peradeniya

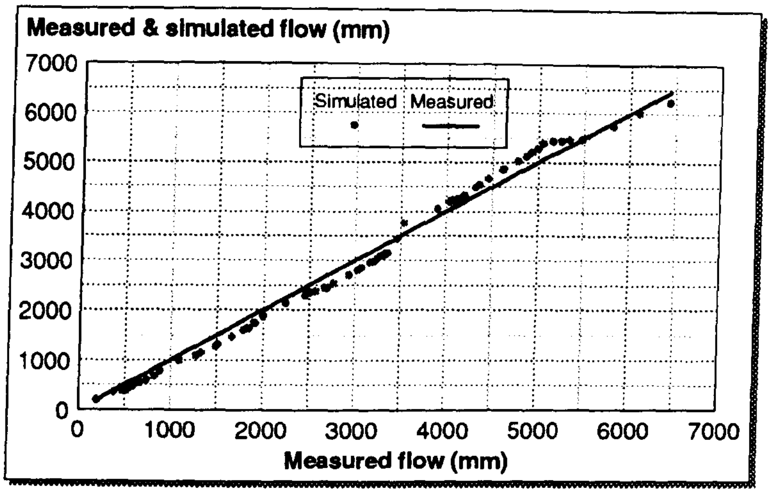


Figure 7.6(d) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ (with fog) for Victoria

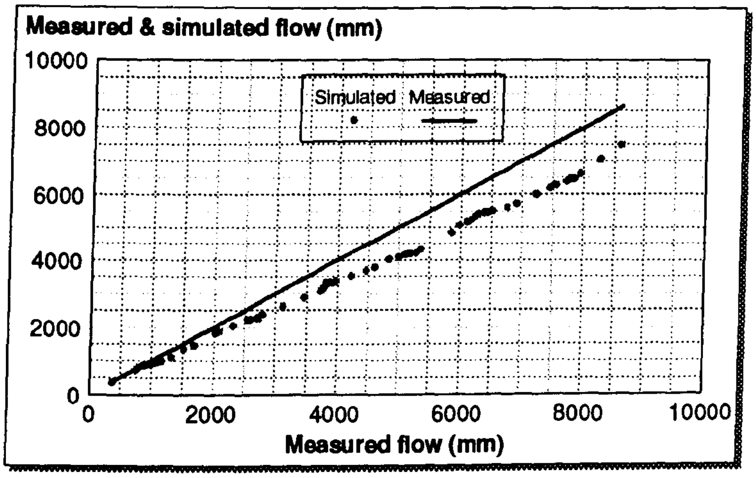


Figure 7.6(e) Plot of $\sum Q_{measured}$ & $\sum Q_{simulated}$ (with fog) for Randenigala

Table 7.4 Statistical Summary of Hydrological Modelling Results (with fog interception)

Sub Catchments / Statistical Parameters		Talawakele	Kotmale	Peradeniya	Victoria	Randenigala
Mean (mm)	Measured	105.12	148.14	163.11	89.51	119.8
	Simulated	111.0	146.62	157.86	88.21	106.2
STD (mm)	Measured	68.8	141.82	111.72	83.34	116.42
	Simulated	96.25	134.65	131.90	85.72	120.15
Coefficient of Determination		0.86	0.83	0.82	0.89	0.96
Cross Correlation Coefficient		0.75	0.70	0.68	0.82	0.92
Lag 01 Correlation		0.23	0.23	0.23	0.30	0.46
Coefficient of Efficiency*1		0.14	0.85	0.22	0.82	0.92
Residual Mass Curve Cof.*2		-1.09	-1.23	-0.79	0.58	0.45

The comparison of the simulated mean values in Table 7.2 and Table 7.4 shows that the model performance in all the sub catchments has improved due to the inclusion of fog interception in the model. However, it also shows the increase of variability in the simulated data which included fog interception, compared with that of the other without fog. All the other statistical measures including the coefficient of determination, the cross correlation coefficient, the coefficient of efficiency and the residual mass curve coefficient do not show any improvement with the fog data. Further improvements are required to establish a better mathematical relationship for interception in the model.

7.5 Sensitivity Analysis

Hydrological sensitivity can be defined as the rate of change of the hydrological output with respect to the change in one or more parameters of a hydrological model (McCuen

& Snyder, 1986). In general, a simplified system is described by the input function, the output function and the response function. The response function is the mechanism responsible for the transformation of inputs to outputs and is often defined by a distribution function which depends on one or more parameters.

Parametric sensitivity takes the following form on absolute terms (McCuen & Snyder, 1986).

$$S = \delta.O / \delta.P \qquad \text{(Eq. 7.4)}$$

where S is the Parametric sensitivity,

$\delta.O$ is the change in output and

$\delta.P$ is the parametric change.

However, for comparison purposes, relative sensitivity is defined as in Eq. 7.5.

$$S = \frac{\delta.O / O_o}{\delta.P / P_o} \qquad \text{(Eq. 7.5)}$$

where O_o is the original output value and

P_o is the original parametric value.

Most of the sensitivity analysis dealt in this chapter are devoted to measure the effects of the parameter variations on the flow regime.

7.5.1 Sensitivity of Spatial Interpolation Algorithm

Four different spatial interpolation techniques, previously discussed in section 6.3, were applied to a daily rainfall data set for the comparison of the interpolation performance of each method. These interpolation techniques were employed separately to derive maps showing the spatial distribution of rainfall over the catchment for each day. For the purpose of comparison of the interpolation methods, a 5 km grid was overlaid upon the daily rainfall maps and the values of rainfall for each interpolation method at each grid point were obtained.

At each point on the 5 km grid, a mean value of interpolation was calculated using the data obtained from these four methods for the purpose of comparison because there were no observed data to make a comparison at ungauged locations. The deviation of each interpolated daily value from the mean value of interpolation was calculated for each point. Both positive and negative deviations were considered separately and cumulated for all grid points in order to establish the range of total deviation from the catchment average as shown in Figures 7.7(a) through 7.7(d). Further, the net deviation for each day, which is the gross total of both negative and positive deviations of all the grid points, was also plotted in the same graphs in order to illustrate the direction of overall deviation of each method from the daily mean interpolated value for the catchment.

According to the results, linear interpolation appears to better than the others due to its capability to produce results with least deviations from the average value derived from all the four methods. Further, in general, the spatial averages of linear interpolation values tend to follow the mean of the four methods very closely (Figure7.7(a)). Non-linear interpolation estimations are mostly on the high side of the mean interpolation (Figure 7.7(b)). Potential mapping also produces values with low net deviations from the mean interpolation but these values are generally found to be slightly lower than the mean figures (Figure 7.7(c)). Thiessen polygons are found with the highest deviations but the values are found both high and low sides of the mean value, producing lower cumulative deviations (Figure 7.7(d)). Since there is no measured absolute reference for the actual rainfall distribution in the catchment and also that the analysis was based on a daily data set for a period of one month, a firm conclusion cannot be drawn from this analysis on the best method of interpolation. However, from the view point of practicality in the spatiotemporal modelling, Thiessen polygon was the most efficient method.

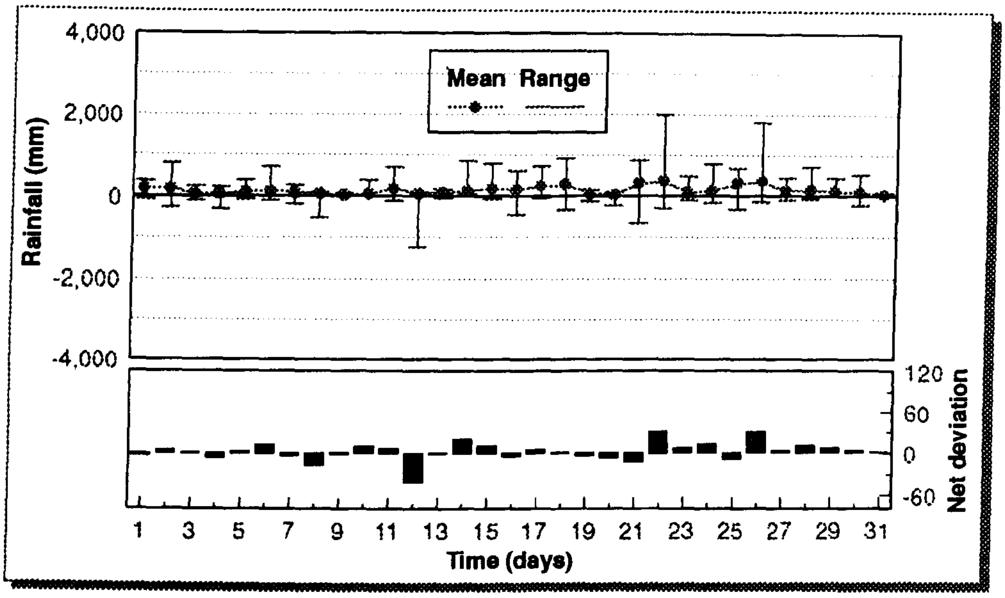


Figure 7.7(a) Comparison of Linear Interpolation with Interpolated Mean

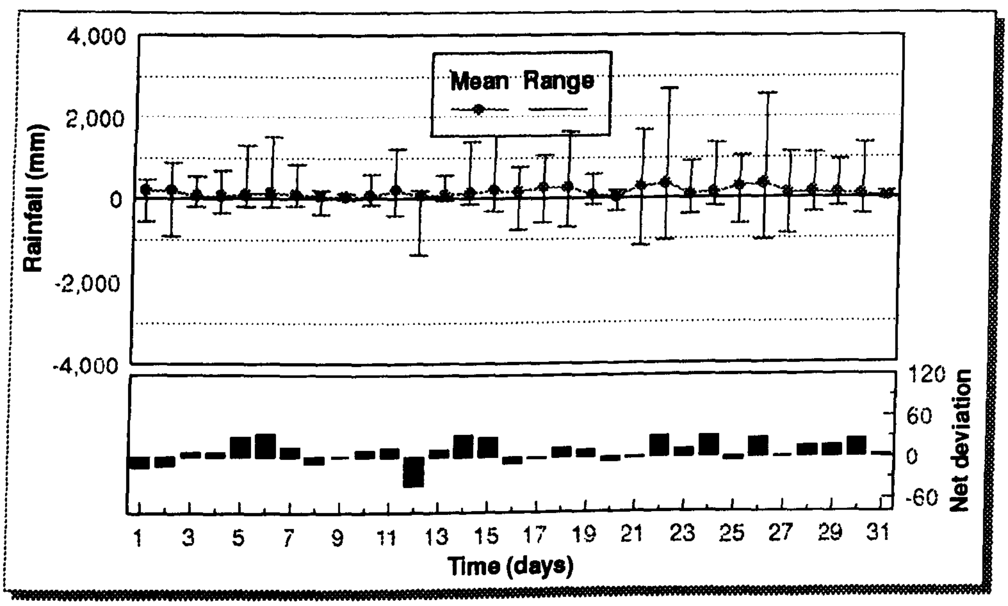


Figure 7.7(b) Comparison of Non-Linear Interpolation with Interpolated Mean

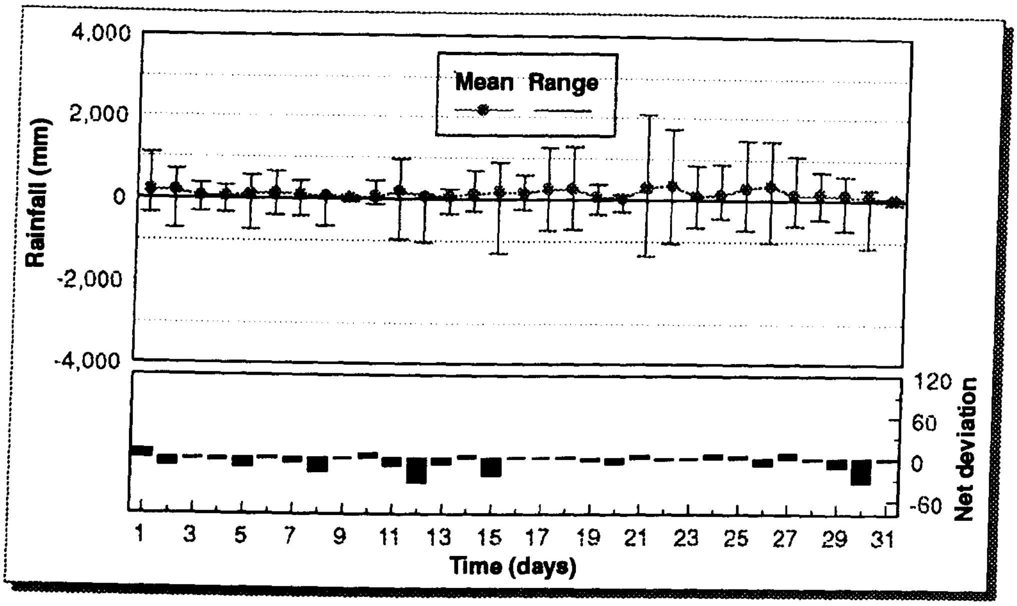


Figure 7.7(c) Comparison of Potential Mapping with Interpolated Mean

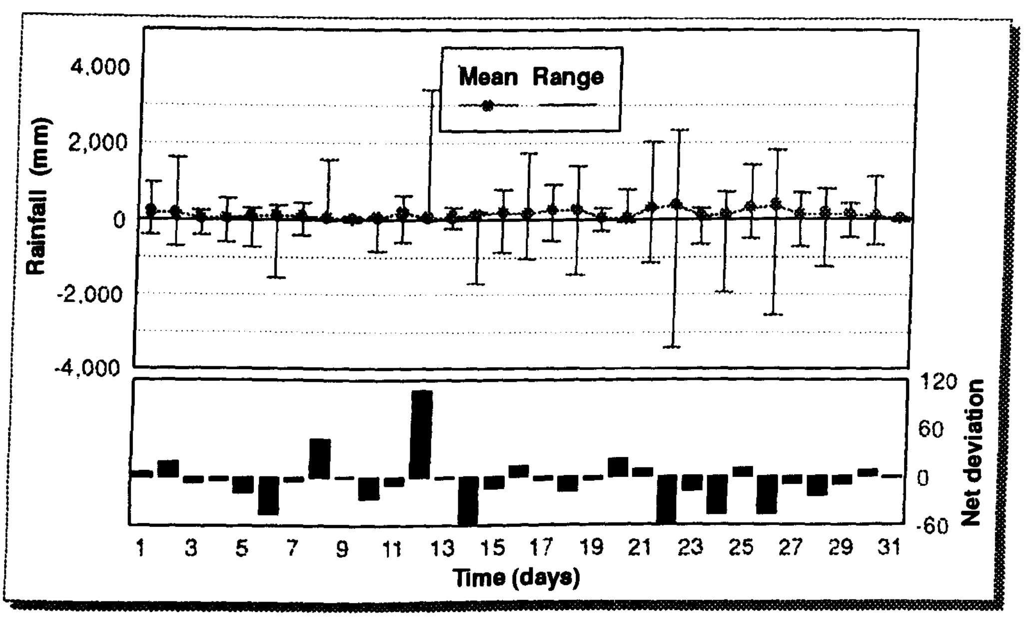


Figure 7.7(d) Comparison of Thiessen Polygon with Interpolated Mean

7.5.2 Model Sensitivity for Parameter Definitions

The sensitivity of the model for the defined parameters of available water and evaporation was assessed independently.

The initial parameters of available water used for the four different land uses namely, forest, grass, tea and plantation forests were 380, 150, 300 and 380, respectively, as discussed in sections 4.4 and 4.5. As shown in Table 7.5, available water for each land use type was doubled independently in each trial run and the model performance was evaluated for a period of 6 years from 1988 to 1993 defining spatial distribution of land use from supervised classification of IRS imagery for the five sub catchments. The rainfall data was used from a different time period in this analysis in order to make use of the image classification for land use data. The use of 1992 image data in the analysis provided statistics on the computational time required for modelling for the comparison of that from 1956 land use. No difference in terms of the required computational time was observed in these two cases.

Table 7.5 Parameter Definitions for Sensitivity Analysis

Land use	Original AW	Trial 1	Trial 2	Trial 3	Trial 4
Forest	380	***760****	380	380	380
Grass	150	150	***300****	150	150
Tea	300	300	300	***600****	300
Plant Forest	380	380	380	380	***760****

* altered parameter

The time series of the originally simulated flow, the simulated flow after changing parameters and the magnitude of change due to the parametric sensitivity are shown in Figures 7.8(a) through 7.8(e). According to the results, natural forests are highly sensitive to the increase in available water. Although the sensitivity was measured for a 100% increase in available water, the effect is large on natural forest due to the fact that initial available water content assumed to be in natural forest is comparatively high and the percentage increase makes it much higher. Plantation forest having the same hydrological parameters seem to show a lower sensitivity due to its comparatively low coverage in the catchment. Grass is the most insensitive land use type despite the fact that it covers the majority of the area as a percentage.

This particular comparison is unique to the UMCA because the land use distribution is a crucial factor affecting the sensitivity. Further, these results do not provide any indication on the strength of the parameters used in the hydrological model. The rationale behind this sensitivity analysis was to identify the direction of change of model output and the degree of such change in the basic simulation due to the change of individual available water parameter in the hydrological model. In almost all cases, the results show higher sensitivity at high flow situations. Accordingly, the sensitivity estimations made in this comparison would be significantly lower in a dry environment.

In addition to the available water, the effect of the evaporation parameter was also assessed. The original model assumed a temporal division of the potential annual evaporation value of 986 mm (1408 mm of open water evaporation x 0.7 efficiency factor) as discussed in section 4.4. The modelling outputs were obtained for the potential evaporation values of 1408 mm (2011 mm * 0.7) and 1972 mm (2816 mm * 0.7). The change of flow regime due to the increase of evaporation is shown in Figures 7.9(a) and 7.9(b) for the UMCA.

It is clear that the increased potential evaporation rates introduced into the model have a marked effect on the derived flow statistics. Hence, it is emphasised that a proper regional index of evaporation is required for better results in hydrological modelling. The temporal partitioning of the annual potential evaporation may also be sensitive due to the bi-modal rainfall distribution pattern in UMCA. However, these result cannot be generalised to apply elsewhere with different rainfall conditions due to the fact that rainfall distribution is undoubtedly responsible for the water balance via the soil moisture stress moderator.

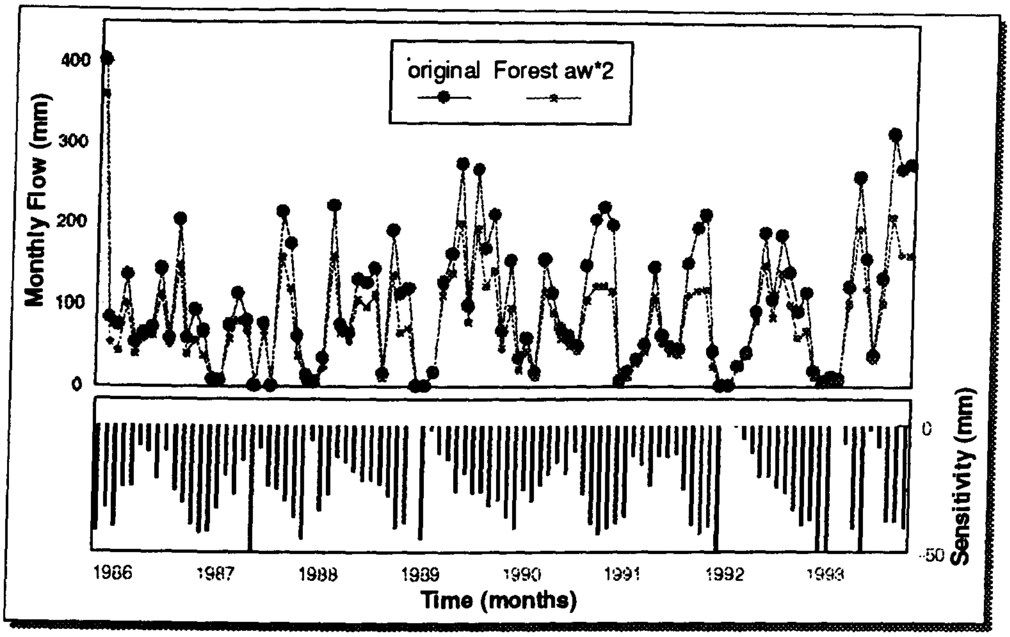


Figure 7.8(a) Sensitivity of Catchment Flow to Available Water Definition for Forest

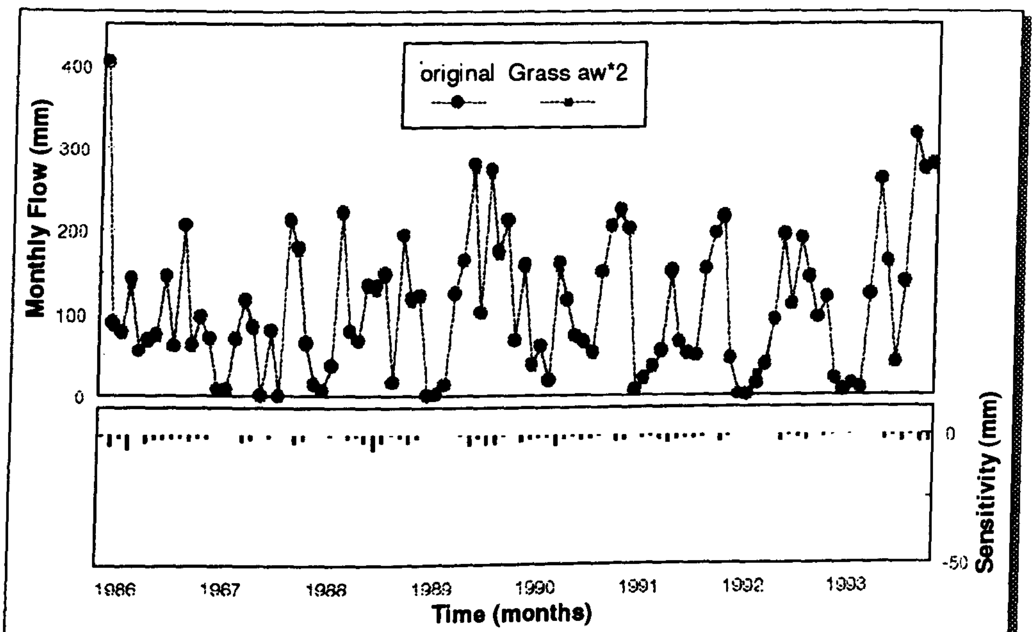


Figure 7.8(b) Sensitivity of Catchment Flow to Available Water Definition for Grass

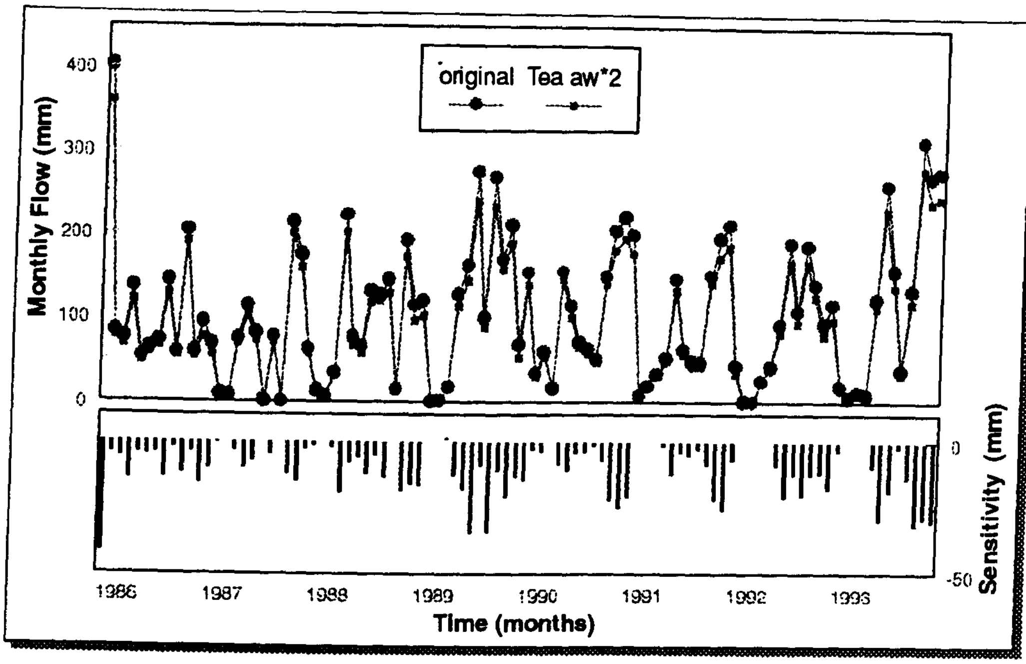


Figure 7.8(c) Sensitivity of Catchment Flow to Available Water Definition for Tea

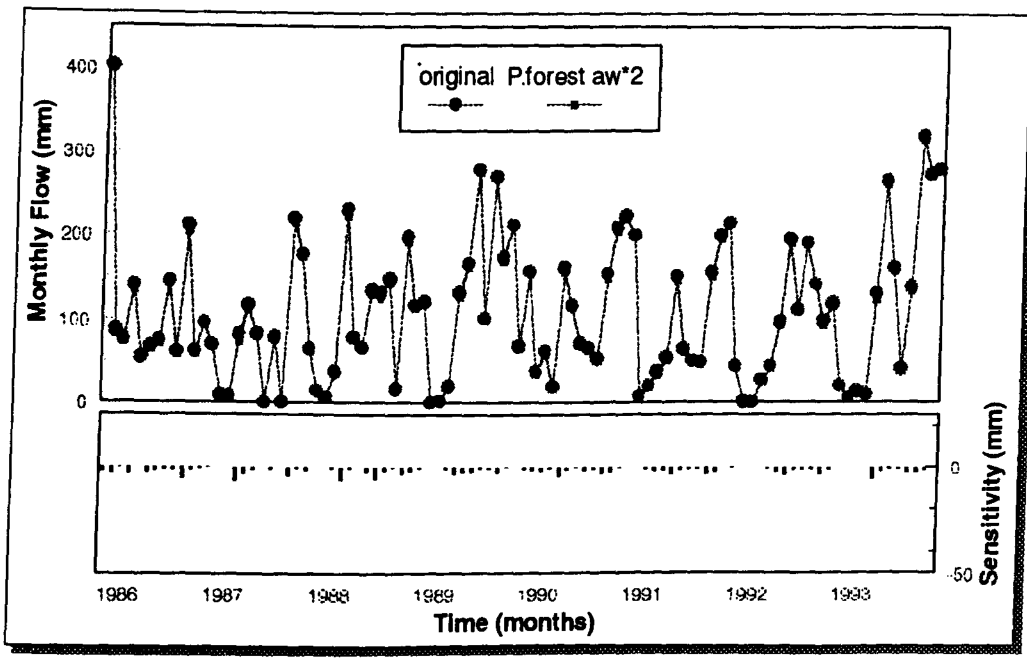


Figure 7.8(d) Sensitivity of Catchment Flow to Available Water Definition for Plant. Forest

7.5.3 Sensitivity for Spatial Definitions of Land Use

The sensitivity of the hydrological model for spatial definitions of land use was critical for the success of simulation scenarios. The issue of spatial changes in the simulation mainly involved in the spatial distribution of land use. The model is expected to be highly sensitive for the land use conversions. An attempt was made in this section to evaluate the model sensitivity for the hypothetical extreme changes of land use.

The hydrological model was considered separately, with and without the fog interception component for the analysis in order to maintain the sensitivity identity of each land use. Fog interception was considered only for natural forest as described in chapter 4. Four individual cases were studied where in each case, individual land use type was assumed to be covering the entire catchment. Hydrological parameters for forests and plantation forest were assumed to be the same in the model and hence, modelling results were limited to three different land uses. Figures 7.10(a) through 7.10(c) illustrate the modelling results without fog interception and Figure 7.10(d) shows the modelling results for natural forest with fog interception in UMCA.

In addition, Table 7.6 shows the water yield for these land use scenarios and the percentage changes in comparison to the total forest scenario. The results show the sensitivity of the model to land use changes. Even with the additional precipitation derived from the fog interception, in most of the cases, the water yield of the forest is comparatively lower than that of grass.

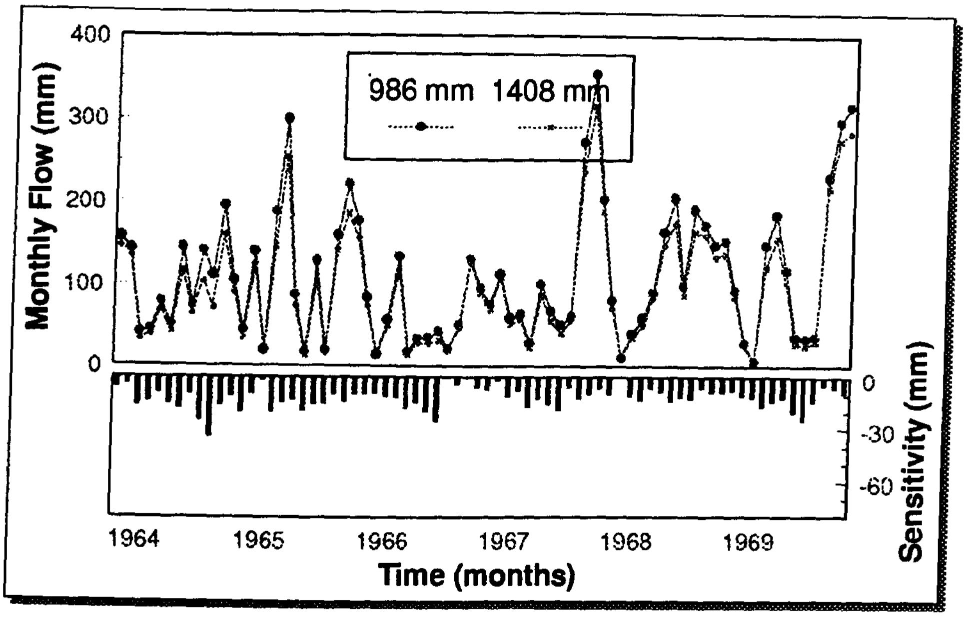


Figure 7.9(a) Sensitivity of Catchment Flow to Evaporation Parameter

(986 - 1408mm)

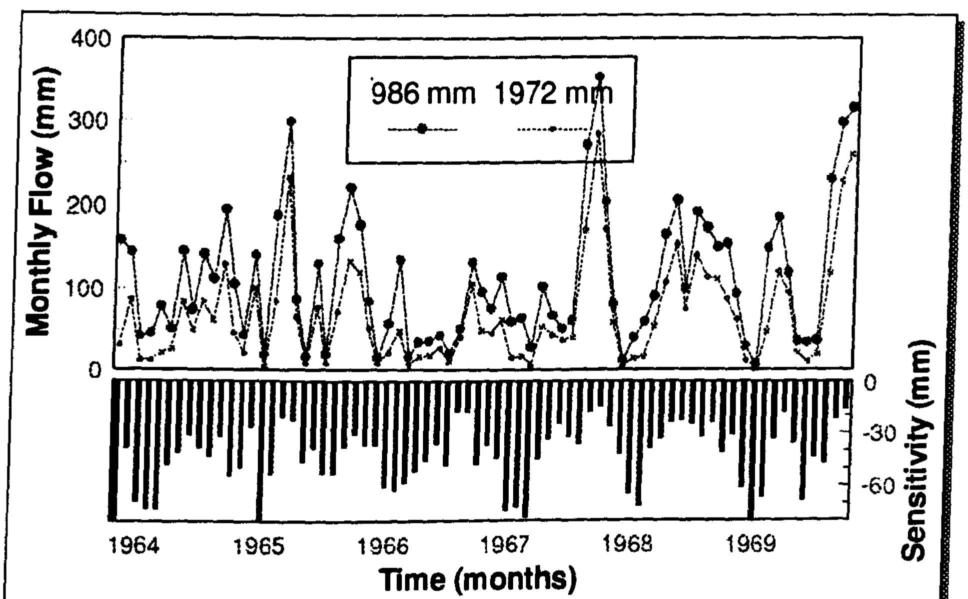


Figure 7.9(b) Sensitivity of Catchment Flow to Evaporation Parameter

(986 - 1972mm)

Table 7.6 Simulated Flow for Hypothetical Extreme Land Use Scenarios and Percentage Changes with Total Forest Scenario

Forest	Grass	% change[1]	Tea	% change[2]	Forest+fog	% change[3]
146.36	168.66	15.24	163.05	10.24	150.82	3.05
135.03	151.79	12.41	144.67	6.66	140.41	3.98
33.74	47.14	39.72	44.63	24.40	36.30	7.59
38.15	50.18	31.53	46.29	17.58	41.43	8.60
70.21	87.84	25.11	80.53	12.82	80.00	13.94
42.61	55.06	29.22	51.72	17.61	52.02	22.08
116.41	152.40	30.92	143.46	18.86	142.68	22.57
65.64	79.66	21.36	76.17	13.82	76.53	16.59
103.98	123.46	18.73	117.28	11.34	140.62	35.24
72.13	98.79	36.96	90.82	20.58	98.81	36.99
160.18	201.41	25.74	186.31	14.03	180.15	12.47
92.04	119.96	30.33	108.39	15.08	98.00	6.48
33.99	48.45	42.54	45.44	25.20	40.76	19.92
124.53	148.35	19.13	142.11	12.37	127.45	2.34
18.30	21.24	16.07	18.36	0.33	19.25	5.19
146.58	205.72	40.35	180.93	18.99	183.18	24.97
252.65	300.55	18.96	287.54	12.13	286.74	13.49
74.14	94.27	27.15	90.60	18.17	75.73	2.14
12.83	16.56	29.07	15.91	19.36	15.07	17.46
107.13	143.99	34.41	136.72	21.64	117.88	10.03
45.86	54.55	18.95	52.14	12.04	48.11	4.91
141.63	191.50	35.21	171.49	17.41	148.71	5.00
186.23	209.70	12.60	202.13	7.87	199.72	7.24
156.51	192.88	23.24	183.99	14.94	162.67	3.94
75.12	92.84	23.59	88.43	15.05	78.81	4.91
12.97	16.10	24.13	15.14	14.33	13.64	5.17
50.03	64.12	28.16	60.35	17.10	54.18	8.30
117.53	136.04	15.75	131.62	10.71	123.91	5.43
13.59	17.98	32.30	17.01	20.11	17.22	26.71
18.05	31.80	76.18	30.23	40.29	33.40	85.04
28.06	38.13	35.89	36.98	24.12	34.78	23.95
21.15	46.14	118.16	43.53	51.41	33.22	57.07
104.95	194.64	85.46	173.92	39.66	132.40	26.16
158.62	209.19	31.88	197.11	19.53	162.08	2.18
88.92	119.96	34.91	114.05	22.03	91.85	3.30
69.08	89.91	30.15	86.39	20.04	74.21	7.43

1, 2 and 3 - in comparison with total forest scenario, the percentage changes in total grass, total tea and total forest with fog scenarios, respectively.

Comparison of Figures 7.10(a) and 7.10(b) provides some insight on the possible increase of flow regime when forests are converted to grassland or its equivalent use and vice versa. Moreover, the results indicate the possibility of further improving water yield by introducing forest plantations at strategic locations for high fog interception.

7.5.4 Spatial Resolution and Sensitivity

Spatial resolution is defined in terms of quad level in the unique quadtree data structure adopted by SPANS GIS. Within the software architecture, the available quad level ranges from 1 to 15 and with increasing level of order, the spatial resolution increases. The number of available quad cells is equal to the $2^n \times 2^n$ where n is the quad level.

The effect of quad level on the spatial discretisation of sub catchments, the storage requirements and the processing speed have been enumerated in chapter 6. Here, the focus is on the results of modelling to determine whether there are significant differences in the simulated flow due to changes in the quad resolution. A data set of randomly selected two consecutive years is used for the analysis.

Table 7.7 summarises the results of modelling at different quad levels. Student t-test was conducted, as discussed in chapter 6, to ascertain whether the mean flows are significantly different at different quad resolutions.

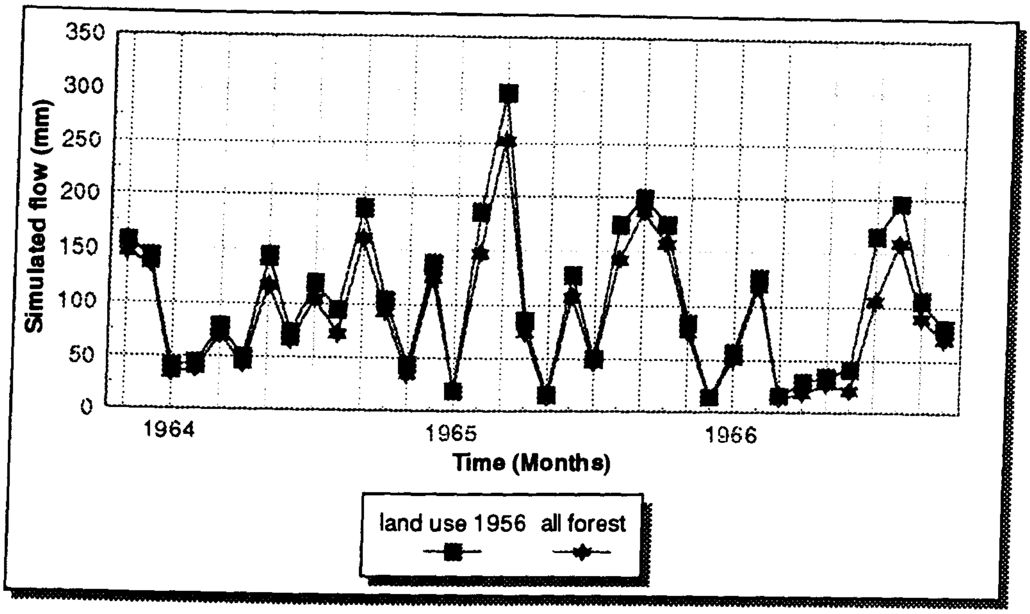


Figure 7.10(a) Flow Comparison of 1956 Land Use and Total Forest/ No Fog Scenario

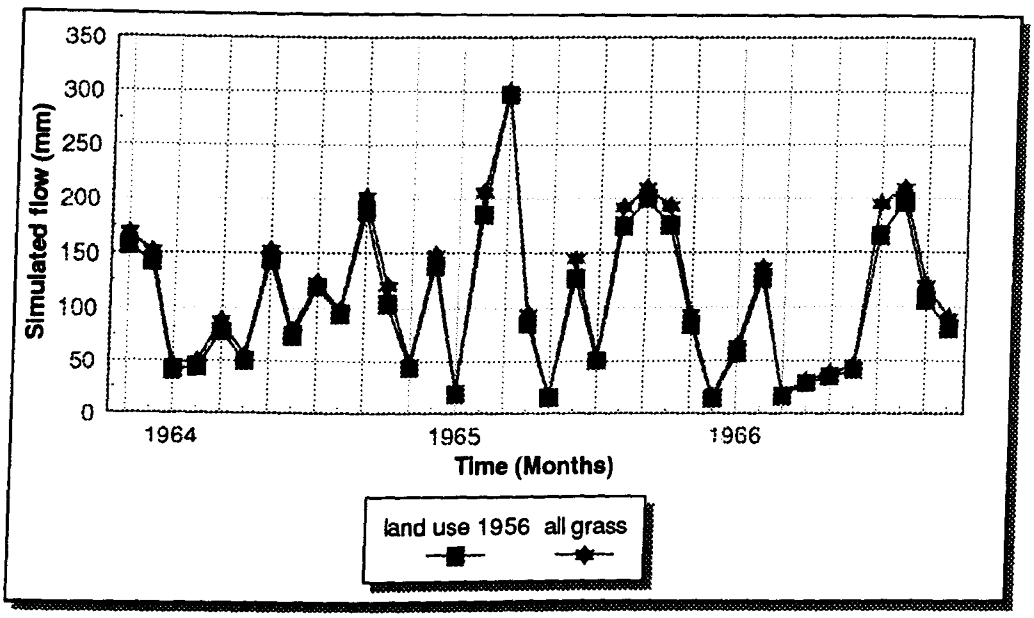


Figure 7.10(b) Flow Comparison of 1956 Land Use and Total Grass Scenario

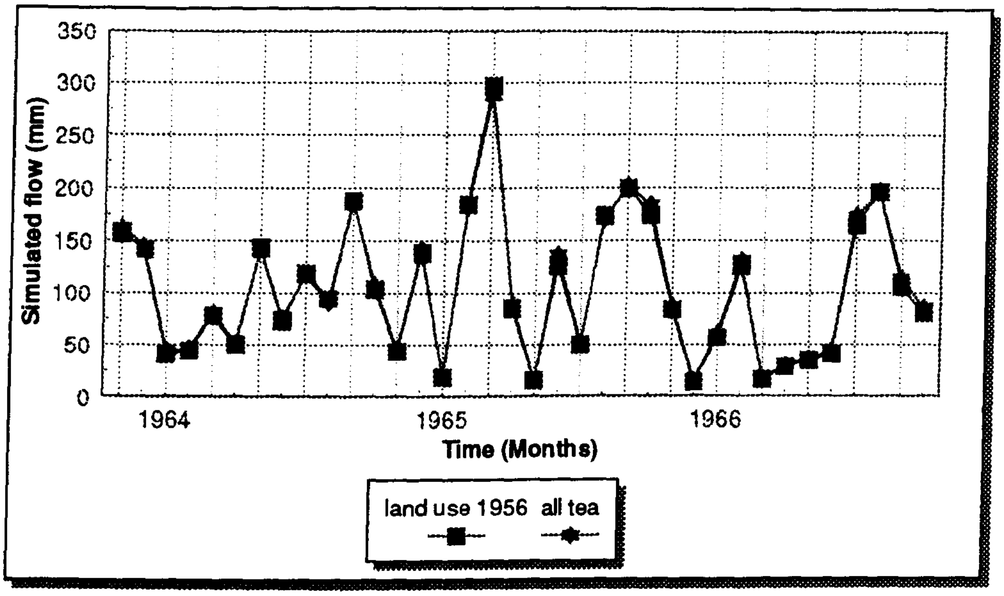


Figure 7.10(c) Flow Comparison of 1956 Land Use and Total Tea Scenario

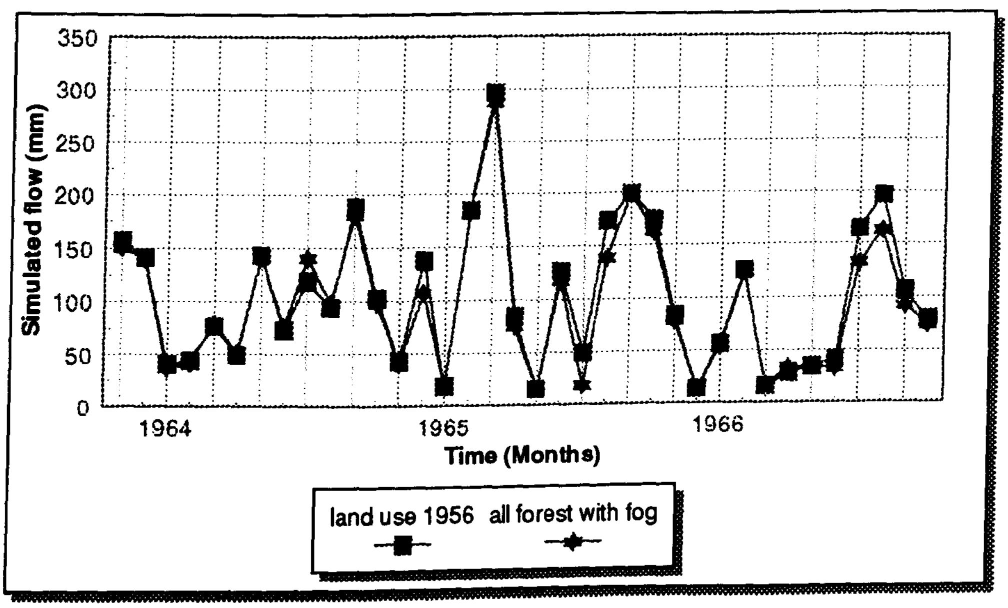


Figure 7.10(d) Flow Comparison of 1956 Land Use and Total Forest with Fog Scenario

Table 7.7 Simulated Flow at Different Quad Resolutions (1986 - 1987)

Month	Quad level	Quad 07	Quad 09	Quad 11	Quad13
1986	Jan	402.084	398.346	397.84	397.06
	Feb	83.387	87.883	86.987	87.05
	Mar	75.263	76.778	76.181	76.19
	Apr	135.592	140.274	139.111	138.95
	May	54.09	54.307	54.056	53.99
	Jun	64.946	68.982	67.629	67.35
	Jul	71.951	37.443	38.59	38.71
	Aug	143.202	145.662	151.015	150.81
	Sep	30.751	30.754	32.501	32.56
	Oct	203.931	210.809	233.968	233.73
	Nov	59.26	62.205	63.174	63.23
	Dec	93.776	95.991	94.806	94.75
1987	Jan	68.431	70.101	69.799	69.84
	Feb	8.305	8.69	9.47	9.47
	Mar	6.945	7.187	7.889	7.96
	Apr	74.822	82.556	82.498	82.71
	May	112.996	117.509	116.891	116.99
	Jun	81.177	84.092	90.455	90.14
	Jul	14.832	15.324	151.146	151.14
	Aug	1.854	10.931	112.707	112.44
	Sep	15.341	15.92	157.098	157.07
	Oct	32.45	33.18	332.022	331.93
	Nov	174.661	176.548	176.112	176.04
	Dec	62.22	65.249	64.928	64.91
	Mean	113.9	116.45	116.95	116.88

In the statistical analysis, a separate time series was generated to represent the difference between simulated flow at one quad level and each of the other quad levels as paired observations. The rationale for using paired observations and the computation procedure of t-test statistics are outlined in section 7.3.2. The null and alternative hypothesis were $\mu=0$ and $\mu \neq 0$, respectively for the two-tailed t-test.

Table 7.8 Matrix of T-test Statistics for Quad Level Comparison ($T_{(0.95, 24)}$ =2.05)

Quad level	Quad 07	Quad 09	Quad 11	Quad 13
Quad 07	0			
Quad 09	4.91	0		
Quad 11	5.27	1.16	0	
Quad 13	5.04	1.00	1.90	0

According to the results in Table 7.8, all the quad levels have produced equal means .except quad level 7. Hence, the quad level 9 is the best resolution for spatiotemporal modelling provided that the all the data used for modelling comply with this resolution. However, the differences of values in Table 7.7 are negligible in practical terms though they are statistically significant. In this case, the differences are mostly within 2-3% while increase in computation time for a higher quad level is more than 100%. This also justifies the selection of quad level 7 for model computations even though it is not the best in terms of statistics.

7.6 Propagation of Error

7.6.1 Overview of Errors in GIS

The fundamental principles of GIS are oriented upon the spatial entities and non-spatial attributes. Positional errors and attribute uncertainties are characteristics of all spatial databases (Brunsdon & Openshaw, 1993). There are errors propagated and amplified by GIS operations which can adversely affect the application potential of the GIS technology. Further, input data quality is often not ascertained, and functions are applied without due regard for accuracy of the resulting products. The derived products are also presented without associated estimates of their reliability or an indication of the types of errors introduced by GIS processing (Lanter & Veregin, 1990).

While the goal of eliminating errors from the output products may at present, prove to be not feasible, decision making process should at minimum be provided with a means of assessing the accuracy of information upon which the decisions are based. Although error models have been developed for certain GIS operations (Brunsdon & Openshaw, 1993; Openshaw et al., 1991; Goodchild, 1989), these models have not widely been adopted in practice. One impediment to their more wide-spread adoption is that no single error model or no single definition of accuracy is applicable to all instances (Veregin, 1993).

7.6.2 Sources of Errors

Errors in the products derived from GIS can mainly be introduced from two sources (Walsh et al., 1987). An assessment of accuracy needs to evaluate the inherent error which is the error present in source data and the operational error produced through the data capture and manipulation functions of GIS. The occurrence of inherent and operational errors in GIS has been well documented by Vilek et al. (1984).

The inherent errors can be assessed by comparing the original field data with digital data in GIS databases. Development of an accuracy matrix is the most common form of evaluation (Walsh et al., 1987). Operational errors are categorised as potential errors and identification errors (Newcomer & Szajgin, 1984). Positional errors stem from inaccuracies in the horizontal placement of boundaries. Identification errors occur in mislabelling of areas, digitising, classification and delineating data boundaries and due to GIS algorithm inaccuracies and human bias (Walsh et al., 1987).

A detailed categorisation of errors in GIS has been presented by Burrough (1986). According to the factors governing errors in GIS, the identified three groups include (i) obvious sources of errors arising from poor data (ii) errors resulting from natural variations or from original measurements (iii) errors arising through processing.

The accuracy of GIS derived products has also been viewed at user's perspective depending on the required quality and allowable error (Marble & Peuquet, 1983). Burrough (1986) suggested that results from some mathematical models in a GIS may have wide error margins as to be useless for specific applications requiring stringent levels of accuracy. As the total elimination of errors seems to be quite a remote possibility, errors should be reduced and managed in order to avoid the invalidation of the results and information produced by GIS (Arnoff, 1985).

7.6.3 Error Propagation in Hydrological Modelling

Numerical estimation of error propagation at each level of processing in the hydrological model is beyond the scope of the study and probably not possible because of data limitations. However, it is possible to provide a brief description of possible errors that may be introduced into the hydrological model, as a guidance for an evaluation of accuracy and reliability characteristics of modelling results. This will help to more comprehensively cope with the errors in subsequent analysis or interpretation of the results. Table 7.9 summarises the possible errors involved in the spatiotemporal hydrological model in GIS.

Table 7.9 Possible Errors involved in Hydrological Modelling

Process	Source	Data Types Involved	Description of Error
Data collection	Errors in original data	Rainfall, flow, land use, satellite data, elevation	Inherent properties in nature such as gradual variations over space Spatial or temporal averaging Inherent errors in data Identification errors Errors in formatting data Conceptual errors
	Errors in measurements	Rainfall, flow, land use, satellite data, elevation	Errors in scale of measurement Human errors in measurement & human bias Errors in sampling and frequency Instrument inaccuracies
Data input	Data encoding	Land use, gauging locations, catchment delineation, numerical data	Digitising errors Scale and resolution errors Keyboard entry errors
Data representation	Functionality limitations of GIS	All spatial data and non-spatial attributes	Scale and resolution errors Feature or boundary definition errors Discretisation errors Errors in entity definition
Data processing	Functionality limitations of GIS	All spatial data and non-spatial attributes	Errors in interpolation, classification, generalisation. Errors in decimal representation Overlaying and vector/ raster conversions
	Functionality selection criteria	All spatial data and non-spatial attributes	Misuse of logic Errors in mathematical formulation
	Image processing	Satellite data	Errors in geometric correction Errors in field data Errors in training data collection and classification
	Process Identification and representation		Errors in fog interception, interception sub model, evaporation sub model.
Data Output	Hardware and software problems	All graphical and tabular outputs	Errors in display & printing / plotting devices Errors in data conversions Incorrect media and form of output
Interpretation of results	Conceptual errors	All graphical and tabular outputs	Poor understanding of the system behaviour

7.7 Discussion and Conclusions

7.7.1 Discussion

The preceding sections of this chapter provide a comprehensive summary of the spatiotemporal modelling results including sensitivity analysis and identification of error propagation in modelling.

Monthly water balance showed that the inputs into the catchment system were equal to the outputs plus gains or losses of soil moisture. Because of the limitation to integer representation in map modelling, mathematical formulation of catchment water balance is correct only up to the nearest integer. This was overcome by scaling the data.

The visual display of the modelling results revealed the general trend of the flow regimes. Cumulative plots and residual mass curves indicated the signs of a marginal systematic error. Detailed statistical analysis including measures of coefficient of efficiency and residual mass curve coefficient on individual monthly data which were derived from the basic hydrological model without fog interception component showed the presence of systematic errors in the model results for some months. However, it was not possible to relate these error distribution with monsoon pattern or any other rainfall characteristics.

Comparison of the modelling results with and without fog interception clearly shows the improved accuracy of the model prediction when fog interception is included. Nevertheless, further improvements are required for hydrological parameters in the model for better simulation results.

Sensitivity analysis provides the insight for the identification of further model improvement criteria. The effect of each parameter was isolated and studied. The model was found to be sensitive to land use changes. The sensitivity on spatial definition of land use is important because one of the objectives of the modelling is to simulate the catchment response for land use change scenarios.

The four different spatial interpolation algorithms produced considerably different results with the monthly data set used for the analysis. Hence, the selection of the interpolation technique requires some information on the potential application of the modelling results. In this analysis, linear interpolation was found to be better than the other methods according to the measure of deviation from the mean of the four methods. Since there is no actual measured distribution to compare with, it was not possible to make a generalised conclusion to be valid elsewhere. Further, the results of each interpolation algorithm may be different depending on the location on the points, density of the points, and also on the magnitude of data and the spatial distribution of data.

The model is particularly sensitive to available water parameter in the forest. The available water was defined as a function of land use in the model. However, the status of available water varies spatially to a considerable extent. For an example, the root zone depth of grass at Dodangolla extends even beyond 1500 mm yielding 300 mm of available water if assumed a 20% volumetric water content of the soil. The 150 mm of available water seems to be appropriate for the Horton Plains where moisture rich environment limits the root depth. The situation is similar with the forest too. Further, there is a considerable spatial variation in soil types, soil characteristics, plant foliage type and orientation which can have significant impact on the water losses. Potential evaporation also requires to be represented as a spatially varying phenomenon. Temporal variation of evaporation needs to be linked with the rainfall distribution and the duration.

As a system, hydrological parameters interact with each other to develop the hydrological environment. Hence, each parameter cannot be considered in isolation. The sensitivity analysis needs to be extended to evaluate the interaction among different parameters.

Only the quad level selection for modelling should not be viewed as the criteria for the accuracy of results of a particular set of data. The resolution of data used for modelling is a key factor affecting the accuracy in addition to the quad resolution. Generalised recommendations for quad level selection should accompany the resolution of input data as well.

In the modelling exercise, the issue of error propagation is very complicated due to the combined use of different GIS and non-GIS algorithms. The modelling results will have more credibility when error terms are attached with results. The detailed calculation of error distribution was not possible due to the limited time availability. This highlights the need for a separate study for numerical estimation of the error propagation in modelling. This study was limited to identify and tabulate the sources of each error term and to provide a brief description of the underlying error term.

In general, this is the first stage of spatiotemporal modelling and further model improvements seem to be necessary for a better simulation of hydrology in UMCA.

7.7.2 Conclusions

1. The hydrological model which includes the fog interception is capable of simulating close approximations to the catchment response in UMCA.

2. The modelling results are required to be subject to a detailed statistical analysis in determining the acceptability. Visual comparisons are mostly subjective and hence, should not be used as the only method.

3. The coefficient of efficiency and residual mass curve coefficient are capable of identifying systematic errors present in the modelling results.

4. Sensitivity analysis should be extended to explore the interactions of parameters and how these interactions determine the model output.

5. Linear interpolation, identified to be better than the other method should not solely be the choice for interpolation. In this analysis, Thiessen polygon method was used to keep the computation time to a reasonable level. The potential mapping results could improve vastly provided that the information on the storm origin and the spatial decay rate are known.

6. The error distribution of the initial data layers should be calculated at the beginning and the error propagation should be carried out along with modelling by incorporation of mathematical formulae in modelling equations for the cumulative error assessment.

Chapter 8

8. GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Introduction

The aim of this study was to develop a spatially distributed and temporally oriented hydrological model to simulate the dynamics and behaviour of the UMCA in order to formulate, implement and monitor an effective conservation planning methodology ensuring the long term sustainability of the land and water resources of UMCA. The foregoing chapters explain the procedures adopted to achieve the aims and objectives of the study, namely hydrological data analysis through advanced statistical techniques including time series analysis, Turbo C++ computer programming for hydrological modelling, digital classification techniques, spatiotemporal modelling with GIS and model validation and simulation. All the preceding chapters have concluded with a comprehensive discussion and a set of conclusions corresponding to the findings of the individual chapter. In this chapter, a general discussion and conclusions of the study are summarised and guidelines for further research work are outlined.

8.2 General Discussion

8.2.1 Hydrological Variability

The hydrological environment is very diverse in UMCA although it covers only 3124 sq. km.. The hydrological behaviour of the catchment was studied in detail in chapter 2 in order to acquire a general understanding of the hydrological characteristics of the catchment environment. This was a pre-requisite for hydrological modelling because some of the working assumptions of the model such as rationale for interpolation, rainfall correlation characteristics, were based on the findings of chapter 2.

Unlike the rest of the country where topography is described as mild and undulating, UMCA terrain conditions are mountainous, steeply dissected, hilly and rolling. The topographic variation is also not uniform in UMCA and creates variations in orographic rainfall. Leeward and windward sides of the mountains receive vastly different quantities of rainfall due to rain-shadow effect. The situation is further complicated by bi-modal pattern of the rainfall in two main monsoon seasons. Hence, it was not possible to derive a generalised spatial rainfall distribution for UMCA. Further, the analysis of hydrological characteristics shows that most of the generalised rainfall correlations derived for Sri Lanka are neither valid nor applicable to UMCA.

8.2.2 Analysis of Hydrological Time Series

The development of the spatiotemporal model was based on the premise that there have been no temporal changes in the hydrological inputs due to land use and land cover changes in the catchment or to local or regional climatic drift. This assumption was extensively tested and verified in chapter 3 through time series analysis of rainfall and derived drought related statistics.

It is evident that the analysis of drought related properties of rainfall has direct relevance to practical agricultural applications. A regional differentiation of drought related statistics would be meaningful due to the high degree of regionality found in rainfall characteristics.

The significant increase of variability in hydrological statistics can have serious implications for the long-term sustainability of hydrological structures constructed under the Mahaweli Development Programme. Further, a parallel research programme is required to identify the agronomic practices affected by the increased variability.

8.2.3 Hydrological Modelling

Development of the spatially lumped hydrological model as a Turbo C++ programme was achieved in chapter 4 incorporating fog interception also as a hydrological input. A lumped model was useful as the starting point for distributed modelling in SPANS GIS due to the similarity of the programming logic in Turbo C++ and SPANS Modelling.

Kandyan forest gardens which are more or less unique to UMCA, offer a viable alternative for the traditional plantation forest option. The multi-layer canopy structure is very efficient in soil and moisture conservation. Further, tall tree canopy can efficiently capture the moisture in the clouds to yield additional moisture. Because of the variety of products available, KFG is advantageous even in economic terms.

In the hydrological model, KFG was reclassified as forest for parameter definitions. UMCA contains a considerable area covered by KFG and the area has been expanding steadily. Hence, hydrological characteristics of the KFG need to be evaluated and accordingly, hydrological parameters of the KFG should be derived.

Referring to the model parameters used for plantation forest, it is doubtful whether plantation forests are as efficient as natural forests in capturing the moisture in the clouds. The nature of forest plantations, mostly with one top layer is not conducive for tapping cloud moisture and hence it demands a separate set of hydrological parameters in modelling. Further, the selection of species for forest plantation needs some consideration on this aspect.

The basic formulation of the hydrological model requires improvements mostly in relation to surface based processes such as infiltration, percolation, and ground water flow. Soil characteristics can also play a crucial role in determining the success of modelling results.

8.2.4 Land Use and Land Cover

The developed lumped model depends upon the land use status of the catchment for its hydrological parameter definitions. Hence, it was necessary to identify the detailed land use with exact geographical references. Further, in the spatiotemporal model, new digital data layers were expected to be added routinely, representing the temporal dynamics of land use. Accordingly, the digital classification of land resource satellite data for land cover identification was achieved in chapter 5. In addition, the applicability of IRS LISS II data for land use assessment was verified in this chapter.

From the hydrological point of view, land cover is much more relevant than land use. A particular land use such as tea can have contrasting land cover status but has been categorised into a single land use according to the classification scheme. A classification based on land cover seems to be a better option for the determination of hydrological characteristics. Hence, it is useful to decide upon a methodology for determining the cover density in the field for the ground data base with a properly defined classification hierarchy for land cover assessment. A comprehensive land cover determination requires a quantitative assessment such as leaf area index, along with an approach for characterisation of leaf shape, orientation and roughness.

The issue of resolution was also an important consideration in land use and land cover assessment. High resolution data would be ideal, provided that all the other hydrological characteristics were evaluated at the same spatial resolution. However, when spatial distribution of rainfall was evolved as a product of the point-area interpolation algorithm and the land use differentiation is marginalised to have only four classes, the strict demarcation of land use through a computationally intensive classification of high resolution digital data cannot be justified. Further, the need for repetitive ground data collection for temporal coverage seems to be beyond a compromise solution. Alternatively, the possibility of using unsupervised vegetation indices needs to be further explored. Because of the highly dynamic behaviour of tropical land use and land cover, more temporal coverage is required to be incorporated into hydrological modelling.

Despite the reforestation programmes, the total forest areas show an obvious decrease in UMCA. Land fragmentation due to the high population pressure was evident not only at the peasant household level but also at the large scale tea plantations. Reforestation efforts are less effective unless measures are taken to avoid large scale land degradation especially in the cleared areas of the estate sector.

8.2.5 Hydrological Modelling in GIS

With the knowledge and data gathered from earlier chapters, spatial and temporal dimensions were introduced into the hydrological model within the SPANS GIS environment and a customised application was designed and developed as described in chapter 6 for spatiotemporal hydrological modelling.

Spatiotemporality in GIS is an active area of research. While GIS software, in general, makes no provision for direct handling of temporal dynamism, in this study, SPANS GIS provided the opportunity to represent the time implicitly via modelling related command mode functionality. The model is capable of hydrological simulation at any temporal scale provided that the requirements for hardware efficiency are met.

Because of the complex programming functions involved in this modelling, and the nature of unique approach adopted to overcome software limitations, a comprehensive knowledge was required of both SPANS GIS modelling and hydrological model structure in Turbo C++ programme in order to derive modelling results. The difficulty has been overcome through the customised version of the model which allows the user to run the model without even knowing the basics of SPANS GIS. However, processing speed, output resolution, thematic details of the model outputs can be vastly improved if the user is familiar with the modelling language of SPANS GIS. Also, creation of new data layers and incorporation of new data into the model can only be accomplished by an experienced SPANS user.

The application of the model elsewhere with a different hydrological model would probably find additional limitations in the modelling language and REXX programming set-up. These problems need to be addressed individually.

8.2.6 Modelling and Simulation Results

Modelling results were compared with the measured flow data to validate the model and several 'what if' scenarios were answered in chapter 7. Model performance was improved when fog interception was introduced. However, further improvements in the quantification of fog are required for better results.

The capability of simulation to answer hypothetical 'what if' scenarios is a key feature of the model. The effect of individual parameters on the model performance was evaluated in this study. The model allows interactions among the parameters to be represented but it requires mathematical background for such interactions.

Efficient and accurate flow data collection methods are urgently required to be introduced in UMCA. The non-availability of flow data or poor quality of data whenever available is a serious constraint in water resources management. In this respect, the capability of the hydrological model to simulate flow at any given point of the river network can play an important role in generating flow records at any given temporal intensity.

8.3 Conclusions

The general conclusions in the context of spatiotemporal hydrological modelling in GIS are as follows:

1. Studies on hydrological characteristics of UMCA need to be focused on a smaller regional scale than the entire UMCA. This could be best achieved at sub catchment level due to the relatively uniform distribution of elevation profile, rain shadow effect, and seasonal behaviour of hydrological characteristics.

2. During the period from 1964 to 1993, hydrological time series do not have any significant deviation from stationarity. There has been no major climatic drift or significant influence of land use changes on local hydrology. However, the increased variability found in data series needs more scrutiny. The time scale of the study should be expanded so that any long term repeat cycles can be detected.

3. A basic hydrological model like the UMCA hydrological model used in this study is mostly efficient enough to simulate the catchment response with reasonable accuracy. Any modifications introduced into the model should improve the overall modelling atmosphere rather than attempting to focus on individual processes.

4. The supervised classification of high resolution satellite imagery is not the best solution for the need of information on land use and land cover in the catchment for spatiotemporal modelling. The use of vegetation indices derived from AVHRR data could be a better option.

5. In the model performance, either spatial or temporal dimension is fixed at any given time while the other is considered to be distributed. The rate of this dimension change could be best optimised according to the situation and the quality of data in order to have better outputs. In this study, the facilities available in SPANS GIS modelling have been best utilised in achieving this task.

6. In addition to the simulation scenarios worked out in this study, interactions among the hydrological parameters can be modelled to understand the hydrological environment of the catchment.

8.4 Recommendations for Future Work

Further studies need to be focused on developing and selecting vegetative indices to identify important hydrological characteristics of land use. The definitions of hydrological parameters in the model should also be taken into account in selecting the best vegetative index. It should also be able to derive from satellite data without having detailed information from ground data.

Process based studies are required to derive model parameters for land cover characteristics found in the area. The definition of four major land use groups used in this study is not very efficient in describing the hydrological characteristics of the major land use types in UMCA.

Detailed studies should be carried out for each sub catchment because it was not possible to generalise the hydrological behaviour at the UMCA level. Useful relationships may be developed for sub catchments which could further improve the model efficiency.

The same modelling approach should be attempted for some other catchments with different sets of hydrological environments and the required modifications in the model structure should be recorded. This would provide useful guidelines in developing a universal model within the existing modelling functionality.

Finally, it should be emphasised that the development of a truly temporal GIS is the ideal solution for spatiotemporal modelling. This piece of work would suggest only a bare sketch of a temporal GIS. However, attempts for a true spatiotemporality in GIS could benefit immensely from the experience gained in this sort of study.

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Appendix A

Appendix A-1 GPS Derived Data - A Summary

a) Recording of an almanac file - GPS receiver needs to collect an almanac file in order for it to orient itself with the available satellite constellation. An almanac file is defined as a reduced subset of the ephemeral parameters required to calculate the elevation and azimuth angles of the satellites. Each satellite broadcasts an almanac for all satellites (Trimble GPS User Guide, 1994). The collected almanac file was later downloaded into a computer so that it can detect the location information on the recorded rover files.

b) Calibrating parameters and setting - The most critical parameters required on the accuracy on the GPS is Position Dilution of Precision (PDOP) which measures signal to noise ratio of the receiving signal. The accuracy of the computation of the location depends on selective Availability (SA) and the User Range accuracy (URA) which are controlled by the Department of Defence (DoD). PDOP is set to a threshold value below which the receiver records data for location computation. The other important setting is the Elevation Mask which is the angle below a satellite is considered to be unusable. In the field data collection, PDOP was set to 4 and the elevation mask was 10^0. All the other settings such as datum, mode were used from defaults as Trimble recommends not to change the default settings without a clearly defined procedure.

c) Georeferencing via Rover files - The location information is recorded in Rover files when the GPS signal is strong enough to be below the threshold PDOP. Rover files are automatically named indicating the date and time of data collection. For each location, location information was recorded for 4 minutes and in two different rover files. The data were collected in 3D mode with a view to look at the error distribution in elevation data. In general, the elevation data were in a range of + or - 100m from actual values.

d) Determining geographical co-ordinates - The collected river files were downloaded to the computer via the serial port connection. MS-DOS based Trimble software was used for the file processing.

Rain Gauging Locations and Estimated & Recorded Elevations

No.	Station Name	Latitude#	Longitude#	MSL (m)*	HAE (m)**	ELEVATION (m)
1	Bandara Eliya	6 47 01	81 00 12	1434	1338	1784
2	Campion Estate	6 46 49	80 42 09	1413	1317	1460
3	Hakgala	6 55 32	80 49 18	1745	1649	1707
4	Hatton Waterworks	6 55 30	80 35 95	1273	1177	1250
5	Kenilworth	7 00 05	80 28 47	702	606	700
6	Lower Spring Val.	6 55 06	81 06 14	1427	1331	1446
7	Maskeliya	6 50 01	80 34 26	1116	1020	1220
8	Welimada	6 54 33	80 53 47	1103	1007	1076
9	Gowrakelle	6 53 59	81 05 29	1302	1207	1261
10	Dunsinane	7 00 16	80 41 44	1510	1414	1480
11	Kurundu oya	7 04 19	80 50 03	1564	1468	1584
12	Nawalapitiya	7 03 19	80 32 09	556	460	580
13	Ledgerwatte	7 01 48	81 00 28	1276	1181	1369
14	Liddesdale	7 01 02	80 51 17	1621	1525	1569
15	West Haputale	6 46 36	80 57 47	1299	1203	1707
16	Annifield Est.	6 52 24	80 38 09	1435	1339	1460
17	Abergeldie	6 54 45	80 34 22	1085	989	1120
18	Debedde	6 57 27	81 07 13	1022	927	1123
19	Hope Estate	7 06 37	80 44 39	1317	1221	1384
20	Wewasse	6 57 45	81 06 17	772	676	1113
21	Kirklees	6 59 07	80 56 20	1503	1407	1446
23	Katugastota	7 20 04	80 37 35	529	433	530
24	Bandarawela	6 49 50	80 59 10	1233	1137	1076
25	Ambewela	6 52 41	80 48 48	1772	1676	1846
26	New Forest	7 09 10	80 40 50	1046	950	1123
27	Sandrineham	6 50 36	80 45 12	1644	1548	1620
28	Wewalthalawa	7 03 10	80 23 05	865	769	892
29	Sogama	7 07 25	80 37 25	1104	1008	1107
30	West Ward Est.	6 59 58	80 44 20	1879	1783	1876
31	Holmwood Estate	6 51 04	80 43 00	1574	1478	1530
32	Peradeniya	7 16 10	80 35 39	416	320	480
33	Helbodde	7 05 05	80 39 48	1073	977	1070
34	Dyraba	6 53 14	80 56 50	1286	1190	1353
36	Narangala	7 01 34	80 59 37	1165	1070	1072
37	Keenakelle	7 02 28	81 01 33	1227	1131	1261

38	Wood side	7 16 53	80 49 31	637	541	820
39	Kirimetiya	7 13 10	80 41 20	966	870	940
40	Kobonella Est.	7 18 49	80 51 47	1168	1073	1120
41	Galpihilla Est.	7 21 07	80 42 40	619	523	700
43	Yellebenda	7 01 20	80 35 43	1166	1070	1200
44	Patiyagama	7 09 56	80 42 06	942	846	1046
45	Norton Bridge	6 54 20	80 31 39	885	789	900
46	Mandara Nuwara	7 03 32	80 45 32	1413	1317	1415
47	Lemasooriyagama	7 09 00	80 50 10	416	320	384
48	Oonangalle	7 24 16	80 43 11	1218	1122	1060
49	Labukelle	7 01 29	80 43 10	1524	1428	1600
50	Duck wari	7 21 17	80 46 52	1046	950	1010
51	Kandy KP	7 18 00	80 38 00	555	459	540
52	Watawala	6 57 02	80 31 56	988	892	1020
53	Sitha Eliya	6 57 07	80 48 01	1979	1883	1984
54	Black water	7 00 18	80 29 50	578	482	620
55	Bopaththalawa	6 50 36	80 42 58	1523	1427	1580
56	Canaweralla	6 53 48	81 07 08	1137	1042	1238
57	Nagarak	6 46 00	80 45 08	2086	1990	2092
58	Norwood	6 50 32	80 36 08	1179	1083	1120
59	Oonoogal oya	7 02 11	80 35 36	1087	991	1040
61	Upperohiya	6 49 05	80 50 40	1808	1712	1815

in degrees, minutes and seconds

* Height Above Mean sea Level

** Height Above Ellipsoid

Appendix A-2. Estimation of Missing Data by Normal Ratio Method

(January, 1964)

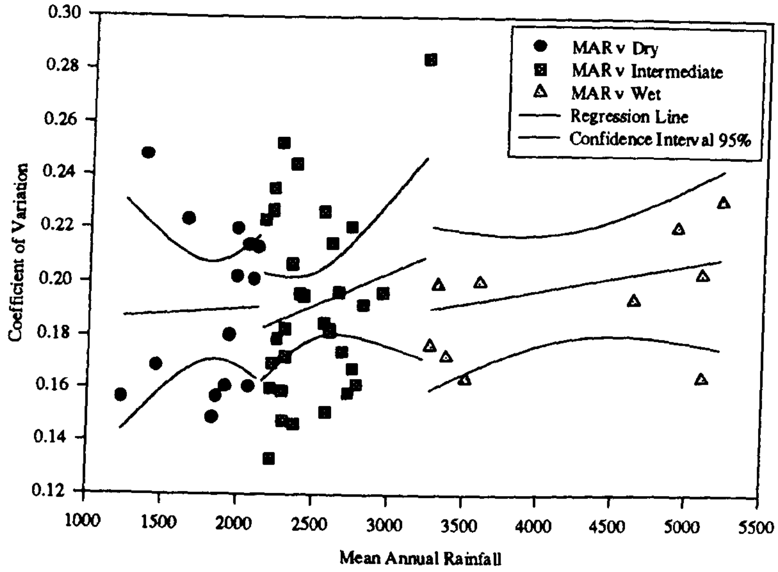
ST-1	ST-2	ST-3	ST-4	ST-5	miss-	jan(3)	jan(x)	3/x	date(x)	1	2	3	4	5	6	7	8	9	10	11
					31.00	169.60	88.20	1.92		0.00	0.00	10.73	28.29	19.99	0.98	13.66	0.49	46.33	18.04	0.00
					26.00	169.60	140.28	1.21		1.54	0.00	5.22	21.51	61.78	6.76	3.69	5.53	62.08	0.00	0.00
					8.00	169.60	302.78	0.56		1.14	0.43	3.41	4.98	17.92	1.14	2.13	0.71	8.53	1.00	0.00
						169.60	292.45	0.58		2.06	1.47	17.53	25.34	26.22	7.22	17.97	11.79	23.28	22.25	2.06
miss-	31.00	26.00	8.00	15.00					ave	1.18	0.47	9.22	20.03	31.48	4.02	9.36	4.63	35.06	10.32	0.52
						jan(18)														
					46.00	64.32	56.48	1.14		2.90	0.00	0.00	0.00	17.37	0.00	0.00	0.00	14.48	0.00	0.00
					4.00	64.32	40.26	1.60		8.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.38	13.41
					5.00	64.32	78.57	0.82		2.29	1.46	0.42	0.83	8.75	0.00	0.00	0.00	2.92	0.00	0.00
					53.00	64.32	68.35	0.94		2.63	0.00	0.00	0.00	4.78	0.00	0.00	0.00	6.45	2.15	0.00
					23.00	64.32	101.16	0.64		10.40	0.00	0.00	8.45	2.76	0.00	0.00	0.00	0.00	0.00	0.00
46.00	4.00	5.00	53.00	23.00					ave	5.27	0.29	0.08	1.86	6.73	0.00	0.00	0.00	4.77	5.31	2.68
					miss-3	jan(54)														
					31.00	135.53	88.20	1.54		0.00	0.00	8.61	22.69	16.04	0.78	10.95	0.39	37.16	14.47	0
					26.00	135.53	128.78	1.05		1.33	0.00	4.53	18.67	53.61	5.87	3.20	4.80	53.87	0.00	0
					8.00	135.53	86.93	1.56		3.17	1.19	9.51	13.87	49.93	3.17	5.94	1.98	23.77	2.77	0
					15.00	135.53	292.45	0.46		1.64	1.17	13.90	20.10	20.80	5.73	14.25	9.35	18.46	17.64	1.6357
	31.00	26.00	8.00	15.00					ave	1.53	0.59	9.14	18.83	35.09	3.89	8.59	4.13	33.32	8.72	0.41
12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	76.57	3.90	0.00	0.00	2.93	2.44	7.32	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.00	29.81	3.69	4.92	3.38	3.07	10.14	37.50	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.55	0.28	0.28	0.00	1.14	2.13	5.12	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.59	35.95	4.12	3.09	3.09	6.48	7.66	14.29	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.15	36.72	3.00	2.07	1.62	3.40	5.59	16.06	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.75	0.00	0.00	0.00	0.00	0.00	3.33	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.46	0.00	0.00	0.00	0.00	3.58	1.19	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.49	6.34	0.65	0.65	1.63	6.18	0.00	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.76	6.40	0.13	0.13	0.33	1.24	1.38	0.24	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	61.41	3.13	0.00	0.00	2.35	1.96	5.87	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.47	25.87	3.20	4.27	2.93	2.67	8.80	32.54	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.68	0.79	0.79	0.00	3.17	5.94	14.26	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.47	28.51	3.27	2.45	2.45	5.14	6.08	11.33	0.00	0.00	0.00	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.98	32.12	2.60	1.88	1.35	3.33	5.69	16.00	0.00	0.00	0.00	

Appendix A-3 Summary of CoV Analysis

The UMCA includes the wettest part of the country and it does not extend over any significant dry areas as such. The estimates of CoV with the time series shows that the estimations made by Sirinanda (1983) are either not applicable to UMCA or no longer valid. In that particular study where Sirinanda (1983) used the data for two periods 1911-1940 and 1941-1970, the variability estimates were within the range of 0.08 to 0.15. However, the period between 1964 to 1993 under the present study resulted in a comparatively higher variability, ranging from 0.13 to 0.28 at extreme cases and an average around 0.19. This suggests that some changes in terms of the variability of the rainfall regime have occurred over the period of time. Nevertheless, further tests on the statistically significant deviations of variability in the time series are carried out and the results are presented in chapter 3.

The relationship between the annual amount of rainfall and the variability of rainfall is more important than the extreme values of variability for the practical applications in the field of water resources management. The latter may be useful for engineering design, construction and maintenance activities. The rainfall variability of the main rain gauging locations was investigated based on annual rainfall records during the period for 1964-1993. The relationship between CoV and rainfall for stations located in relatively wet, intermediate and dry areas of the UMCA in terms of mean annual rainfall distribution is presented below.

According to Domros (1974), the coefficient of variation shows an exponential decrease with the increasing rainfall. Such a relationship was not evident in the data collected between 1964 and 1993 as shown in the figure below. It was not possible to derive any sort of statistically valid correlation between mean annual rainfall and coefficient of variation for UMCA during the study period. This suggests that the scale of the catchment selected for the data analysis is beyond the limits of acceptance for a generalized scenario.



Relationship between Mean Annual Rainfall and Coefficient of Variation (1964-1993)

Appendix A-4 Seasonal Rainfall Correlation Matrices

(a) Gauging stations on Southwest slope for Dec-Feb Season (correlation with distance, r^2= 0.158)

No.*	1	2	3	4	5
1	1.00				
2	0.80	1.00			
3	0.88	0.85	1.00		
4	0.81	0.78	0.86	1.00	
5	0.72	0.64	0.75	0.78	1.00

(b) Gauging stations on Northeast slope for Dec-Feb Season (correlation with distance, r^2= 0.083)

No*	6	7	8	9	10
6	1.00				
7	-0.07	1.00			
8	0.39	-0.06	1.00		
9	0.45	-0.17	0.13	1.00	
10	0.75	-0.02	0.30	0.64	1.00

(c) Gauging stations on Southwest slope for May-Apr Season (correlation with distance, r^2= 0.21)

No*	1	2	3	4	5
1	1.00				
2	0.48	1.00			
3	0.61	0.46	1.00		
4	0.54	0.66	0.43	1.00	
5	0.45	0.54	0.43	0.57	1.00

(d) Gauging stations on Northeast slope for May-Apr Season (correlation with distance, r^2= 0.056)

No*	6	7	8	9	10
6	1.00				
7	-0.25	1.00			
8	0.63	-0.13	1.00		
9	0.69	0.01	0.53	1.00	
10	0.51	0.05	0.55	0.49	1.00

(e) Gauging stations on Southwest slope for May-Sept Season (correlation with distance, r^2= 0.216)

No.*	1	2	3	4	5
1	1.00				
2	0.38	1.00			
3	0.53	0.53	1.00		
4	0.45	0.71	0.72	1.00	
5	0.61	0.83	0.42	0.45	1.00

(f) Gauging stations on Northeast slope for May-Sept Season (correlation with distance, r^2= 0.023)

No*	6	7	8	9	10
6	1.00				
7	0.78	1.00			
8	0.72	0.60	1.00		
9	0.48	0.55	0.41	1.00	
10	0.71	0.57	0.74	0.63	1.00

(g) Gauging stations on Southwest slope for May-Apr Season (correlation with distance, r^2= 0.157)

No*	1	2	3	4	5
1	1.00				
2	0.80	1.00			
3	0.88	0.85	1.00		
4	0.81	0.78	0.86	1.00	
5	0.72	0.64	0.75	0.79	1.00

(h) Gauging stations on Northeast slope for May-Apr Season (correlation with distance, r^2= 0.000)

No*	6	7	8	9	10
6	1.00				
7	-0.07	1.00			
8	0.39	-0.06	1.00		
9	0.45	-0.17	0.13	1.00	
10	-0.37	-0.01	0.08	-0.44	1.00

(i) Distance matrix (km) for the gauging stations on the Southwest slope

No*	1	2	3	4	5
1	0				
2	14	0			
3	26	22	0		
4	31	24	11	0	
5	58	22	39	29	0

(j) Distance matrix (km) for the gauging stations on the Northeast slope

No*	6	7	8	9	10
6	0				
7	16	0			
8	23	38	0		
9	31	42	12	0	
10	18	20	25	25	0

* Station Names are given in Table 2.2

Appendix B

Appendix B-1. Turbo C++ Programme for Drought Statistics Calculation

```
/* DROUGHT STATISTICS CALCULATION MODEL - SRI LANKA */

#include <stdio.h>
#include <ctype.h>
#include <math.h>

void delete_leading_blanks(char string[]); /* function declarations */
void stringdelete(char str[],int n);
double new_atof(char s[]);

main()
{
 FILE *fptr, *fptr1, *fptr2; /* file pointer */

 int day, count = 0; /* variable declaration */
 int pos, tcount = 0, day_count = 0;

 char inputstring[200];
 char station[40];
 char datastring[10];
 char ch, cha, strch[2];
 char numberstring[10];

 float data[31];

 printf("\n Do you want to change input/output filename? ");
 printf("\n enter Y/N");
 cha = getch();
 if ((cha == 'y') || (cha == 'Y'))
 {
 printf("\n please modify the program\n");
 exit();
 }

 if( (fptr = fopen("c:\\rainfall\\p196401.txt", "r")) == NULL)
 {
  printf("Can't open file");
  exit();
 }

 if ((fptr1=fopen("c:\\drought.txt", "w")) == NULL)
 {
  printf("Can't write on file");
  exit();
 }
```

```
 if ((fptr2=fopen("c:\\drought1.txt", "w")) == NULL)
 {
  printf("Can't write on file");
  exit();
 }

 do
 {
  fgets(inputstring,199,fptr);
 }
 while (strlen(inputstring) < 3);

 stringdelete(inputstring, 199);
 fprintf(fptr1,"Station Name\n");
 fprintf(fptr2,"Station Name\n");

 while ( fgets(inputstring,199,fptr) != NULL)
 {
  delete_leading_blanks(inputstring);
  strncpy(station,inputstring,20);
  station[20]='\0';
  fprintf(fptr1, "%s ", station);
  fprintf(fptr2, "%s ", station);
  printf("%s ", station);
      stringdelete(inputstring,21);

 for(day=0;day<30;day++)
 {
  pos=strcspn(inputstring," ");
  strncpy(datastring,inputstring,pos);
  datastring[pos]='\0';
  stringdelete(inputstring,pos+1);
  data[day]= new_atof(datastring);
 }

 data[30]= new_atof(inputstring);
      /* processing begins */

 clrscr();

 for(day=0; (day<31) && (data[day] != -999.99); day++)
 {            /* day loop begins */

  if (data[day] < 0)
  {
    printf("\n check the data again, rainfall cannot be negative\n");
    exit();
```

```
        }
        else
        {
            if (data[day] > 900)
            {
             printf("\n check the data again, dalily rainfall cannot be so high \n");
             exit();
            }
            else
            {
              if (data[day] <= 4)
              {
                count = count + 1;
                day_count = day_count + 1;
              }
             else
             {
              if (tcount < count)
              {
                   tcount = count;
                   count = 0;
               }
             }
            }
          }
      }
      fprintf(fptr1, "%5.2f", tcount);
      fprintf(fptr2, "%5.2f", day_count);
  }
  }

void delete_leading_blanks(char string[])
{
  while (string[0] == ' ')
   strcpy(&string[0],&string[1]);
}

void stringdelete(char str[],int n)
{
  strcpy(&str[0],&str[n]);
}

double new_atof(char s[])
{
  double val, power;
  int i, sign;

  for (i=0;isspace(s[i]);i++)
    ;
```

```
  sign=(s[i] == '-') ? -1 : 1;
  if (s[i] == '+' || s[i] == '-')
    i++;
  for (val = 0.0; isdigit(s[i]); i++)
    val = 10.0 * val + (s[i] -'0');
  if (s[i] == '.')
    i++;
  for (power = 1.0; isdigit(s[i]); i++) {
    val = 10.0 * val + (s[i] - '0');
    power *= 10.0;
  }
  return sign * val / power;
}
```

Appendix B-2(a). Maximum Consecutive Number of Non-rainy Days - Peradeniya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	21	17	15	4	12	14	6	24	9	12	7	7
1965	31	15	27	6	10	8	15	6	10	7	8	8
1966	13	11	28	6	31	13	13	11	6	6	6	7
1967	12	16	8	14	12	7	8	6	20	5	4	15
1968	18	19	13	7	18	6	8	13	7	9	11	12
1969	20	16	14	7	11	9	8	10	15	4	5	11
1970	14	7	23	4	23	4	7	8	7	8	4	8
1971	7	22	19	8	12	9	12	11	13	16	11	8
1972	31	29	8	9	16	20	11	20	8	2	9	7
1973	31	21	11	6	8	7	7	5	14	7	9	9
1974	31	24	10	4	5	9	3	10	6	11	14	9
1975	17	17	22	8	12	6	10	7	15	6	5	8
1976	16	29	28	8	31	24	11	20	17	5	5	12
1977	31	23	11	6	8	7	9	18	12	4	5	17
1978	13	11	22	8	6	8	14	31	5	13	5	12
1979	24	17	21	12	17	10	5	16	9	7	2	11
1980	31	29	17	8	16	6	8	12	14	7	9	11
1981	27	28	22	10	16	6	6	17	4	7	5	13
1982	31	28	21	8	7	6	7	18	13	5	5	13
1983	15	14	25	26	11	7	8	11	11	18	11	7
1984	5	10	9	6	9	4	10	14	16	12	5	11
1985	12	18	8	17	9	4	7	6	12	10	7	8
1986	16	12	8	4	20	7	14	17	12	3	9	21
1987	11	28	11	9	6	8	31	11	15	4	4	8
1988	31	14	8	4	10	16	7	8	4	11	28	18
1989	27	28	18	14	11	4	9	11	8	5	5	14
1990	26	18	20	21	7	6	15	22	13	11	24	10
1991	22	28	21	8	15	6	20	18	13	11	11	13
1992	31	29	31	15	12	10	8	14	15	14	7	16
1993	31	28	20	19	29	23	18	27	20	9	12	9
Mean	21.53	20.20	17.30	9.53	13.67	9.13	10.50	14.07	11.43	8.30	8.40	11.10
STD	8.37	6.82	6.92	5.38	6.98	5.23	5.39	6.43	4.33	3.89	5.52	3.56
Coeff.var	0.39	0.34	0.40	0.56	0.51	0.57	0.51	0.46	0.38	0.47	0.66	0.32
Skewness	-0.23	-0.07	0.12	1.38	1.21	1.62	1.94	0.72	0.03	0.58	2.12	0.92

Appendix B-2(b). Maximum Consecutive Number of Non-rainy Days - Kirimetiya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	15	13	16	4	12	12	4	14	15	7	7	7
1965	16	13	11	12	7	10	18	6	11	6	6	9
1966	11	23	13	12	31	12	12	11	8	5	11	6
1967	8	12	15	15	15	4	9	11	19	7	6	10
1968	11	22	8	6	15	8	7	12	5	4	10	14
1969	11	18	16	9	9	8	9	10	10	4	7	7
1970	7	7	27	7	9	8	8	11	7	8	7	10
1971	10	19	25	6	9	7	7	11	9	17	4	7
1972	6	29	31	12	16	12	15	20	6	3	7	5
1973	28	28	23	13	23	5	12	6	12	4	8	11
1974	31	11	24	4	7	7	5	10	6	13	14	6
1975	17	21	20	10	13	5	10	5	16	3	5	7
1976	12	29	28	5	19	15	16	13	21	8	3	7
1977	22	28	6	5	13	3	8	10	28	5	4	10
1978	12	18	16	13	10	9	6	6	8	10	10	10
1979	23	18	16	15	10	11	5	18	4	7	1	9
1980	31	29	31	7	14	8	7	11	12	8	3	8
1981	28	22	22	6	14	8	5	14	10	8	8	14
1982	31	28	28	10	16	12	12	15	16	5	2	6
1983	16	28	31	22	9	8	8	11	10	11	16	8
1984	5	5	13	11	10	2	7	13	8	12	7	10
1985	12	18	11	9	13	5	6	9	15	9	8	6
1986	19	14	7	14	27	7	11	18	8	3	7	10
1987	11	28	9	12	11	10	31	11	16	5	11	9
1988	31	14	15	3	19	12	10	8	4	29	12	14
1989	14	25	19	16	12	9	8	7	9	9	10	31
1990	24	18	8	10	5	10	11	17	19	10	8	15
1991	12	28	22	18	9	5	11	11	17	5	6	7
1992	14	29	31	12	12	8	6	14	11	13	4	5
1993	13	14	21	16	9	14	6	21	30	3	13	7
Mean	16.70	20.30	18.77	10.47	13.27	8.47	9.67	11.80	12.33	8.03	7.50	9.50
STD	7.99	7.10	7.80	4.54	5.73	3.15	5.19	4.04	6.37	5.19	3.53	4.81
Coeff.var	0.48	0.35	0.42	0.43	0.43	0.37	0.54	0.34	0.52	0.65	0.47	0.51
Skewness	0.62	-0.32	0.09	0.34	1.40	-0.00	2.38	0.46	1.06	2.25	0.38	2.96

Appendix B-2(c) Maximum Consecutive Number of Non-rainy Days - Nawalapitiya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	16	15	13	7	7	7	3	13	5	5	11	8
1965	31	13	13	3	4	7	12	2	8	9	5	8
1966	14	28	13	3	18	6	9	5	9	4	10	14
1967	12	14	9	11	8	6	3	5	15	3	5	15
1968	31	22	13	6	22	5	7	6	3	8	12	18
1969	14	10	15	8	9	6	7	5	10	4	8	6
1970	19	8	23	5	6	3	7	11	6	8	6	14
1971	24	19	21	3	12	7	9	9	18	16	10	14
1972	31	29	18	6	9	7	8	20	6	2	9	6
1973	31	21	19	7	13	5	6	4	17	6	13	8
1974	31	11	13	3	7	3	2	12	6	15	16	9
1975	19	18	18	6	10	4	16	7	15	3	3	8
1976	21	29	17	5	21	17	13	13	12	8	4	9
1977	31	14	10	4	1	5	9	16	10	3	4	24
1978	31	14	16	21	4	6	3	4	10	10	6	16
1979	27	9	11	8	8	8	4	14	3	7	1	11
1980	31	29	9	4	10	3	3	10	13	7	3	11
1981	28	20	12	9	15	7	4	6	5	8	6	15
1982	31	28	16	9	7	3	8	4	13	4	4	13
. 1983	8	20	31	21	5	5	8	4	7	11	12	4
1984	6	6	10	7	6	3	4	6	12	6	3	22
1985	13	19	9	19	9	3	3	7	7	6	17	15
1986	17	11	21	8	12	5	6	18	2	3	12	22
1987	22	28	10	14	8	5	31	2	17	3	5	8
1988	31	12	9	3	7	10	5	4	4	11	11	10
1989	15	28	10	8	5	3	9	6	5	5	9	28
1990	25	24	5	11	4	4	7	11	5	6	8	12
1991	14	25	18	8	31	9	12	6	12	9	14	13
1992	31	29	31	11	11	11	8	20	15	18	9	18
1993	31	14	12	13	13	10	9	11	18	6	10	15
Mean	22.87	18.90	14.83	8.37	10.07	6.10	7.83	8.70	9.60	7.13	8.20	13.13
STD	8.12	7.30	6.04	4.95	6.17	3.01	5.43	5.07	4.81	3.93	4.07	5.60
Coeff.var	0.36	0.39	0.41	0.59	0.61	0.49	0.69	0.58	0.50	0.55	0.50	0.43
Skewness	-0.43	0.03	1.11	1.24	1.54	1.62	2.56	0.79	0.25	1.11	0.27	0.74

Appendix B-2(d) Maximum Consecutive Number of Non-rainy Days - Hatton

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	19	8	5	12	7	2	13	5	5	8	16
1965	17	14	7	4	5	8	5	3	11	7	6	8
1966	15	14	14	4	25	13	9	13	9	4	11	14
1967	16	24	9	30	8	7	5	8	11	5	4	12
1968	17	22	9	7	13	7	6	8	6	7	11	22
1969	11	12	15	5	7	8	7	9	14	7	13	7
1970	7	11	23	7	16	12	5	11	7	8	6	12
1971	11	19	25	6	9	5	7	10	7	6	6	13
1972	23	17	11	7	16	8	8	19	6	4	8	11
1973	28	20	11	8	20	4	6	5	14	5	9	9
1974	31	23	11	5	5	5	2	10	3	11	8	6
1975	19	17	9	4	10	3	10	5	14	3	4	12
1976	19	23	22	3	21	23	12	18	11	8	3	6
1977	31	14	12	3	3	9	6	9	10	4	6	11
1978	23	11	14	7	6	7	4	4	9	13	10	18
1979	31	5	13	4	14	9	5	11	4	3	4	7
1980	31	29	7	4	13	3	4	10	15	7	5	14
1981	15	18	9	8	10	7	5	7	8	7	5	15
1982	26	28	13	6	9	4	7	9	8	2	4	22
1983	25	20	29	10	8	5	7	10	6	9	11	3
1984	6	9	15	6	7	3	7	7	17	7	4	26
1985	13	18	11	20	7	3	6	13	8	13	17	7
1986	10	7	6	2	13	7	8	18	3	3	15	21
1987	20	28	14	4	13	5	31	8	16	2	5	15
1988	24	12	10	4	15	13	3	3	4	20	12	12
1989	16	28	18	8	9	5	5	4	4	6	9	19
1990	26	16	5	11	6	8	5	18	6	9	6	20
1991	13	21	19	17	11	5	7	5	10	8	6	18
1992	31	19	16	12	10	6	5	11	6	17	7	8
1993	25	12	9	7	6	7	3	8	18	2	7	5
Mean	19.70	17.67	13.13	7.60	10.90	7.20	6.73	9.57	9.00	7.07	7.67	12.97
STD	7.59	6.25	5.71	5.70	5.04	3.96	5.00	4.39	4.23	4.21	3.46	5.76
Coeff.var	0.39	0.35	0.43	0.75	0.46	0.55	0.74	0.46	0.47	0.60	0.45	0.44
Skewness	0.02	0.04	1.03	2.40	0.91	2.16	3.76	0.60	0.52	1.31	0.92	0.34

Appendix B-2(e) Maximum Consecutive Number of Non-rainy Days - Dunsinane

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	13	15	9	12	11	13	19	14	10	30	5
1965	15	13	18	5	7	9	23	9	11	8	5	10
1966	11	10	13	5	14	7	12	20	13	6	15	13
1967	11	9	9	15	20	12	20	28	11	8	9	7
1968	8	23	11	8	20	23	11	11	8	4	9	13
1969	8	19	14	12	15	15	11	11	19	5	7	6
1970	7	5	15	5	10	15	9	13	10	7	5	8
1971	10	10	20	8	17	16	12	7	12	16	5	9
1972	6	29	31	14	17	13	10	23	20	0	8	9
1973	25	12	8	11	7	18	12	7	13	13	4	2
1974	31	11	20	4	4	8	17	15	7	11	8	5
1975	12	16	11	7	12	7	15	11	15	10	5	6
1976	7	15	28	5	16	6	16	12	19	12	6	5
1977	31	9	12	7	6	9	9	9	24	8	5	6
1978	9	14	16	15	4	27	8	15	14	6	6	6
1979	7	12	23	9	9	10	6	25	8	4	3	6
1980	17	29	14	9	12	18	11	12	20	9	6	7
1981	28	21	15	18	9	13	15	26	10	9	6	13
1982	31	28	20	12	7	27	8	31	28	3	6	6
1983	12	28	27	26	9	12	8	13	13	10	9	2
1984	3	4	7	8	8	6	9	13	15	15	3	8
1985	10	20	10	19	12	10	14	10	21	7	16	6
1986	9	12	11	15	21	14	9	19	10	5	8	5
1987	8	21	22	12	5	12	29	14	16	4	5	12
1988	17	13	12	7	10	28	10	10	7	26	16	4
1989	15	24	24	16	12	7	11	15	12	7	8	15
1990	24	15	7	12	12	8	19	19	12	9	8	6
1991	11	21	20	22	9	9	14	9	16	7	2	7
1992	15	29	31	14	9	8	7	14	14	15	2	9
1993	14	13	18	12	8	16	10	29	16	9	3	6
Mean	14.10	16.60	16.73	11.37	11.10	13.13	12.60	15.63	14.27	8.77	7.60	7.40
STD	7.90	7.18	6.73	5.26	4.61	6.18	4.97	6.67	4.93	4.84	5.47	3.16
Coeff.var	0.56	0.43	0.40	0.46	0.42	0.47	0.39	0.43	0.35	0.55	0.72	0.43
Skewness	1.03	0.36	0.56	0.80	0.55	1.09	1.45	0.84	0.78	1.40	2.45	0.70

Appendix B-2(f) Maximum Consecutive Number of Non-rainy Days - Hakgala

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	13	15	9	12	11	13	19	14	10	30	5
1965	15	13	18	5	7	9	23	9	11	8	5	10
1966	11	10	13	5	14	7	12	20	13	6	15	13
1967	11	9	9	15	20	12	20	28	11	8	9	7
1968	8	23	11	8	20	23	11	11	8	4	9	13
1969	8	19	14	12	15	15	11	11	19	5	7	6
1970	7	5	15	5	10	15	9	13	10	7	5	8
1971	10	10	20	8	17	16	12	7	12	16	5	9
1972	6	29	31	14	17	13	10	23	20	0	8	9
1973	25	12	8	11	7	18	12	7	13	13	4	2
1974	31	11	20	4	4	8	17	15	7	11	8	5
1975	12	16	11	7	12	7	15	11	15	10	5	6
1976	7	15	28	5	16	6	16	12	19	12	6	5
1977	31	9	12	7	6	9	9	9	24	8	5	6
1978	9	14	16	15	4	27	8	15	14	6	6	6
1979	7	12	23	9	9	10	6	25	8	4	3	6
1980	17	29	14	9	12	18	11	12	20	9	6	7
1981	28	21	15	18	9	13	15	26	10	9	6	13
1982	31	28	20	12	7	27	8	31	28	3	6	6
1983	12	28	27	26	9	12	8	13	13	10	9	2
1984	3	4	7	8	8	6	9	13	15	15	3	8
1985	10	20	10	19	12	10	14	10	21	7	16	6
1986	9	12	11	15	21	14	9	19	10	5	8	5
1987	8	21	22	12	5	12	29	14	16	4	5	12
1988	17	13	12	7	10	28	10	10	7	26	16	4
1989	15	24	24	16	12	7	11	15	12	7	8	15
1990	24	15	7	12	12	8	19	19	12	9	8	6
1991	11	21	20	22	9	9	14	9	16	7	2	7
1992	15	29	31	14	9	8	7	14	14	15	2	9
1993	14	13	18	12	8	16	10	29	16	9	3	6
Mean	14.10	16.60	16.73	11.37	11.10	13.13	12.60	15.63	14.27	8.77	7.60	7.40
STD	7.90	7.18	6.73	5.26	4.61	6.18	4.97	6.67	4.93	4.84	5.47	3.16
Coeff.var	0.56	0.43	0.40	0.46	0.42	0.47	0.39	0.43	0.35	0.55	0.72	0.43
Skewness	1.03	0.36	0.56	0.80	0.55	1.09	1.45	0.84	0.78	1.40	2.45	0.70

Appendix B-2(g) Maximum Consecutive Number of Non-rainy Days - Woodside

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	8	11	11	17	16	8	16	16	19	8	5
1965	12	13	13	12	10	10	18	12	16	6	5	8
1966	9	6	13	12	28	12	25	18	11	4	4	7
1967	9	7	12	11	31	12	12	16	12	9	6	4
1968	9	20	9	9	17	16	31	12	5	7	4	9
1969	8	10	31	5	9	30	11	12	0	3	5	3
1970	7	5	25	4	8	30	14	8	7	8	3	8
1971	6	18	10	6	10	10	12	9	9	16	4	5
1972	20	13	29	9	16	25	14	24	11	3	6	5
1973	28	10	11	12	12	12	16	7	12	7	5	6
1974	31	11	13	8	2	17	13	11	6	9	8	5
1975	14	16	11	9	15	12	19	14	13	8	5	6
1976	13	15	28	8	31	25	22	22	29	7	9	8
1977	31	8	10	15	6	16	19	15	23	5	7	12
1978	31	18	17	13	17	30	13	21	25	9	10	12
1979	10	18	27	10	12	10	13	22	5	6	2	11
1980	22	29	16	6	15	11	15	11	19	10	4	10
1981	14	20	13	5	17	16	9	18	10	12	9	10
1982	31	28	19	16	9	26	16	19	17	3	3	3
1983	12	28	27	26	14	17	16	17	20	7	10	3
1984	5	10	19	10	18	23	11	14	18	22	4	16
1985	12	22	9	11	12	6	13	14	21	14	17	6
1986	17	6	10	6	24	22	12	20	20	5	11	6
1987	9	22	19	9	13	15	27	13	16	3	4	9
1988	18	13	15	6	18	30	11	10	6	20	9	15
1989	16	23	19	8	12	20	8	31	9	9	8	16
1990	24	12	11	12	14	17	28	25	13	8	7	5
1991	11	26	22	16	12	18	17	15	18	14	4	6
1992	14	29	31	16	13	12	8	23	15	13	6	12
1993	12	13	8	16	8	17	16	30	20	6	5	8
Mean	15.53	15.90	16.93	10.57	14.67	17.77	15.57	16.63	14.07	9.07	6.40	7.97
STD	7.94	7.32	7.20	4.51	6.63	6.77	5.87	6.01	6.56	5.04	3.06	3.66
Coeff.var	0.51	0.46	0.43	0.43	0.45	0.38	0.38	0.36	0.47	0.56	0.48	0.46
Skewness	0.86	0.36	0.67	1.22	0.92	0.49	1.03	0.61	0.06	1.00	1.36	0.70

Appendix B-2(h) Maximum Consecutive Number of Non-rainy Days - Liddesdale

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	7	10	10	13	22	5	20	19	11	8	4
1965	12	13	15	6	6	30	16	9	23	7	4	11
1966	8	15	14	6	27	12	21	9	18	5	12	4
1967	11	7	9	9	22	8	25	31	9	8	1	3
1968	10	20	7	7	10	17	28	12	8	7	7	9
1969	7	10	14	4	8	20	11	15	19	5	7	5
1970	12	6	12	6	12	29	18	22	15	10	5	8
1971	8	11	8	8	16	11	11	8	6	16	4	4
1972	9	29	24	9	16	12	14	20	6	3	6	8
1973	23	8	16	7	11	26	21	16	12	9	8	6
1974	31	11	21	7	16	14	17	13	12	23	8	4
1975	12	15	18	6	12	12	17	9	16	21	5	7
1976	5	15	22	5	16	30	27	13	21	17	9	6
1977	21	9	5	9	13	15	10	12	24	8	6	4
1978	9	13	16	15	8	30	15	16	25	5	6	3
1979	7	7	26	9	16	11	15	23	8	6	3	7
1980	13	29	14	6	12	30	28	17	20	8	3	9
1981	23	20	23	9	21	15	15	16	14	6	5	11
1982	28	28	16	10	12	26	31	25	13	4	4	4
1983	12	28	28	26	15	15	17	25	7	11	10	2
1984	3	4	10	5	8	29	10	22	13	20	3	6
1985	10	16	9	9	8	12	13	17	19	14	9	6
1986	8	11	10	6	14	14	10	11	13	5	9	3
1987	6	20	14	10	11	25	31	13	16	4	7	10
1988	10	13	8	3	13	28	10	10	13	14	10	4
1989	13	23	20	8	12	13	3	10	14	9	3	14
1990	23	10	7	13	8	17	23	17	13	12	5	5
1991	14	17	22	9	7	8	13	28	12	13	4	7
1992	5	29	31	18	11	30	8	16	11	17	6	4
1993	13	7	10	10	11	19	17	20	14	6	4	2
Mean	12.57	15.03	15.30	8.83	12.83	19.33	16.67	16.50	14.43	10.13	6.03	6.00
STD	6.84	7.58	6.76	4.42	4.58	7.60	7.32	5.95	5.10	5.39	2.55	2.90
Coeff.var	0.54	0.50	0.44	0.50	0.36	0.39	0.44	0.36	0.35	0.53	0.42	0.48
Skewness	1.16	0.63	0.54	2.15	1.11	0.22	0.38	0.57	0.27	0.79	0.31	0.85

Appendix B-2(i) Maximum Consecutive Number of Non-rainy Days - Dyraba

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	14	11	5	24	27	14	14	8	5	7	5
1965	13	13	17	10	7	30	14	9	11	9	8	11
1966	13	27	13	10	26	12	22	8	8	7	15	21
1967	7	9	7	11	22	8	16	12	11	11	5	10
1968	11	29	12	13	12	10	17	16	18	7	12	15
1969	9	11	13	4	10	30	12	11	21	5	12	5
1970	12	6	9	4	19	29	18	15	15	16	7	8
1971	9	19	27	7	12	26	18	11	5	8	7	5
1972	10	29	26	6	12	10	15	19	9	3	6	10
1973	23	11	19	9	10	20	21	16	12	10	11	6
1974	31	11	30	6	10	15	15	13	6	29	10	9
1975	13	16	11	6	17	9	15	12	9	18	5	6
1976	7	15	27	5	16	13	17	14	6	13	8	7
1977	31	20	11	5	5	18	17	16	14	9	6	7
1978	12	14	17	11	8	29	13	21	24	7	10	6
1979	7	18	27	9	13	17	10	23	4	5	3	10
1980	18	29	17	8	12	20	31	16	20	6	8	9
1981	28	21	15	9	12	13	15	21	14	8	6	11
1982	30	25	17	7	10	26	15	25	22	6	6	12
1983	12	27	27	24	9	12	17	14	13	11	11	5
1984	5	9	12	4	10	14	10	22	6	24	3	8
1985	8	18	4	9	4	25	13	16	21	14	19	6
1986	9	12	5	3	11	15	16	19	13	6	6	7
1987	8	21	12	9	4	21	27	10	13	2	6	14
1988	12	13	16	4	10	22	10	8	17	25	17	10
1989	15	26	20	16	6	14	11	10	13	6	8	14
1990	25	9	11	13	14	22	21	17	8	11	16	6
1991	14	21	21	7	6	21	13	15	15	11	6	5
1992	8	29	31	19	17	30	16	23	11	15	4	9
1993	14	13	22	13	7	13	16	10	10	7	8	7
Mean	14.17	17.83	16.90	8.87	11.83	19.03	16.17	15.20	12.57	10.47	8.53	8.80
STD	7.55	7.02	7.38	4.67	5.50	6.99	4.59	4.67	5.31	6.40	4.00	3.62
Coeff.var	0.53	0.39	0.44	0.53	0.46	0.37	0.28	0.31	0.42	0.61	0.47	0.41
Skewness	1.16	0.27	0.30	1.36	0.88	0.18	1.36	0.35	0.43	1.35	1.00	1.40

Appendix B-2(j) Maximum Consecutive Number of Non-rainy Days - Bandaraeliya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	11	15	13	8	14	21	11	13	24	9	10	8
1965	15	14	15	5	8	30	18	13	24	7	6	12
1966	17	28	9	5	22	17	11	9	8	4	10	8
1967	7	14	9	11	11	12	25	18	10	11	10	9
1968	19	23	12	5	10	13	31	29	17	5	12	6
1969	12	9	15	4	6	30	22	13	14	5	5	3
1970	7	5	10	3	6	29	16	10	14	7	4	8
1971	10	19	9	3	15	15	10	11	5	17	5	4
1972	9	12	6	9	9	15	15	20	8	2	6	7
1973	24	16	18	7	12	12	9	16	11	8	9	6
1974	22	11	11	4	6	10	21	13	9	22	6	9
1975	13	23	15	3	10	12	18	8	12	18	6	7
1976	8	15	22	3	11	16	31	11	13	9	5	6
1977	21	8	13	9	6	18	10	16	17	3	6	4
1978	10	10	15	14	9	30	13	31	14	5	10	10
1979	16	16	18	6	11	11	16	25	6	4	1	7
1980	18	28	13	4	11	20	31	31	20	7	5	11
1981	28	15	12	4	12	15	10	23	14	7	5	7
1982	31	28	16	7	6	26	20	16	17	5	4	10
1983	13	27	25	26	7	11	19	13	8	9	7	5
1984	4	8	9	5	17	30	12	20	12	21	4	12
1985	13	8	8	9	8	30	17	16	23	17	12	15
1986	9	8	8	5	24	22	14	30	13	5	18	7
1987	8	26	12	10	10	30	31	11	16	2	6	17
1988	31	15	10	5	9	21	19	14	13	17	26	17
1989	15	27	20	16	23	18	19	22	26	20	7	15
1990	25	16	5	7	12	23	16	17	5	9	5	10
1991	14	21	16	7	4	4	10	25	15	14	9	6
1992	9	29	31	13	12	30	16	18	15	15	2	10
1993	23	13	9	5	8	21	16	16	10	6	3	4
Mean	15.40	16.90	13.47	7.40	10.97	19.73	17.57	17.60	13.77	9.67	7.47	8.67
STD	7.26	7.24	5.61	4.79	4.94	7.52	6.57	6.58	5.49	5.91	4.84	3.69
Coeff.var	0.47	0.43	0.42	0.65	0.45	0.38	0.37	0.37	0.40	0.61	0.65	0.43
Skewness	0.64	0.30	1.16	2.12	1.25	0.03	0.82	0.69	0.50	0.68	2.07	0.75

Appendix B-2(k) Total Number of non-rainy days in a month - Peradeniya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	29	28	25	20	25	20	23	28	17	21	15	23
1965	31	24	28	19	27	20	27	20	26	17	15	19
1966	28	25	29	19	31	23	27	26	16	18	18	23
1967	26	25	25	23	28	18	22	22	26	17	16	26
1968	29	27	26	21	28	16	13	24	20	16	21	22
1969	29	27	27	23	19	19	24	24	24	11	21	20
1970	25	19	28	17	27	19	9	20	19	16	13	22
1971	19	23	26	14	25	16	22	23	18	21	23	23
1972	31	29	26	21	16	25	23	25	21	7	17	23
1973	31	27	27	20	26	23	21	15	28	19	19	17
1974	31	24	26	17	16	22	11	20	15	25	23	25
1975	29	25	25	16	22	18	22	17	20	12	11	24
1976	26	29	29	18	31	27	22	24	28	17	16	23
1977	31	27	27	18	13	18	24	24	26	12	19	29
1978	28	26	26	23	20	19	22	31	20	26	21	28
1979	29	24	29	24	24	19	17	28	21	16	10	23
1980	31	29	28	21	25	20	21	23	24	17	17	24
1981	28	28	28	19	24	17	21	26	16	23	17	27
1982	31	28	29	21	16	16	17	25	28	17	17	24
1983	30	26	29	27	24	20	23	24	22	25	23	15
1984	19	21	20	19	25	17	16	28	21	20	18	23
1985	25	23	19	26	20	9	21	24	27	19	18	24
1986	21	20	25	18	25	21	26	19	23	12	22	29
1987	26	28	27	19	23	23	31	20	24	12	15	25
1988	31	27	27	16	24	26	21	20	15	25	28	28
1989	30	28	30	27	23	13	17	23	19	15	19	29
1990	29	25	29	26	21	12	26	29	27	16	25	25
1991	28	28	27	21	30	21	29	29	28	18	20	26
1992	31	29	31	19	22	21	18	22	25	19	15	27
1993	31	28	29	29	30	24	21	27	28	22	21	19
Mean	28.10	25.90	26.90	20.70	23.67	19.40	21.23	23.67	22.40	17.70	18.43	23.83
STD	3.39	2.66	2.52	3.60	4.53	3.94	4.86	3.69	4.24	4.54	3.93	3.40
Coeff.var	0.12	0.10	0.09	0.17	0.19	0.20	0.23	0.16	0.19	0.26	0.21	0.14
Skewness	-1.52	-0.99	-1.50	0.56	-0.47	-0.45	-0.55	-0.21	-0.21	-0.09	0.11	-0.59

Appendix B-2(l) Total Number of non-rainy days in a month - Kirimetiya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	24	21	25	22	25	21	15	24	20	16	19	20
1965	27	21	25	22	19	20	26	15	23	15	15	18
1966	22	27	22	23	31	20	23	25	14	15	18	21
1967	23	23	26	26	27	18	23	23	27	20	15	22
1968	26	27	21	21	26	16	11	25	16	15	21	23
1969	26	23	30	21	20	19	25	23	22	10	23	16
1970	23	16	29	18	23	21	22	22	23	17	15	21
1971	23	23	29	14	23	19	19	23	16	24	18	14
1972	17	29	31	20	18	23	26	25	19	13	14	13
1973	29	28	30	25	30	22	25	19	25	23	22	18
1974	31	21	27	19	21	19	14	19	11	28	25	17
1975	29	25	26	23	23	12	20	16	21	15	13	22
1976	21	29	28	15	30	26	22	23	27	17	13	22
1977	30	28	23	19	21	12	22	26	29	15	13	24
1978	28	25	25	22	16	17	19	16	23	17	19	23
1979	29	26	29	27	21	20	19	25	8	9	5	20
1980	31	29	31	21	26	24	18	21	22	21	17	23
1981	28	26	29	18	28	24	21	25	20	22	21	27
1982	31	28	29	20	27	21	16	21	24	12	11	19
1983	27	28	31	27	20	21	19	22	24	22	23	18
1984	17	13	23	21	21	4	13	25	18	22	24	25
1985	26	23	27	26	24	11	14	23	24	16	17	19
1986	21	26	23	21	28	24	24	19	19	14	21	24
1987	27	28	25	21	24	23	31	20	21	13	21	25
1988	31	27	27	15	26	23	25	23	13	29	13	22
1989	26	27	28	28	20	17	17	23	19	20	20	31
1990	27	25	24	27	13	16	23	27	26	15	19	19
1991	17	28	28	26	23	17	24	25	24	13	14	19
1992	27	29	31	17	23	17	14	20	18	16	5	18
1993	25	26	29	24	14	20	13	30	30	11	19	15
Mean	25.63	25.17	27.03	21.63	23.03	18.90	20.10	22.43	20.87	17.17	17.10	20.60
STD	4.05	3.77	2.86	3.75	4.44	4.56	4.78	3.32	5.07	4.89	4.89	3.83
Coeff.var	0.16	0.15	0.11	0.17	0.19	0.24	0.24	0.15	0.24	0.28	0.29	0.19
Skewness	-0.73	-1.60	-0.39	-0.16	-0.31	-1.30	-0.04	-0.38	-0.56	0.69	-0.75	0.35

Appendix B-2(m) Total Number of non-rainy days in a month - Nawalapitiya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	16	17	18	23	26	26	20	27	27	24	21	14
1965	20	18	25	17	17	30	27	23	27	17	11	16
1966	16	24	20	18	29	24	30	24	21	14	19	13
1967	20	18	22	20	27	24	30	31	25	18	4	9
1968	18	26	15	21	26	26	30	28	22	17	16	16
1969	16	19	27	12	21	28	27	27	22	14	20	9
1970	17	13	24	15	23	29	29	30	26	23	11	11
1971	15	22	25	11	26	24	24	19	15	20	11	9
1972	19	29	29	21	25	27	28	30	20	7	11	15
1973	24	21	25	23	27	27	27	27	27	18	17	12
1974	31	21	25	20	25	26	26	24	23	26	23	11
1975	20	19	25	17	22	25	22	26	23	27	17	20
1976	17	26	25	18	27	30	30	26	27	24	10	11
1977	28	21	24	18	22	28	24	26	25	11	16	8
1978	23	21	23	25	17	30	27	29	28	14	19	12
1979	21	22	27	23	25	25	27	29	15	12	9	15
1980	24	29	27	10	22	30	30	30	25	20	14	20
1981	25	23	28	24	26	27	21	26	26	22	18	20
1982	29	28	23	25	21	26	31	30	23	16	13	13
1983	23	28	30	28	26	28	27	28	24	19	21	6
1984	14	12	18	16	26	29	24	29	19	25	13	24
1985	17	18	21	24	24	21	29	27	24	21	17	12
1986	19	18	21	16	23	27	26	24	26	16	21	9
1987	13	25	25	15	19	29	31	25	25	12	19	22
1988	26	21	24	11	27	28	26	22	21	27	14	12
1989	17	26	27	23	24	25	16	27	26	21	13	21
1990	25	18	22	26	23	26	28	27	25	19	16	11
1991	19	23	24	22	21	24	27	29	24	18	12	16
1992	19	29	31	26	25	30	26	27	24	25	10	12
1993	23	23	25	22	21	23	28	28	23	13	13	8
Mean	20.47	21.93	24.17	19.67	23.77	26.73	26.60	26.83	23.60	18.67	14.97	13.57
STD	4.50	4.44	3.49	4.83	2.95	2.34	3.39	2.65	3.17	5.09	4.35	4.56
Coeff.var	0.22	0.20	0.14	0.25	0.12	0.09	0.13	0.10	0.13	0.27	0.29	0.34
Skewness	0.54	-0.17	-0.51	-0.40	-0.65	-0.34	-1.26	-0.91	-1.27	-0.17	-0.22	0.65

Appendix B-2(n) Total Number of non-rainy days in a month - Hatton

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	27	26	22	20	23	19	6	16	8	12	15	26
1965	29	26	24	9	8	14	20	9	20	14	16	16
1966	23	26	22	10	29	19	21	21	17	10	14	21
1967	29	27	18	30	21	14	10	15	24	17	12	26
1968	30	27	22	20	22	12	6	13	7	15	17	27
1969	29	25	26	11	13	19	16	19	19	16	25	20
1970	23	22	25	17	29	18	13	14	20	13	18	24
1971	26	24	29	20	22	19	15	14	16	22	17	19
1972	29	27	26	14	18	18	18	19	15	11	16	27
1973	28	26	22	14	28	10	13	10	26	16	19	18
1974	31	23	23	6	16	13	7	19	4	18	25	22
1975	30	23	24	9	21	8	19	8	20	5	7	24
1976	29	28	23	5	29	26	15	19	23	13	13	22
1977	31	24	21	7	9	11	11	20	23	9	18	28
1978	29	20	20	16	10	10	10	5	16	14	21	27
1979	31	19	24	17	24	14	13	21	8	9	9	19
1980	31	29	22	11	24	15	9	13	20	18	14	27
1981	27	24	18	17	17	15	8	19	12	19	18	28
1982	30	28	23	14	14	9	10	18	19	9	13	27
1983	29	27	30	24	22	19	16	18	20	23	19	12
1984	22	20	18	11	21	7	12	20	18	17	19	28
1985	26	22	17	21	13	7	12	15	18	14	19	20
1986	23	19	23	7	26	18	17	18	4	13	22	23
1987	30	28	26	13	20	14	31	13	20	8	18	27
1988	29	18	24	10	17	17	11	12	11	29	17	27
1989	28	28	26	21	14	12	7	9	15	17	17	24
1990	28	27	18	23	16	14	15	21	23	11	19	25
1991	26	25	25	23	19	15	16	18	24	14	18	30
1992	31	28	30	14	21	8	8	13	10	18	16	25
1993	30	25	25	16	16	12	10	15	26	9	18	15
Mean	28.13	24.70	23.20	15.00	19.40	14.20	13.17	15.47	16.87	14.43	16.97	23.47
STD	2.57	3.07	3.36	6.01	5.76	4.38	5.27	4.25	6.20	4.94	3.83	4.37
Coeff.var	0.09	0.12	0.14	0.40	0.30	0.31	0.40	0.27	0.37	0.34	0.23	0.19
Skewness	-1.07	-0.73	0.07	0.38	-0.10	0.34	1.25	-0.64	-0.61	0.73	-0.33	-0.87

Appendix B-2(o) Total Number of non-rainy days in a month - Dunsinane

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	27	23	26	24	23	16	13	20	13	16	15	26
1965	30	25	26	16	11	17	25	14	21	17	18	18
1966	27	27	23	16	30	18	21	20	19	15	14	19
1967	26	23	23	24	23	14	15	17	22	17	20	25
1968	26	29	23	23	25	11	9	17	8	15	20	20
1969	29	25	28	12	15	13	19	23	20	13	26	22
1970	24	20	28	17	27	14	18	15	18	15	16	24
1971	26	21	29	17	22	15	16	17	15	18	20	18
1972	29	29	29	16	14	23	17	21	17	7	14	24
1973	31	27	27	23	25	14	14	9	24	21	19	16
1974	31	21	27	20	13	14	20	19	7	23	24	20
1975	27	22	25	15	21	9	22	8	19	9	9	24
1976	26	29	28	12	27	25	18	20	24	15	13	28
1977	31	22	27	17	10	11	11	17	22	11	15	24
1978	31	23	26	24	9	10	14	5	18	21	20	26
1979	30	25	31	21	22	13	13	22	10	18	12	22
1980	30	29	27	15	23	15	10	17	21	19	16	22
1981	28	24	24	21	19	17	13	13	15	22	17	26
1982	31	28	22	23	15	10	11	22	21	18	13	22
1983	31	27	29	28	19	19	18	18	21	20	19	16
1984	19	16	21	15	22	10	13	26	15	11	10	25
1985	31	24	23	25	13	7	16	16	21	16	18	20
1986	22	19	29	19	24	18	23	18	8	13	26	24
1987	28	28	27	17	20	17	31	13	20	6	17	24
1988	29	23	21	17	23	23	15	19	18	26	15	25
1989	28	27	28	23	13	23	10	19	17	16	18	27
1990	28	26	24	28	17	10	15	19	24	16	19	22
1991	24	28	27	29	22	17	20	21	23	12	18	24
1992	28	29	31	19	19	12	8	19	16	17	11	26
1993	29	25	28	26	16	17	10	21	23	10	15	16
Mean	27.90	24.80	26.23	20.07	19.40	15.07	15.93	17.50	18.00	15.77	16.90	22.50
STD	2.87	3.33	2.72	4.67	5.38	4.47	5.12	4.44	4.79	4.57	4.10	3.33
Coeff.var	0.10	0.13	0.10	0.23	0.28	0.30	0.32	0.25	0.27	0.29	0.24	0.15
Skewness	-1.22	-0.62	-0.33	0.19	-0.21	0.46	0.85	-1.01	-0.92	-0.11	0.34	-0.57

Appendix B-2(p) Total Number of non-rainy days in a month - Hakgala

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	20	19	24	26	27	24	23	28	20	24	30	21
1965	26	19	27	17	15	22	30	21	27	15	11	20
1966	20	24	19	17	27	22	29	28	17	18	21	23
1967	22	19	21	26	26	26	29	30	21	18	12	17
1968	24	28	23	25	27	25	14	24	17	13	18	19
1969	19	23	27	16	21	25	28	22	21	13	23	16
1970	18	12	25	16	24	26	25	25	24	18	17	15
1971	21	19	26	15	27	20	22	15	19	20	20	12
1972	22	29	31	17	25	25	28	30	22	0	17	18
1973	26	22	24	24	26	28	26	23	26	22	13	10
1974	31	19	22	16	15	23	22	23	11	22	19	13
1975	20	20	20	13	22	19	21	24	19	16	13	19
1976	15	27	28	13	26	23	26	18	24	14	9	16
1977	31	22	25	16	14	22	21	25	24	9	14	16
1978	23	24	23	24	12	28	22	28	25	9	19	16
1979	22	24	30	24	22	19	21	26	15	12	11	16
1980	28	29	27	18	23	26	29	23	24	21	16	24
1981	28	24	27	27	23	20	18	30	24	21	21	25
1982	31	28	28	25	17	27	22	31	29	9	19	22
1983	26	28	29	28	27	25	25	25	23	19	19	10
1984	16	13	20	20	22	19	21	28	19	24	14	23
1985	23	22	22	26	22	18	28	27	26	16	20	19
1986	23	22	23	20	28	24	24	22	24	19	23	20
1987	22	26	30	23	19	23	30	25	24	14	18	26
1988	28	23	27	15	24	28	22	27	22	30	21	20
1989	23	27	30	26	21	20	21	28	24	21	21	25
1990	27	24	24	26	23	19	24	27	24	16	21	13
1991	20	26	26	27	21	21	25	24	23	16	15	18
1992	26	29	31	22	19	20	22	23	24	23	8	18
1993	27	25	28	27	21	21	20	29	26	16	16	17
Mean	23.60	23.20	25.57	21.17	22.20	22.93	23.93	25.30	22.27	16.93	17.30	18.23
STD	4.18	4.30	3.35	4.84	4.23	3.01	3.78	3.58	3.76	5.73	4.66	4.21
Coeff.var	0.18	0.19	0.13	0.23	0.19	0.13	0.16	0.14	0.17	0.34	0.27	0.23
Skewness	0.02	-0.79	-0.18	-0.21	-0.75	0.13	-0.23	-0.79	-1.05	-0.56	0.16	-0.07

Appendix B-2(q) Total Number of non-rainy days in a month - Woodside

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	14	16	21	27	27	27	23	26	22	23	19	18
1965	22	17	28	21	21	26	29	21	27	19	12	16
1966	17	22	20	21	30	25	30	28	19	15	15	17
1967	24	19	27	24	31	25	26	28	27	20	11	12
1968	21	25	22	25	28	24	31	24	16	11	12	17
1969	20	20	31	18	22	30	29	26	0	7	19	12
1970	20	13	27	11	25	30	28	22	22	14	10	13
1971	11	20	24	13	24	24	24	20	20	19	20	15
1972	27	26	30	23	20	28	27	30	25	11	8	17
1973	29	24	24	23	29	28	27	21	24	19	15	11
1974	31	21	23	19	15	28	22	23	12	21	22	14
1975	22	21	21	18	24	21	27	24	19	16	9	19
1976	25	28	28	22	31	29	30	28	29	21	15	18
1977	31	24	27	20	21	28	28	29	27	9	16	22
1978	31	26	25	25	23	30	26	29	27	22	20	18
1979	25	25	28	26	23	24	26	29	15	13	11	21
1980	27	29	28	18	28	27	29	27	25	19	11	21
1981	27	25	26	18	27	28	23	28	17	22	15	23
1982	31	28	27	26	24	26	26	28	27	17	14	15
1983	24	28	30	29	23	29	30	29	27	19	21	14
1984	20	16	22	20	30	27	20	29	20	27	14	26
1985	22	22	25	26	25	18	26	27	23	23	24	21
1986	19	18	24	20	26	27	26	26	26	15	21	21
1987	26	26	28	24	25	29	29	28	24	15	13	26
1988	29	27	27	19	30	30	27	27	23	25	19	20
1989	22	26	28	24	25	25	25	31	24	20	20	26
1990	27	20	28	27	26	27	28	30	24	17	20	15
1991	20	26	28	24	25	26	28	27	25	20	18	21
1992	26	29	31	27	24	24	23	28	22	25	13	20
1993	26	24	26	26	23	23	28	30	29	15	13	18
Mean	23.87	23.03	26.13	22.13	25.17	26.43	26.70	26.77	22.23	17.97	15.67	18.23
STD	4.92	4.22	2.94	4.17	3.54	2.75	2.60	2.89	5.85	4.76	4.23	4.07
Coeff.var	0.21	0.18	0.11	0.19	0.14	0.10	0.10	0.11	0.26	0.26	0.27	0.22
Skewness	-0.57	-0.56	-0.42	-0.75	-0.44	-1.04	-0.67	-0.94	-2.02	-0.36	0.09	0.21

Appendix B-2(r) Total Number of non-rainy days in a month - Liddesdale

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	16	17	18	23	26	26	20	27	27	24	21	14
1965	20	18	25	17	17	30	27	23	27	17	11	16
1966	16	24	20	18	29	24	30	24	21	14	19	13
1967	20	18	22	20	27	24	30	31	25	18	4	9
1968	18	26	15	21	26	26	30	28	22	17	16	16
1969	16	19	27	12	21	28	27	27	22	14	20	9
1970	17	13	24	15	23	29	29	30	26	23	11	11
1971	15	22	25	11	26	24	24	19	15	20	11	9
1972	19	29	29	21	25	27	28	30	20	7	11	15
1973	24	21	25	23	27	27	27	27	27	18	17	12
1974	31	21	25	20	25	26	26	24	23	26	23	11
1975	20	19	25	17	22	25	22	26	23	27	17	20
1976	17	26	25	18	27	30	30	26	27	24	10	11
1977	28	21	24	18	22	28	24	26	25	11	16	8
1978	23	21	23	25	17	30	27	29	28	14	19	12
1979	21	22	27	23	25	25	27	29	15	12	9	15
1980	24	29	27	10	22	30	30	30	25	20	14	20
1981	25	23	28	24	26	27	21	26	26	22	18	20
1982	29	28	23	25	21	26	31	30	23	16	13	13
1983	23	28	30	28	26	28	27	28	24	19	21	6
1984	14	12	18	16	26	29	24	29	19	25	13	24
1985	17	18	21	24	24	21	29	27	24	21	17	12
1986	19	18	21	16	23	27	26	24	26	16	21	9
1987	13	25	25	15	19	29	31	25	25	12	19	22
1988	26	21	24	11	27	28	26	22	21	27	14	12
1989	17	26	27	23	24	25	16	27	26	21	13	21
1990	25	18	22	26	23	26	28	27	25	19	16	11
1991	19	23	24	22	21	24	27	29	24	18	12	16
1992	19	29	31	26	25	30	26	27	24	25	10	12
1993	23	23	25	22	21	23	28	28	23	13	13	8
Mean	20.47	21.93	24.17	19.67	23.77	26.73	26.60	26.83	23.60	18.67	14.97	13.57
STD	4.50	4.44	3.49	4.83	2.95	2.34	3.39	2.65	3.17	5.09	4.35	4.56
Coeff.var	0.22	0.20	0.14	0.25	0.12	0.09	0.13	0.10	0.13	0.27	0.29	0.34
Skewness	0.54	-0.17	-0.51	-0.40	-0.65	-0.34	-1.26	-0.91	-1.27	-0.17	-0.22	0.65

Appendix B-2(s) Total Number of non-rainy days in a month - Dyraba

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	21	21	19	20	27	27	21	26	19	19	25	20
1965	25	18	25	22	21	30	27	24	24	19	17	16
1966	21	27	22	23	27	26	30	24	21	20	22	23
1967	21	22	23	21	29	24	29	27	25	19	14	25
1968	25	29	25	24	26	26	30	28	26	16	22	21
1969	21	23	27	15	24	30	29	21	25	18	23	13
1970	21	17	23	15	27	29	30	27	24	23	14	17
1971	18	24	28	14	27	29	28	21	16	18	18	15
1972	23	29	27	19	24	25	28	29	22	8	16	21
1973	29	26	26	22	26	29	28	29	24	18	17	13
1974	31	23	30	16	20	28	24	26	18	29	24	18
1975	21	25	23	15	26	24	27	23	20	27	19	20
1976	20	28	27	15	27	26	28	26	24	23	12	21
1977	31	25	25	15	21	29	25	29	21	13	17	19
1978	27	24	23	22	17	29	28	29	28	16	22	19
1979	25	25	30	24	29	25	26	29	19	14	12	20
1980	28	29	25	15	25	29	31	28	25	19	20	22
1981	28	25	28	25	21	25	21	27	23	24	17	23
1982	30	27	26	24	19	27	27	29	25	20	17	21
1983	25	27	29	26	23	28	25	28	27	21	17	12
1984	18	15	19	15	23	27	24	27	18	26	13	25
1985	24	21	15	23	19	29	29	29	24	24	23	19
1986	22	22	20	13	24	26	27	26	26	19	22	21
1987	20	27	25	20	14	29	30	24	20	8	19	25
1988	28	22	27	13	26	27	24	23	22	29	26	19
1989	25	27	29	25	21	25	21	24	26	14	17	23
1990	28	23	20	25	26	27	28	25	23	19	25	16
1991	22	26	27	21	21	28	29	27	23	19	15	17
1992	23	29	31	25	26	30	26	29	22	25	13	18
1993	28	26	29	23	21	26	28	25	20	15	15	19
Mean	24.30	24.40	25.10	19.83	23.57	27.30	26.93	26.30	22.67	19.40	18.43	19.37
STD	3.73	3.52	3.74	4.28	3.58	1.81	2.71	2.40	2.91	5.15	4.06	3.41
Coeff.var	0.15	0.14	0.15	0.22	0.15	0.07	0.10	0.09	0.13	0.27	0.22	0.18
Skewness	0.18	-0.88	-0.74	-0.25	-0.67	-0.19	-0.87	-0.63	-0.37	-0.19	0.21	-0.34

Appendix B-2(t) Total Number of non-rainy days in a month - Bandalraeliya

Month / Year	1	2	3	4	5	6	7	8	9	10	11	12
1964	22	22	23	19	25	29	20	27	25	16	24	25
1965	27	22	24	13	23	30	28	21	26	17	17	21
1966	30	28	17	13	26	28	28	25	16	14	18	21
1967	23	25	24	21	24	26	30	30	26	19	18	24
1968	29	28	22	21	25	28	31	30	25	11	18	19
1969	26	21	27	12	17	30	29	19	25	10	16	10
1970	19	13	21	10	22	29	29	26	25	18	9	17
1971	20	21	23	9	28	28	28	24	19	19	19	13
1972	27	25	22	17	20	27	28	30	22	6	11	18
1973	29	26	21	15	27	24	25	27	22	14	16	14
1974	30	23	27	14	16	27	27	27	22	26	17	20
1975	24	24	23	11	23	25	26	24	22	23	17	23
1976	21	28	26	9	28	28	31	24	24	22	10	17
1977	29	24	27	21	23	27	25	28	23	12	15	23
1978	27	21	24	20	21	30	28	31	28	15	20	22
1979	28	24	29	21	25	27	30	29	18	12	9	22
1980	29	28	22	15	20	27	31	31	23	20	14	25
1981	28	23	24	16	19	29	22	28	21	24	17	24
1982	31	28	25	21	18	27	29	28	27	13	14	22
1983	29	27	29	27	19	25	28	27	20	20	14	13
1984	18	15	14	19	27	30	26	29	22	24	14	26
1985	25	20	15	23	22	30	27	26	27	22	21	23
1986	23	20	22	13	26	27	24	30	25	10	27	23
1987	20	27	23	22	20	30	31	25	22	8	17	26
1988	31	25	24	16	24	27	27	24	22	29	26	26
1989	25	27	26	23	29	27	26	29	28	30	19	27
1990	27	22	17	21	23	29	25	28	19	15	24	23
1991	23	26	24	20	16	16	27	29	22	18	12	16
1992	24	29	31	19	24	30	29	26	18	25	6	19
1993	29	25	24	21	26	26	28	29	19	14	12	17
Mean	25.77	23.90	23.33	17.40	22.87	27.43	27.43	27.03	22.77	17.53	16.37	20.63
STD	3.69	3.74	3.82	4.62	3.58	2.69	2.56	2.82	3.09	6.05	4.93	4.35
Coeff.var	0.14	0.16	0.16	0.27	0.16	0.10	0.09	0.10	0.14	0.35	0.30	0.21
Skewness	-0.51	-1.09	-0.58	-0.23	-0.30	-2.59	-0.90	-0.94	-0.18	0.20	0.19	-0.69

Appendix B-3(a) Test Statistics of Rainfall for Linear Trend Determination - Peradeniya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.12	0.06	Jul	0.48	0.11
Feb	0.12	0.10	Aug	0.43	0.29
Mar	0.07	0.35	Sep	0.09	0.23
Apr	0.26	0.08	Oct	0.10	0.16
May	0.07	0.51	Nov	0.08	0.10
Jun	0.05	0.11	Dec	0.09	0.14

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(b) Test Statistics of Rainfall for Linear Trend Determination - Kirimetiya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|* *(2.11)
Jan	0.32	1.31	Jul	1.02	0.56
Feb	1.67	0.28	Aug	1.30	0.16
Mar	2.15	0.26	Sep	0.16	0.12
Apr	0.32	0.52	Oct	0.57	0.07
May	0.05	0.64	Nov	0.73	0.05
Jun	0.04	0.30	Dec	0.00	0.58

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(c) Test Statistics of Rainfall for Linear Trend Determination - Nawalapitiya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	1.23	0.10	Jul	0.03	2.80
Feb	0.06	0.86	Aug	1.17	1.24
Mar	0.78	1.27	Sep	1.45	1.47
Apr	0.55	1.62	Oct	0.41	1.44
May	0.94	2.00	Nov	0.07	4.35
Jun	0.35	0.95	Dec	1.36	1.82

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(d) Test Statistics of Rainfall for Linear Trend Determination - Hatton

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.61	0.80	Jul	0.22	0.28
Feb	0.14	1.72	Aug	1.89	0.01
Mar	1.22	2.99	Sep	1.19	1.08
Apr	0.39	1.68	Oct	0.15	1.07
May	1.08	0.09	Nov	0.61	1.43
Jun	1.01	1.60	Dec	0.07	0.54

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(e) Test Statistics of Rainfall for Linear Trend Determination - Dunsinane

Month	|TC|* (2.16)	|TC|* *(2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.53	1.22	Jul	1.20	0.69
Feb	0.83	0.40	Aug	2.43	0.51
Mar	1.75	0.26	Sep	0.11	0.59
Apr	0.95	1.88	Oct	1.01	0.95
May	0.40	0.39	Nov	1.70	0.78
Jun	0.77	0.92	Dec	0.62	0.63

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(f) Test Statistics of Rainfall for Linear Trend Determination - Hakgala

Month	|TC|* (2.16)	|TC|* *(2.11)	Month	|TC|* (2.16)	|TC|**(2.11)
Jan	0.21	1.65	Jul	0.73	0.51
Feb	1.51	0.22	Aug	0.68	0.46
Mar	1.14	1.29	Sep	0.44	0.08
Apr	1.00	1.18	Oct	0.18	0.65
May	0.53	1.00	Nov	0.52	0.52
Jun	1.53	1.31	Dec	1.26	1.06

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(g) Test Statistics of Rainfall for Linear Trend Determination - Woodside

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.42	0.45	Jul	0.30	0.02
Feb	0.65	0.02	Aug	0.12	0.12
Mar	0.46	0.12	Sep	0.03	0.10
Apr	0.30	0.23	Oct	0.00	0.21
May	0.09	0.14	Nov	0.12	0.02
Jun	0.06	0.34	Dec	0.02	0.26

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(h) Test Statistics for of Rainfall Linear Trend Determination - Liddesdale

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.62	1.31	Jul	0.36	0.11
Feb	2.12	0.09	Aug	0.21	0.01
Mar	1.76	0.99	Sep	0.65	0.21
Apr	0.49	0.53	Oct	0.69	2.27
May	0.10	0.25	Nov	0.19	0.26
Jun	0.98	0.76	Dec	0.95	0.65

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(i) Test Statistics of Rainfall for Linear Trend Determination - Dyraba

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.48	1.10	Jul	0.79	0.72
Feb	2.06	0.15	Aug	0.17	3.55
Mar	1.88	0.08	Sep	0.73	0.36
Apr	0.40	0.12	Oct	1.09	1.41
May	0.31	0.26	Nov	0.41	0.16
Jun	0.16	1.31	Dec	1.56	0.64

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(j) Test Statistics of Rainfall for Linear Trend Determination - Bandaraeliya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.24	0.83	Jul	0.06	0.03
Feb	0.22	0.00	Aug	0.02	0.04
Mar	0.05	0.02	Sep	0.65	0.02
Apr	0.71	0.25	Oct	0.15	0.17
May	0.11	0.35	Nov	0.89	0.13
Jun	1.01	0.23	Dec	0.37	0.52

*, ** Time series before 1977 and 1977 onwards respectively.

( ) T-table values.

Appendix B-3(k). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Peradeniya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.36/ 0.15	0.51/ 0.09	Jul	0.62/ 1.03	1.71/ 0.76
Feb	2.41/ 0.34	1.12/ 0.59	Aug	0.13/ 1.85	0.27/ 0.65
Mar	0.14/ 0.10	0.46/ 0.71	Sep	0.87/ 0.54	1.76/ 1.06
Apr	0.19/ 1.56	1.30/ 0.84	Oct	0.44/ 0.35	0.76/ 0.04
May	0.04/ 1.08	1.19/ 2.48	Nov	0.51/ 0.17	1.99/ 1.24
Jun	0.77/ 1.32	1.56/ 0.65	Dec	0.20/ 0.32	0.03/ 0.23

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(l). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Kirimetiya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	1.14/ 0.47	1.39/ 1.74	Jul	0.45/ 0.09	0.83/ 0.06
Feb	1.64/ 1.24	0.36/ 0.23	Aug	0.24/ 0.80	1.10/ 1.16
Mar	3.42/ 1.99	0.27/ 0.46	Sep	0.46/ 0.20	0.87/ 0.42
Apr	0.64/ 1.43	1.25/ 0.51	Oct	0.44/ 1.17	0.50/ 0.26
May	0.02/ 0.10	0.49/ 0.86	Nov	0.49/ 0.28	1.50/ 0.01
Jun	0.37/ 0.25	1.12/ 0.07	Dec	0.72/ 0.39	0.50/ 1.19

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(m). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Nawalapitiya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	1.03/ 1.41	0.70/ 1.44	Jul	1.20/ 0.07	1.33/ 0.13
Feb	0.86/ 1.11	1.25/ 0.15	Aug	1.25/ 0.15	0.35/ 1.01
Mar	2.00/ 2.16	0.57/ 0.19	Sep	1.31/ 0.34	1.01/ 0.21
Apr	0.42/ 0.26	0.02/ 0.36	Oct	0.68/ 1.11	1.07/ 1.34
May	0.78/ 0.40	1.89/ 0.39	Nov	0.15/ 0.00	2.79/ 0.99
Jun	0.73/ 0.47	1.87/ 1.32	Dec	0.96/ 0.02	0.08/ 0.18

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(n). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Hatton

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	2.05/ 1.23	0.81/ 0.62	Jul	1.80/ 0.34	0.28/ 0.52
Feb	1.02/ 0.75	0.49/ 1.00	Aug	0.64/ 0.05	0.24/ 0.34
Mar	1.27/ 0.91	0.03/ 1.57	Sep	0.56/ 0.61	0.12/ 0.53
Apr	0.76/ 1.81	1.67/ 1.22	Oct	0.64/ 0.20	0.77/ 0.35
May	0.48/ 0.79	0.41/ 0.60	Nov	1.26/ 0.03	0.53/ 0.85
Jun	0.40/ 0.18	0.02/ 0.10	Dec	1.74/ 0.10	0.12/ 0.51

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(o). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Dunsinane

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.80/ 0.43	0.76/ 1.36	Jul	0.47/ 0.36	1.08/ 0.45
Feb	0.48/ 0.11	0.52/0.98	Aug	1.11/ 0.92	0.05/ 1.45
Mar	1.24/ 1.74	0.74/ 0.32	Sep	0.87/ 0.35	0.97/ 0.84
Apr	0.43/ 1.30	0.75/ 1.34	Oct	1.06/ 0.22	1.16/ 1.12
May	0.48/ 0.04	1.00/ 0.97	Nov	2.41/ 0.59	0.06/ 0.13
Jun	0.53/ 0.39	1.00/ 1.37	Dec	1.80/ 0.45	0.60/ 0.36

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(p). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Hakgala

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.80/ 0.10	0.65/ 0.72	Jul	0.47/ 0.69	0.92/ 0.23
Feb	0.48/ 0.62	0.45/ 0.61	Aug	1.11/ 1.41	0.04/ 0.40
Mar	1.24/ 0.52	0.64/ 0.84	Sep	0.87/ 0.28	0.83/ 0.70
Apr	0.43/ 2.19	0.64/ 1.08	Oct	1.06/ 0.55	1.00/ 1.84
May	0.48/ 0.28	0.86/ 1.27	Nov	2.41/ 1.78	0.05/ 0.01
Jun	0.53/ 0.45	0.86/ 1.24	Dec	1.80/ 2.41	0.52/ 0.02

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(q). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Woodside

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	1.93/ 2.06	1.57/ 1.74	Jul	0.22/ 0.25	0.24/ 0.02
Feb	1.31/ 2.11	0.17/ 0.25	Aug	0.17/ 0.18	1.34/ 0.29
Mar	0.97/ 0.37	0.08/ 0.91	Sep	0.67/ 0.03	0.64/ 0.69
Apr	1.27/ 1.06	0.30/ 1.25	Oct	0.67/ 0.09	0.67/ 1.01
May	0.42/ 0.62	0.06/ 0.69	Nov	0.89/ 0.09	0.09/ 0.49
Jun	0.81/ 0.27	0.10/ 1.18	Dec	0.00/ 0.08	0.25/ 0.03

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(r). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Liddesdale

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.95/ 1.41	0.70/ 1.44	Jul	0.89/ 0.07	0.68/ 0.13
Feb	0.74/ 1.11	0.11/ 0.15	Aug	0.68/ 0.15	0.09/ 1.01
Mar	2.77/ 2.16	0.13/ 0.19	Sep	0.69/ 0.34	1.86/ 0.21
Apr	1.05/ 0.26	0.07/ 0.36	Oct	2.61/ 1.11	1.53/ 1.34
May	0.11/ 0.40	1.50/ 0.39	Nov	0.28/ 0.00	0.19/ 0.99
Jun	0.01/ 0.47	0.30/ 1.32	Dec	0.06/ 0.02	0.06/ 0.18

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(s). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Dyraba

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	1.04/ 0.60	1.00/ 1.14	Jul	0.30/ 0.28	0.17/ 2.29
Feb	0.27/ 1.49	0.36/ 1.31	Aug	1.33/ 0.29	1.59/ 0.58
Mar	2.33/ 2.56	0.56/ 3.23	Sep	0.94/ 0.51	1.00/ 0.53
Apr	1.41/ 2.44	0.92/ 1.23	Oct	2.08/ 1.18	0.76/ 0.14
May	1.20/ 0.36	0.16/ 0.35	Nov	0.66/ 1.23	0.57/ 0.57
Jun	1.25/ 0.53	0.09/ 0.99	Dec	1.38/ 0.54	0.01/ 0.49

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-3(t). Test Statistics of Max. Consecutive and Total No. of Non-rainy Days in a Month for Linear Trend Determination - Bandaraeliya

Month	|TC|* (2.16)	|TC|** (2.11)	Month	|TC|* (2.16)	|TC|** (2.11)
Jan	0.26/ 0.24	0.12/ 1.16	Jul	0.66/ 0.75	0.11/ 0.05
Feb	0.33/ 0.40	0.77/ 0.66	Aug	0.60/ 0.02	1.12/ 1.18
Mar	1.24/ 1.10	0.09/ 0.26	Sep	2.12/ 0.64	0.13/ 0.99
Apr	1.46/ 1.82	0.06/ 0.17	Oct	1.64/ 1.35	1.63/ 0.84
May	1.04/ 0.22	0.49/ 0.77	Nov	1.94/ 2.20	0.36/ 0.06
Jun	1.75/ 2.09	0.13/ 0.83	Dec	1.29/ 1.21	0.60/ 0.74

*, ** Time series before 1977 and 1977 onwards respectively. ( ) T-table values.

Appendix B-4 Mean Monthly and Seasonal Rainfall Percentages for Northeast Monsoon Period

Station	Jan	Feb	Dec	Total	Jan %	Feb %	Dec %
Peradeniya	59.26	56.67	155.68	271.60	21.82	20.86	57.32
Nawalapitiya	60.89	62.63	139.48	262.99	23.15	23.81	53.03
Woodside	174.95	114.63	346.00	635.58	27.53	18.04	54.44
Hakgala	165.96	97.78	260.88	524.62	31.63	18.64	49.73
Hatton	36.92	43.67	100.15	180.74	20.43	24.16	55.41
Bandaraeliya	111.03	95.40	240.79	447.22	24.83	21.33	53.84
Kirimetiya	149.18	74.98	200.35	424.50	35.14	17.66	47.20
Dunsinane	65.13	56.42	156.05	277.59	23.46	20.32	56.21
Liddesdale	292.45	142.06	466.92	901.42	32.44	15.76	51.80
Dyraba	124.53	65.77	220.47	410.77	30.32	16.01	53.67

Appendix C

```
/* HYDROLOGICAL MODEL FOR UMCA,  SRI LANKA */
/* basic model structure adopted from Land Use Model, Sri Lanka (1994) */
/* C Programming and compilation  by Ranjith Premalal */

#include <stdio.h>
#include <ctype.h>
#include <math.h>
#define array 4                        /* definition of array 1-4 */

void delete_leading_blanks(char string[]); /* function declarations */
void stringdelete(char str[],int n);
double new_atof(char s[]);

main()
{
    float aw[array] = {150, 380, 380, 300};          /* available water */
    float tb[array] = {150, 380, 380, 300};      /* initial moisture content */
    float gam[array] = {0, 6.91, 6.91, 2.65};   /* interception parameters */
    float delta[array] = {0.1, 0.099, 0.099, 0.36};   /* delta parameters */
    float beta[array] = {1, 0.85, 0.9, 1};       /* transpiration parameters */
    float ce[array] = {0,0,0,0};           /* initialising the null arrays */
    float crun[array] = {0,0,0,0};

    FILE *fptr, *fptr1;                          /* file pointers */

    int index, day, month_count = 0;             /* variable declaration */
    int pos, count, elev =1780,
    int eo = 1408;

    char inputstring[200];
    char station[20];
    char year_month[8];
    char datastring[10];
    char ch, cha, strch[2];
    char numberstring[10];

    float data[31], ed[12], fm[4], id[4];
    float a, b, et;
    float cet = 0;                      /* cumilative evapotranspirtion */
    float cr= 0;                              /* cumilative rainfall */
    et = (0.7 * eo /365);                     /* daily evapotranspiration */

   printf("\n Do you want to change default value of annual evaporation? ");
   printf("\n enter Y/N");
   cha = getch();
```

```
if ((cha == 'y') || (cha == 'Y'))
    {
        printf("\n please modify the source code\n");
        exit();
    }

    printf("\n Do you want to change default value of elevation? ");
    printf("\n enter Y/N");
    cha = getch();
    if ((cha == 'y') || (cha == 'Y'))
    {
        printf("\n please modify the source code\n");
        exit();
    }

    printf("\n Do you want to change input/output filename? ");
    printf("\n enter Y/N");
    cha = getch();
    if ((cha == 'y') || (cha == 'Y'))
    {
        printf("\n please modify the source code\n");
        exit();
    }

    if( (fptr = fopen("a:\\srilanka\\trial.dat", "r")) == NULL)
    {
        printf("Can't open file");
        exit();
    }

    if ((fptr1=fopen("a:\\output.txt", "w")) == NULL)
    {
        printf("Can't write on file");
        exit();
    }

    do
    {
        fgets(inputstring,199,fptr);
    }
    while (strlen(inputstring) < 3);

    delete_leading_blanks(inputstring);
    strcpy(station,inputstring);
    fprintf(fptr1, "%s\n", station);
    printf("%s", station);

    while ( fgets(inputstring,199,fptr) != NULL)
```

```
{
     delete_leading_blanks(inputstring);
     strncpy(year_month,inputstring,7);
     year_month[7]='\0';
     fprintf(fptr1, "%s\n", year_month);
     printf("%s ", year_month);
     stringdelete(inputstring,8);

for(day=0;day<30;day++)
{
     pos=strcspn(inputstring,",");
     strncpy(datastring,inputstring,pos);
     datastring[pos]='\0';
     stringdelete(inputstring,pos+1);
     data[day]= new_atof(datastring);
}

   data[30]= new_atof(inputstring);
   /* processing begins */
   count =0;
   month_count = month_count + 1;
   if (month_count == 13)
   {
        cr = 0;
        cet = 0;
        for (index = 0; index <4; index ++)
        crun[index]=0;
        month_count = 1;
   }
   clrscr();

   for(day=0; (day<31) && (data[day] != -99999); day++)
   {                                 /* day loop begins */
        if (data[day] < 0)
        {
             printf("\n check the data again, rainfall cannot be negative\n");
             exit();
        }
        else
        {
             if (data[day] > 300)
             {
                  printf("\n check  data again, rainfall cannot be so high \n");
                  exit();
             }
             else
             {
                  cr = cr + data[day];
                  cet = cet + et;
```

```
                        count = count + 1;

                for(index=0;index<4;index++)
                    {
                        if ((index==1)||(index==2))
                        if ((month_count >4)||(month_count<10))
                        data[day]=data[day]+data[day]*((-43.6+0.0436*elev)/100);
                        else
                        data[day]=data[day]+data[day]*((-11.8+0.0118*elev)/100);
                    }

                for(index=0;index<4;index++)
                    {
                        fm[index] = (tb[index]) / (aw[index]/ 2);
                                /* soil moisture stress moderator */
                        if (fm[index] > 1)
                        fm[index] = 1;      /* daily exponential interception model */
                        b = -delta[index] * data[day];
                        a =(float) exp(b);
                        id[index] = gam[index] * (1 - a);

                        if (index == 0)
                        ed[index] = fm[index] * beta [index] * et;
                                /* Daily transpiration model */
                        else
                        ed[index] = fm[index] * beta[index] * et* (1 - id[index]/
gam[index]);

                /* water balance update */
        tb[index] = tb[index] + data[day] - id[index] - ed[index];

        if(tb[index] > aw[index])
        {
            crun[index] = crun[index] + tb[index] - aw[index];
            tb[index] = aw[index];
        }
        else if ((tb[index] > 0) && (tb[index] <= aw[index]))
            tb[index] = tb[index];
        else if (tb[index] < 0)
            tb[index] =0;

        ce[index] = ce[index] + id[index] + ed[index];

        if (( count % 10 == 0) && (index == 0))
        {
            fprintf(fptr1, "%5.2f  %5.2f  ", cr, cet);
            fprintf(fptr1, "%5.2f  ", tb[index]-aw[index]);
            fprintf(fptr1, "%5.2f  %5.2f  %5.2f\n", crun[index],
            ed[index], id[index]);
```

```
            }
            else if ((count % 10 == 0) && (index != 0))
            {
                fprintf(fptr1, "            %5.2f ",
                tb[index]-aw[index]);
                fprintf(fptr1, "%5.2f  %5.2f  %5.2f\n", crun[index], ed[index], id[index]);
            }
            }   /* for (i) loop closure */
            }   /* else closure */
        }   /* else closure */
        }   /* for (day) loop closure */
        }
    }
    }
    void delete_leading_blanks(char string[])
    {
        while (string[0] == ' ')
        strcpy(&string[0],&string[1]);
    }

    void stringdelete(char str[],int n)
    {
        strcpy(&str[0],&str[n]);
    }
    double new_atof(char s[])
    {
        double val, power;
        int i, sign;

        for (i=0;isspace(s[i]);i++)
        ;
        sign=(s[i] == '-') ? -1 : 1;
        if (s[i] == '+' || s[i] == '-')
        i++;
        for (val = 0.0; isdigit(s[i]); i++)
        val = 10.0 * val + (s[i] -'0');
        if (s[i] == '.')
        i++;
        for (power = 1.0; isdigit(s[i]); i++) {
        val = 10.0 * val + (s[i] - '0');
        power *= 10.0;
        }
        return sign * val / power;
```

Appendix D

Appendix D-1(a) GCP for I2163A2 Image

ID	Map X	Map Y	File X	File Y
1	223544	237358	1161	2177
2	222235	240009	1115	2111
3	234618	243393	1437	1963
4	221996	253840	1045	1731
5	222742	268536	1003	1325
6	225738	266464	1091	1367
7	234118	267376	1319	1307
8	224643	273167	1033	1189
9	238066	274083	1399	1105
10	231825	296913	1125	505
11	223401	290358	923	719
12	207451	280513	529	1061
13	200423	278234	349	1159
14	198741	274890	315	1255
15	201870	261591	461	1607
16	207529	297012	543	540
17	224862	290012	1027	735
18	222855	265012	984	1450
19	230913	274960	1100	1246
20	200961	298543	435	580
21	222709	290487	980	701
22	207305	267098	525	1324
23	222089	274590	963	1212
24	232373	293121	1140	654
25	198960	292876	321	687
26	243850	281595	1527	869

Appendix D-1 (b) GCP for Image I2164A1

ID	Map X	Map Y	File X	File Y
1	222220	240000	1256	26
2	230580	230000	1537	269
3	226800	226020	1443	390.
4	203450	230620	781	365
5	204140	235940	773	218
6	216980	239590	1113	61.
7	194280	231100	523	391
8	197430	240630	570	118
9	202920	241550	719	18
10	186450	232490	305	387
11	186720	235970	299	289
12	189410	228360	403	486
13	196940	243010	549	10
14	189480	238250	366	220
15	172630	180760	153	1868
16	179360	179880	341	1867
17	172360	177390	159	1962
18	172710	184810	140	1759
19	174730	187870	180	1667
20	181320	185520	370	1706
21	183270	181390	441	1806
22	181820	177670	422	1917
23	190480	190580	599	1520
24	190860	185230	629	1666
25	188950	165650	668	2215
26	182560	169240	478	2142
27	223090	198440	1467	1162
28	220350	191590	1419	1365
29	186580	202720	440	1202
30	192420	205980	588	1092
31	179540	213710	199	933
32	180720	206620	256	1125
33	191000	200840	570	1239
34	184610	216500	329	835
35	191510	204440	568	1137
36	188380	212900	444	917

Appendix D-1(c) GCP for I2263B2 Image

ID	Map X	Map Y	File X	File Y
1	148500	260330	574	1303
2	148700	258390	58	1361
3	147110	270640.	489	1025
4	145040	272440	423	989
5	156010	264540	761	1154
6	141790	268570	352	1110
7	139010	272570	259	1013
8	137440	268300	234	1131
9	144640	267810	433	1114
10	161820	257480	953	1323
11	158680	262520	841	1194
12	163370	255200	989	1393
13	166600	257140	1083	1312
14	169660	262120	1148	1161
15	183690	258770	1544	1193
16	183400	253140	1563	1349
17	182660	246780	1570	1528
18	187520	260840	1642	1119
19	188340	257890	1676	1195
20	191440	256300	1768	1227
21	186460	296700	1452	142
22	188230	231030	1799	1943
23	194280	231080	1957	1905
24	188940	236230	1791	1792
25	178440	236180	1501	1838
26	178610	229630	1538	2014
27	189400	228370	1839	2001
28	197400	240620	2003	1632
29	180000	230520	1569	1984
30	174250	228750	1419	2059
31	177840	217860	1569	2340
32	182840	216140	1717	2370
33	181360	221530	1650	2225
34	163560	227590	1121	2135
35	167770	222140	1227	2283

Appendix D-1(d) GCP for I2264B1 Image

ID	Map X	Map Y	File X	File Y
1	176088	209286	1695	515
2	188276	192696	2115	908
3	186521	202859	2020	636
4	182478	177321	2025	1358
5	170554	170266	1729	1602
6	176629	166714	1820	1666
7	173505	167355	1746	1403
8	162617	172145	1306	1394
9	155171	175805	1278	1516
10	150402	176557	1144	1516
11	172327	177212	1499	1583
12	159486	199332	1290	850
13	164733	197953	1441	865
14	168810	191001	1587	1039
15	155431	190279	1218	1119
16	160826	187827	1380	1161
17	172565	204946	1622	640
18	169935	201753	1568	735
19	181312	221594	1791	145
20	164146	226136	1297	94
21	177559	217996	1703	259
22	169865	221424	1476	198
23	178646	214868	1748	341
24	180750	212509	1816	397
25	182314	215875	1840	296
26	185923	219581	1925	177
27	180582	223599	1761	91

Appendix D-2 (a) Subset FileCoordinates (TM)

Image : Final.lan

695 898 Sub 01	1795 548 Sub 02	X	1995 698 Sub 03	X	X	X
X	695 1398 Sub 04	1195 1198 Sub 05	(1) 1545 1098 Sub 06	(2) 2295 1348 Sub 07	(3) 2545 1348 Sub 08	X
X	895 1498 Sub 09	1345 1848 Sub 10	(4) 1445 948 Sub 11	(5) 1945 1798 Sub 12	(6) 2745 1848 Sub 13	X
X	745 2348 Sub 14	(7) 1195 2248 Sub 15	(8) 1495 2348 Sub 16	(9) 2395 2098 Sub 17	2495 2098 Sub 18	2945 2348 Sub 19
345 2698 Sub 20	845 2498 Sub 21	(10) 1395 2498 Sub 22	(11) 1745 2848 Sub 23	(12) 1945 2598 Sub 24	(13) 2745 2748 Sub 25	3045 2898 Sub 26
X	795 3348 Sub 27	(14) 1045 3048 Sub 28	(15) 1895 3148 Sub 29	(16) 2145 3298 Sub 30	(17) 2795 3398 Sub 31	(18) 3095 3248 Sub 32
X	X	1195 3698 Sub 33	(19) 1545 3698 Sub 34	(20) 2395 3698 Sub 35	(21) 2745 3598 Sub 36	(22) 3145 3848 Sub 37
X	X	X	X	X	2695 3998 Sub 38	X

( ) shows the subsets from the main quadrant I2164A1.LAN

Appendix D-2 (b) Subset Image Coordinates (TM)

Image : FINAL.LAN

175000 241000 Sub 01	X	197000 248000 Sub 02	201000 245000 Sub 03	X	X	X
X	175000 231000 Sub 04	185000 235000 Sub 05	(1) 192000 237000 Sub 06	(2) 207000 232000 Sub 07	(3) 212000 232000 Sub 08	X
X	179000 229000 Sub 09	188000 222000 Sub 10	(4) 190000 240000 Sub 11	(5) 200000 223000 Sub 12	(6) 216000 222000 Sub 13	X
X	176000 212000 Sub 14	(7) 185000 214000 Sub 15	(8) 191000 212000 Sub 16	(9) 209000 217000 Sub 17	211000 217000 Sub 18	220000 212000 Sub 19
168000 205000 Sub 20	178000 209000 Sub 21	(10) 189000 209000 Sub 22	(11) 196000 202000 Sub 23	(12) 200000 207000 Sub 24	(13) 216000 204000 Sub 25	222000 201000 Sub 26
X	177000 192000 Sub 27	(14) 182000 198000 Sub 28	(15) 199000 196000 Sub 29	(16) 204000 193000 Sub 30	(17) 217000 191000 Sub 31	(18) 223000 194000 Sub 32
X	X	185000 185000 Sub 33	(19) 192000 185000 Sub 34	(20) 209000 185000 Sub 35	(21) 216000 187000 Sub 36	(22) 224000 194000 Sub 37
X	X	X	X	X	215000 179000 Sub 38	X

( ) shows the subsets from the main quadrant I2164A1.LAN

Appendix D-3 IRS - LISS 2 Ground Survey Document

Date :	1996-03-20	Observer:	RP/ PD

Site No:	09	Remarks:

Parcel No.	Vegetation	Land Cover	Remarks
1	Grass	Poor	Short grasses, some areas are bare, lowland.
2	Urban	No	No trees, several small houses, also some bare land.
3	Tea	Medium	Scattered shade trees (*Gravilia robusta*) seedling tea.
4	Tea	Medium - poor	No many shade trees, seedling tea, scatterd rocks.
5	Urban	No	Playground and small houses, no tree cover.
6	Grass	Poor	Same as 1.
7	Grass	Poor	Transition stage to VPT, previously under marginal seedling tea.
8	Tea	Medium	Diversified tea, some minor export crops which provides some canopy cover.
9	Plantation forest	Medium	Uniform ground cover, terpentine plantation, steep slopes.
10	Tea	Medium	Same as 8.
11	Tea	Medium	Same as 8.
12	KFG	Medium - good	Not typical KFG, canopy density is lower, different tree species
13	KFG	Medium - good	Same as 12.
14	Grass	Poor	Some rock outcrops, scatterd small trees.
15			
16			
17			

Appendix D-4 (a) Mean and standard deviation of digital numbers for each class (50 classes) and for each band (4 bands) used in unsupervised classfication

No.	Mean 1	STD 1	Mean 2	STD 2	Mean 3	STD 3	Mean 4	STD 4
1	46.78	2.61	23.48	2.55	21.66	3.90	22.86	3.79
2	42.22	1.67	21.84	1.07	20.46	1.99	47.77	2.49
3	41.77	1.23	21.86	.78	19.67	1.26	53.59	1.59
4	49.63	3.15	26.45	2.50	30.03	3.28	39.91	4.37
5	42.31	1.22	22.46	.80	20.39	1.29	58.71	1.30
6	44.24	1.44	23.48	.74	22.84	1.46	54.55	2.03
7	49.01	1.78	26.52	1.37	30.49	2.34	50.05	2.56
8	46.80	1.56	25.40	.96	26.81	1.44	55.46	1.80
9	42.09	1.08	22.50	.82	20.41	1.03	63.43	1.18
10	53.23	2.96	30.59	2.55	37.99	3.22	49.99	4.20
11	46.23	1.39	25.08	.90	25.14	1.41	60.07	1.24
12	44.96	1.07	23.70	.72	21.18	1.00	61.17	1.35
13	43.92	.99	24.16	.78	23.58	1.05	63.38	1.32
14	48.97	1.54	27.33	1.07	30.88	1.45	57.83	1.57
15	43.33	1.31	23.32	.92	21.04	1.08	67.24	1.37
16	46.68	1.17	25.72	.83	25.97	.95	64.12	1.11
17	51.48	1.59	29.47	1.22	35.50	1.84	58.10	1.96
18	46.34	1.06	24.77	.81	22.68	1.02	65.34	1.05
19	45.87	1.14	25.37	.81	24.50	1.16	67.61	.91
20	49.22	1.31	26.96	1.07	28.60	1.33	61.43	1.22
21	47.17	1.10	26.73	.86	28.95	.99	63.94	1.15
22	44.98	1.27	24.60	.90	22.27	1.16	70.52	1.09
23	48.88	1.06	26.73	.97	26.78	1.02	66.62	1.23
24	48.94	1.18	28.10	.94	31.96	1.14	63.57	1.34
25	47.30	1.07	27.23	.89	29.70	1.23	67.27	.91
26	47.03	1.26	26.25	.86	25.92	1.20	69.88	.91
27	44.63	1.37	24.62	1.05	22.07	1.19	74.94	1.42
28	51.35	1.37	29.44	1.11	34.12	1.35	63.21	1.36
29	46.44	1.23	26.01	.81	24.66	1.11	73.48	1.16
30	47.98	1.45	27.24	.93	27.68	1.03	72.55	1.03
31	50.61	1.11	28.30	1.05	30.56	1.07	66.47	1.24
32	48.30	1.18	26.81	.92	30.00	1.24	70.11	.97
33	45.54	1.45	25.84	1.08	23.66	1.50	79.83	1.88
34	50.56	1.47	29.38	1.06	33.69	1.18	67.34	1.02
35	47.17	1.48	27.00	.95	26.73	1.30	76.32	1.07
36	50.85	1.22	28.95	1.13	31.74	1.18	71.38	1.28
37	47.40	1.54	27.99	.99	28.55	1.53	79.87	1.70
38	48.40	1.29	28.47	.95	31.04	1.19	74.72	1.41
39	52.32	1.66	30.95	1.13	38.00	1.51	64.82	1.59
40	46.30	2.00	27.50	1.63	25.48	2.40	87.66	4.01
41	49.51	1.28	29.68	.96	34.94	1.32	70.52	1.29
42	52.91	1.62	31.09	1.19	37.35	1.64	69.28	1.31
43	49.06	1.65	29.90	1.15	32.90	2.02	81.88	2.47
44	54.71	2.41	32.65	1.85	42.34	3.03	59.28	2.57
45	50.59	1.50	30.23	1.11	34.99	1.52	75.49	1.67
46	53.20	2.22	33.28	1.66	41.98	3.02	78.83	2.64
47	52.24	1.76	31.88	1.20	39.73	1.68	72.72	1.71
48	54.96	2.18	33.24	1.47	43.35	2.44	66.02	1.80
49	55.95	2.38	34.47	1.60	45.89	2.46	71.30	2.45
50	61.13	3.61	38.54	2.92	55.43	4.79	71.08	5.35

Appendix D-4 (b) Combination of Classes in Fusion Dendrogram for Unsupervised Classification

Case	Class	Case	Class
Case 1	1	Case 30	6
Case 6	2	Case 31	6
Case 2	2	Case 25	6
Case 3	2	Case 16	6
Case 4	3	Case 24	6
Case 10	3	Case 23	6
Case 7	3	Case 21	6
Case 18	4	Case 28	6
Case 9	4	Case 26	6
Case 5	4	Case 17	7
Case 22	4	Case 44	7
Case 12	4	Case 40	8
Case 13	4	Case 43	8
Case 15	4	Case 37	8
Case 19	4	Case 35	8
Case 20	5	Case 33	8
Case 14	5	Case 27	8
Case 11	5	Case 29	8
Case 8	5	Case 48	9
Case 34	6	Case 49	9
Case 32	6	Case 39	9
Case 41	6	Case 47	9
Case 36	6	Case 46	9
Case 45	6	Case 42	9
Case 38	6	Case 50	10

Appendix D-5(a) Jeffries-Matusita Signature Separability Listing (Bands 1,3 and 4)

Class	Land Use	(Weight) / (Total Weight)
1	Urban	0.075
2	Paddy	0.050
3	Other Crops	0.150
4	Open Forest	0.050
5	Plantation Forest	0.025
6	Dense Forest	0.094
7	Water	0.050
8	Tea	0.150
9	Grass	0.162
10	KFG	0.194

Best Average SeparabilityUsing Jeffries-Matusita Distance (3 Bands)

Bands	Ave	Min	Class Pairs:						
			1: 2	1: 3	1: 4	1: 5	1: 6	1: 7	1: 8
			1: 9	1:10	2: 3	2: 4	2: 5	2: 6	2: 7
			2: 8	2: 9	2:10	3: 4	3: 5	3: 6	3: 7
			3: 8	3: 9	3:10	4: 5	4: 6	4: 7	4: 8
			4: 9	4:10	5: 6	5: 7	5: 8	5: 9	5:10
			6: 7	6: 8	6: 9	6:10	7: 8	7: 9	7:10
			8: 9	8:10	9:10				
1, 3, 4	1356	1005	1414	1405	1382	1335	1414	1414	1413
			1414	1414	1414	1414	1237	1414	1342
			1246	1414	1414	1053	1414	1313	1397
			1401	1358	1414	1400	1365	1383	1323
			1055	1414	1414	1378	1314	1414	1414
			1387	1409	1375	1414	1005	1237	1414
			1205	1414	1414				

Appendix D-5(b) Best Average SeparabilityUsing Jeffries-Matusita Distance (2 Bands)

Bands	Ave	Min	Class Pairs:						
			1: 2	1: 3	1: 4	1: 5	1: 6	1: 7	1: 8
			1: 9	1:10	2: 3	2: 4	2: 5	2: 6	2: 7
			2: 8	2: 9	2:10	3: 4	3: 5	3: 6	3: 7
			3: 8	3: 9	3:10	4: 5	4: 6	4: 7	4: 8
			4: 9	4:10	5: 6	5: 7	5: 8	5: 9	5:10
			6: 7	6: 8	6: 9	6:10	7: 8	7: 9	7:10
			8: 9	8:10	9:10				
1, 4	1338	858	1110	1373	1401	1412	1412	1403	1413
			1134	1400	1209	1337	1401	1406	1414
			1414	1356	1358	952	1359	1379	1414
			1412	1393	1040	858	1376	1414	1381
			1400	1160	1404	1414	1326	1413	1327
			1414	1414	1351	1414	1414	1406	1414
			1283	1399	1413				
1, 3	1206	617	1339	1399	1235	1368	1386	1399	1361
			1222	1377	1209	1337	1401	1406	1414
			1349	1291	1334	1104	1265	1362	1355
			1228	1206	906	978	1048	1234	1215
			1305	907	604	1377	1149	1259	1344
			1346	1255	1322	1395	1322	1348	1240
			654	1202	1285				
3, 4	1313	541	1095	1366	1406	1413	1393	1392	1406
			1086	1411	1186	1363	1391	1404	1414
			1401	1230	1387	1139	1275	1368	1414
			1370	1358	1173	541	1367	1414	1172
			1407	1104	1404	1414	1136	1414	845
			1414	1314	1382	1414	1402	1222	1414
			1263	1273	1412				

Appendix E

Appendix E-1(a) Rainfall Data Format in SPANS Modelling

. ID	rainfall				
TITLE	rainfall				
MAPID	rainfall				
WINDOW	0	0	0	19840	10400
TABTYPE	2				
FTYPE	2				
KEYFIELD	33				
KEYBASE	0				
NRECORD	58				
1	5	8.00	0	morton	morton
2	1	7.20	0	Day1	Day1
3	1	7.20	0	Day2	Day2
4	1	7.20	0	Day3	Day3
5	1	7.20	0	Day4	Day4
6	1	7.20	0	Day5	Day5
7	1	7.20	0	Day6	Day6
8	1	7.20	0	Day7	Day7
9	1	7.20	0	Day8	Day8
10	1	7.20	0	Day9	Day9
11	1	7.20	0	Day10	Day10
12	1	7.20	0	Day11	Day11
13	1	7.20	0	Day12	Day12
14	1	7.20	0	Day13	Day13
15	1	7.20	0	Day14	Day14
16	1	7.20	0	Day15	Day15
17	1	7.20	0	Day16	Day16
18	1	7.20	0	Day17	Day17
19	1	7.20	0	Day18	Day18
20	1	7.20	0	Day19	Day19
21	1	7.20	0	Day20	Day20
22	1	7.20	0	Day21	Day21
23	1	7.20	0	Day22	Day22
24	1	7.20	0	Day23	Day23
25	1	7.20	0	Day24	Day24
26	1	7.20	0	Day25	Day25
27	1	7.20	0	Day26	Day26
28	1	7.20	0	Day27	Day27
29	1	7.20	0	Day28	Day28
30	1	7.20	0	Day29	Day29
31	1	7.20	0	Day30	Day30
32	1	7.20	0	Day31	Day31
33	3	4.00	0	Key1	Key1

contd...

DATA	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

727db7	30	0	0	13	401	0	0	0	660	107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	203	41	20	0	1
76e884	5	33	119	104	66	0	0	10	198	71	0	0	0	0	0	0	0	0	0	0	0	33	25	43	12	10	71	0	0	2
bd7d17	28	18	5	10	107	0	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	168	0	0	0	0	0	41	0	3
c6601a	25	0	0	0	152	0	0	0	127	0	0	0	0	0	0	0	0	0	0	0	0	102	0	0	0	0	0	0	0	4
ced8c3	28	0	0	0	51	0	0	0	69	23	0	0	0	0	0	0	0	0	0	0	0	0	122	0	0	0	0	38	13	5
d2dc4e	53	3	1	19	67	0	0	0	48	53	27	0	0	0	0	0	0	0	0	0	0	78	64	1	1	3	12	14	2	6
d49164	51	0	0	0	0	0	0	0	0	152	84	0	0	0	0	0	0	0	0	0	0	0	89	0	0	0	0	0	0	7
e8d6d0	30	0	0	0	76	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	203	0	0	0	0	0	71	0	8
fe2eba	53	0	5	33	71	0	0	0	20	13	0	0	0	0	0	0	0	0	0	0	0	343	0	0	188	5	0	13	0	9
10dd399	145	38	5	20	69	0	3	0	152	191	3	0	5	0	0	0	0	0	0	0	0	165	3	0	13	53	3	66	0	10
116b7df	0	215	61	17	0	198	0	0	0	203	154	0	0	0	0	0	0	0	0	0	0	0	304	17	101	10	0	0	281	11
12a90b8	74	0	8	20	64	0	5	188	76	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	15	0	12
132eb32	162	0	0	0	116	0	0	0	304	0	0	0	0	0	0	0	0	0	0	0	0	101	0	0	0	0	66	0	0	13
136ea72	127	8	18	25	64	8	25	5	191	5	0	0	0	0	0	0	0	0	0	0	0	178	0	0	0	0	5	84	0	14
1386918	99	0	91	8	84	0	0	0	297	0	0	0	0	0	0	0	0	0	0	0	0	79	0	0	0	0	0	0	0	15
1659c11	348	15	127	134	287	22	68	27	391	139	0	0	0	0	0	0	0	0	0	0	0	342	58	17	0	27	38	50	0	16
16be75c	13	0	43	178	511	56	30	46	513	0	0	0	0	0	0	0	0	0	0	0	33	246	30	41	28	25	84	310	0	17
16cc49e	163	0	0	132	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	211	99	10	10	25	97	0	0	18
1ad9596	33	0	10	13	56	0	0	0	180	46	0	0	0	0	0	0	0	0	0	0	0	584	0	0	0	0	0	38	0	19
1b97022	0	0	56	147	104	5	71	3	241	94	0	0	0	0	0	0	0	0	0	0	0	399	20	0	0	15	13	38	0	20
1bac7d9	56	0	142	216	180	23	117	20	145	97	0	0	0	0	0	0	0	0	0	0	8	765	0	10	0	0	15	36	0	21
1cb8a79	15	6	91	188	351	39	86	41	333	87	4	0	0	0	0	0	0	0	0	0	10	321	26	19	13	33	57	160	0	22
1cc264f	12	5	92	200	315	40	94	46	351	103	5	0	0	0	0	0	0	0	0	0	11	367	30	21	16	34	56	161	0	23
1d62643	20	8	61	89	320	20	38	13	152	18	0	0	0	0	0	0	0	0	0	0	0	81	5	5	0	20	38	91	0	24
1ef5ed9	36	25	302	437	452	124	310	203	401	384	36	0	0	0	0	0	0	0	0	0	10	620	71	53	53	112	132	246	0	25
20656c9	13	0	132	0	218	0	0	8	0	10	0	0	0	0	0	0	0	0	0	0	0	193	104	0	0	0	0	13	0	26
2467506	69	0	0	0	183	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	259	0	0	0	0	0	0	0	27
2540ae9	61	0	10	38	124	0	5	0	33	10	0	0	0	0	0	0	0	0	0	0	0	380	0	0	55	33	0	10	0	28
275ec04	46	0	30	114	173	5	71	8	25	5	0	0	0	0	0	0	0	0	0	0	0	470	0	5	8	0	8	5	0	29
2f4893f	0	18	325	0	0	0	38	25	33	157	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30
309f0a4	13	0	53	13	127	0	25	0	76	79	0	0	0	0	0	0	0	0	0	0	0	0	584	0	51	0	0	0	0	31
3167983	71	5	249	328	198	81	122	99	300	104	28	0	0	0	0	0	0	0	0	0	0	838	0	8	38	97	46	81	0	32
32c6cce	38	0	165	259	483	89	203	51	152	89	13	0	0	0	0	0	0	0	0	0	0	114	13	0	46	38	13	114	0	33
32f52e2	28	0	104	373	488	117	61	58	112	150	25	0	0	0	0	0	0	0	0	0	0	139	20	10	48	112	20	142	0	34
33409ae	56	25	318	445	508	122	335	229	254	335	46	0	0	0	0	0	0	0	0	0	0	149	0	46	69	89	36	178	0	35
34c53da	28	38	505	546	409	145	389	198	262	511	53	0	0	0	0	0	0	0	0	0	5	166	76	28	51	119	91	211	0	36
36c7715	0	25	127	376	691	168	64	89	64	292	0	0	0	0	0	0	0	0	0	0	0	181	0	25	0	208	51	157	0	37
387abb7	8	0	23	335	325	53	10	8	36	20	20	0	0	0	0	0	0	0	0	0	0	125	38	10	28	71	61	107	0	38
3a824ed	0	0	221	203	249	0	0	0	66	61	0	0	0	0	0	0	0	0	0	0	0	105	0	0	0	23	0	0	0	39
3e6348b	51	64	203	546	686	203	84	89	64	0	0	0	0	0	0	0	0	0	0	0	1	170	46	71	89	102	104	76	0	40
3f8bebe	33	236	325	105	241	264	69	124	282	147	155	0	0	0	0	0	0	0	0	0	0	130	152	267	127	246	328	211	0	41
4096d65	185	33	15	0	0	274	0	0	0	218	36	0	0	0	0	0	0	0	0	0	0	0	297	18	0	51	0	0	61	42
40df170	150	13	51	152	330	36	46	0	333	91	0	0	0	0	0	0	0	0	0	0	0	572	36	20	0	0	10	132	0	43
4267532	10	5	5	10	5	10	8	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	5	3	15	0	44
48074a8	38	10	124	132	411	61	66	48	211	109	10	0	0	0	0	0	0	0	0	0	0	221	30	30	23	25	38	208	0	45
4a29439	43	102	597	241	579	142	203	175	424	356	36	0	0	0	0	0	0	0	0	0	3	472	46	41	69	137	102	170	0	46
4af9b2c	38	163	673	302	427	165	272	312	566	345	38	8	0	0	0	0	8	0	3	0	15	483	79	56	58	191	53	178	0	47
4baa9a1	41	241	569	203	508	104	257	226	470	310	30	18	0	0	0	0	0	0	0	0	5	427	13	66	53	150	58	180	0	48
4c0ea4d	38	140	178	305	559	305	152	178	572	165	0	0	0	0	0	0	0	0	0	0	0	660	140	76	38	89	152	432	0	49
4c1f5cd	12	63	10	236	533	61	10	27	266	30	0	0	0	0	0	0	0	0	0	0	0	520	101	58	63	7	76	426	0	50
4c3ae7c	71	119	132	381	792	41	150	142	396	173	0	0	0	0	0	0	0	0	0	0	15	544	61	43	51	81	208	284	0	51
4e125ed	0	0	0	0	127	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	615	5	467	13	52
4e4019c	51	137	97	361	638	69	64	114	450	109	0	0	0	0	0	0	0	0	0	0	0	419	33	97	66	132	135	254	0	53
61182bc	122	198	848	389	544	122	226	318	729	318	41	0	0	0	0	0	0	0	0	0	53	528	51	53	191	178	86	211	0	54
85552ed	0	0	119	234	231	8	0	0	64	41	33	0	0	0	0	0	0	0	0	0	0	775	0	0	0	23	8	23	0	55
9121123	0	3	64	381	452	0	8	0	28	0	0	0	0	0	0	0	0	0	0	0	0	838	0	0	0	58	0	23	0	56
91ae7d4	25	0	81	589	432	0	25	0	25	38	33	0	0	0	0	0	0	0	0	0	0	100	51	0	25	13	51	0	0	57
94208ec	30	30	114	673	726	157	43	13	64	38	15	0	0	0	0	0	0	0	0	0	0	856	30	58	30	33	46	5	0	58

Appendix E-1(b) Land Use Parameter Format in SPANS Modelling

```
ID          lusedata
TITLE       lusedata
MAPID       lusedata
WINDOW      00 0 0 19840 10400
TABTYPE 2
FTYPE       free
KEYFIELD 1
KEYBASE   0
NRECORD 4
 1 4   11.000000   0   landuse landuse
 2 1   10.400000   0   beta Beta parameters
 3 1   10.400000   0   delta delta parameters
 4 1   10.400000   0   gamma gamma parameters
 5 1   10.400000   0   tb Intital moisture
 6 1   10.400000   0   aw available water
DATA
```

1	0.8500	0.0990	6.9100	380.0000	380.0000
2	1.0000	0.0001	0.0001	300.0000	300.0000
3	1.0000	0.3600	2.6500	300.0000	300.0000
4	0.9000	0.0990	6.9100	380.0000	380.0000

Appendix E-2 Structure of Modelling Equations

E Moi86011 Soil Moisture Map 01

```
: This equation calculates soil moisture on odd days
:initial runoff mapclass is 10 to include one decimal place
ro=(class('runof071'))/10;
:Available water from lusedata table column 6
aw=table('lusedata',class('relu0792'),'aw');
:soil moisture is initially set to actual * 10
sm=(class('moist071')/10);
:in fog map devide by 100 to substrat to balance base map class in classification
fog=(class('fogmp071')-1)/100;
:map required to increment rainfall data columns
z=class('incrm071');
:get the actual rainfall, need to devide by 10
:Data8601 denotes 1986 and month January
rain=(table('Data8601',class('rainf07'),z)/10);
:total  precipitation includes rainfall plus fog
:fog is calculated as a fraction of rainfall
r=rain+fog*rain;
:interception parameters from table lusedata column 6
ip=table('lusedata',class('relu0792'),'gamma');
:getting type of landuse
g=table('lusedata',class('relu0792'),1);
:estimate the interception loss
i=ip*(1-exp(-table('lusedata',class('relu0792'),'delta')*r));
:calculate soil moisture stress moderator
y=2*sm/aw;
x={1 if y>1,y};
:to avoid zero evaporation when i and ip becomes equal
g={2 if i/ip<1.0001 & i/ip>0.9999};
:accounting spatial distribution of evaporation
c=class('evapor07');
:calulate evaporation
d={((x*(c/365)*table('lusedata',class('relu0792'),'beta'))*(1-(i/ip))) if
g<>2,((x*(c/365)*table('lusedata', class('relu0792'),'beta')))};
:calculate the total soil moisture
sm1=sm+r-i-d;
:substracting water holding capacity, avoid negative values
sm2={aw if sm1>aw, 0 if sm1<0,sm1};
:to avoid zero, and also to  take one decimal point
b={(sm2*10) if sm2>0.05, (sm2*10)+0.51};
:remove decimals beyond first
down=floor(b);
up=ceil(b);
value={b if up-down<0.5, b+1};
result(value)
```

E Run86011 Runoff in Odd Days

```
: This equation calculates soil moisture on odd days
:initial runoff mapclass is 10 to include one decimal place
ro=(class('runof071'))/10;
:Available water from lusedata table column 6
aw=table('lusedata',class('relu0792'),'aw');
:soil moisture is initially set to actual * 10
sm=(class('moist071')/10);
:in fog map devide by 100 to substrat to balance base map class in classification
fog=(class('fogmp071')-1)/100;
:map required to increment rainfall data columns
z=class('incrm071');
:get the actual rainfall, need to devide by 10
:Data8601 denotes 1986 and month January
rain=(table('Data8601',class('rainf07'),z)/10);
:total precipitation includes rainfall plus fog
:fog is calculated as a fraction of rainfall
r=rain+fog*rain;
:interception parameters from table lusedata column 6
ip=table('lusedata',class('relu0792'),'gamma');
:getting type of landuse
g=table('lusedata',class('relu0792'),1);
:estimate the interception loss
i=ip*(1-exp(-table('lusedata',class('relu0792'),'delta')*r));
:calculate soil moisture stress moderator
y=2*sm/aw;
x={1 if y>1,y};
:to avoid zero evaporation when i and ip becomes equal
g={2 if i/ip<1.0001 & i/ip>0.9999};
:accounting spatial distribution of evaporation
c=class('evapor07');
:calulate evaporation
d={((x*(c/365)*table('lusedata',class('relu0792'),'beta'))*(1-(i/ip))) if
g<>2,((x*(c/365)*table('lusedata', class('relu0792'),'beta')))};
:calculate the water balance and 10 for include first decimal point
run=(sm+r-i-d-aw);
:to remove negative values from 00 classification
ba={0 if run<0, run};
b=(ba+ro)*10;
:remove decimals beyond first
down=floor(b);
up=ceil(b);
value={b if up-down<0.5, b+1};
result(value)
```

E Run86012 Runoff in Even Days

```
: This equation calculates soil moisture on odd days
:initial runoff mapclass is 10 to include one decimal place
ro=(class('runof071'))/10;
:Available water from lusedata table column 6
aw=table('lusedata',class('relu0792'),'aw');
:soil moisture is initially set to actual * 10
sm=(class('moist072')/10);
:in fog map devide by 100 to substrat to balance base map class in classification
fog=(class('fogmp071')-1)/100;
:map required to increment rainfall data columns
z=class('incrm072');
:get the actual rainfall, need to devide by 10
:Data8601 denotes 1986 and month January
rain=(table('Data8601',class('rainf07'),z)/10);
:total precipitation includes rainfall plus fog
:fog is calculated as a fraction of rainfall
r=rain+fog*rain;
:interception parameters from table lusedata column 6
ip=table('lusedata',class('relu0792'),'gamma');
:getting type of landuse
g=table('lusedata',class('relu0792'),1);
:estimate the interception loss
i=ip*(1-exp(-table('lusedata',class('relu0792'),'delta')*r));
:calculate soil moisture stress moderator
y=2*sm/aw;
x={1 if y>1,y};
:to avoid zero evaporation when i and ip becomes equal
g={2 if i/ip<1.0001 & i/ip>0.9999};
:accounting spatial distribution of evaporation
c=class('evapor07');
:calulate evaporation
d={((x*(c/365)*table('lusedata',class('relu0792'),'beta'))*(1-(i/ip))) if
g<>2,((x*(c/365)*table('lusedata', class('relu0792'),'beta')))};
:calculate the water balance and 10 for include first decimal point
run=(sm+r-i-d-aw);
:to remove negative values from 00 classification
ba={0 if run<0, run};
b=(ba+ro)*10;
:remove decimals beyond first
down=floor(b);
up=ceil(b);
value={b if up-down<0.5, b+1};

result(value)
```

E Moi86012 Soil Moisture Map 02

```
: This equation calculates soil moisture on odd days
:initial runoff mapclass is 10 to include one decimal place
ro=(class('runof071'))/10;
:Available water from lusedata table column 6
aw=table('lusedata',class('relu0792'),'aw');
:soil moisture is initially set to actual * 10
sm=(class('moist072')/10);
:in fog map devide by 100 to substrat to balance base map class in classification
fog=(class('fogmp071')-1)/100;
:map required to increment rainfall data columns
z=class('incrm072');
:get the actual rainfall, need to devide by 10
:Data8601 denotes 1986 and month January
rain=(table('Data8601',class('rainf07'),z)/10);
:total precipitation includes rainfall plus fog
:fog is calculated as a fraction of rainfall
r=rain+fog*rain;
:interception parameters from table lusedata column 6
ip=table('lusedata',class('relu0792'),'gamma');
:getting type of landuse
g=table('lusedata',class('relu0792'),1);
:estimate the interception loss
i=ip*(1-exp(-table('lusedata',class('relu0792'),'delta')*r));
:calculate soil moisture stress moderator
y=2*sm/aw;
x={1 if y>1,y};
:to avoid zero evaporation when i and ip becomes equal
g={2 if i/ip<1.0001 & i/ip>0.9999};
:accounting spatial distribution of evaporation
c=class('evapor07');
:calulate evaporation
d={((x*(c/365)*table('lusedata',class('relu0792'),'beta'))*(1-(i/ip))) if
g<>2,((x*(c/365)*table('lusedata', class('relu0792'),'beta')))};
:calculate the total soil moisture
sm1=sm+r-i-d;
:substracting water holding capacity, avoid if negative arises
sm2={aw if sm1>aw, 0 if sm1<0,sm1};
:to avoid zero, take one decimal point
b={(sm2*10) if sm2>0.05, (sm2*10)+0.51};
:remove decimals beyond first
down=floor(b);
up=ceil(b);
value={b if up-down<0.5, b+1};

result(value)
```

E fogint1 fog percentage

```
:this is to calculate the percentage of fog
:for monsoon period
:read the elevation from map
f=class('elevat09');
g=f*10;
y={0 if g<1001,((0.0118*g)-11.8)};
fog=y*10;
result(floor(fog))
```

E fogint2 fog percentage

```
:this is to calculate the percentage of fog
:for intermonsoon period
:read the elevation from map
f=class('elevat09');
g=f*10;
y={0 if g<1001,((0.0436*g)-43.6)};
fog=y*10;
result(floor(fog))
```

E incrm071 incremental map

```
: This incrments rainfall table column by 1
z=class('incrm071');
z+1
```

E incrm072 incremental map

```
: This incrments rainfall table column by 1
z=class('incrm072');
z+1
```

Appendix E-3 Structure of Monthly Command Files

:Command file for 1993 December
:day01
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day02
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day03
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day04
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day05
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
os copy day.map dx59312.map
:day06
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day07
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day08
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day09
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day10
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
os copy day.map dx109312.map
:day11
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day12
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day13
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0

```
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
:day14
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
:day15
longoverlay  e =run93121 m =Runof072 c =5 q =0
longoverlay  e =moi93121 m =Moist072 c =7 q =0
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
os copy day.map dx159312.map
:day16
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
:day17
longoverlay  e =run93121 m =Runof072 c =5 q =0
longoverlay  e =moi93121 m =Moist072 c =7 q =0
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
:day18
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
:day19
longoverlay  e =run93121 m =Runof072 c =5 q =0
longoverlay  e =moi93121 m =Moist072 c =7 q =0
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
:day20
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
os copy day.map dx209312.map
:day21
longoverlay  e =run93121 m =Runof072 c =5 q =0
longoverlay  e =moi93121 m =Moist072 c =7 q =0
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
:day22
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
:day23
longoverlay  e =run93121 m =Runof072 c =5 q =0
longoverlay  e =moi93121 m =Moist072 c =7 q =0
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
:day24
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
:day25
longoverlay  e =run93121 m =Runof072 c =5 q =0
longoverlay  e =moi93121 m =Moist072 c =7 q =0
longoverlay  e =Incrm071 m =Incrm072 c =0 q =0
os copy day.map dx259312.map
:day26
longoverlay  e =run93122 m =Runof071 c =5 q =0
longoverlay  e =moi93122 m =Moist071 c =7 q =0
longoverlay  e =Incrm072 m =Incrm071 c =0 q =0
```

```
:day27
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day28
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day29
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:day30
longoverlay e =run93122 m =Runof071 c =5 q =0
longoverlay e =moi93122 m =Moist071 c =7 q =0
longoverlay e =Incrm072 m =Incrm071 c =0 q =0
:day31
longoverlay e =run93121 m =Runof072 c =5 q =0
longoverlay e =moi93121 m =Moist072 c =7 q =0
longoverlay e =Incrm071 m =Incrm072 c =0 q =0
:copying files for monthly archives
os copy Runof072.map R9312071.map
os copy Moist072.map M9312071.map
:copying moisture file for next month
:soil moisture is a continuum
os copy Moist072.map Moist071.map
: producing data tables
:use 6 major subcatchements
avgclass m =r9312071 n =subcat09 w =00 r =r9312071 s =y p =n
avgclass m =m9312071 n =subcat09 w =00 r =m9312071 s =y p =n
:moving maps and report files to respective directory
os move r93*.rep c:\ranjith\repfil14
os move m93*.rep c:\ranjith\repfil14
os move r93*.map c:\ranjith\repfil14
os del m93*.map
:initializing runoff and increment maps for next monthfile
reclass m =basef o =Runof071 w =00 b =y s =y f =Runof071 q =7
reclass m =basef o =Incrm071 w =in b =y s =y f =Incrm071 q =7
:executing next month's commandfile
exec f=aud94jan
```

Appendix E-4 REXX Programming Codes to Automate Hydrological Modelling Process

REXX & OS/2 CODES

```
OS/2> EXECUTE REXX1
        /*REXX1.CMD file*/
        /*initialising the system*/
        x=lineout(initial.cmd, "reclass m=base o=incrmnt1 f=incrm071 q=7"
                               "reclass m=base o=runof071 f=runof071 q=7"
                               "reclass m=base o=moist071 f=moist071 q=7"
                               "os copy equati64.inp equation.inp"
                               "exec f=audit64jan")
        end
        exit

OS>2EXECUTE REXX2
        /*REXX2.CMD file*/
        /*Producing equations for one year*/
        do n=1 to 12
                {x=lineout(equati64.inp,"E Run64"n"1 Monthly runoff equations"
                                        "............................"
                                        "E Moi64"n"1 Mothly equations for Moisture"
                                        "............................"
                                        "E Incrmn01   Modeling equation to Increment")
                                        "............................"
                                        "E Run64"n"2 Monthly equations for Runoff"
                                        "............................"
                                        "E Moi64"n"2 Mothly equations for Moisture"
                                        "............................"
                                        "E Incrmn02   Modeling equation to Increment")
                                        "............................"

                ........
                ........}
        end
        exit
OS/2>EXECUTE REXX3
        /*REXX3.CMD file*/
        /*producing command line functions for each month*/
        /*month of January*/
        do m=1 to 31
                {x=lineout(aud64jan.cmd,
                        ":day"m
                        "longoverlay e=run6411 m=runof072 c=1"
                        "longoverlay e=moi6411 m=moist072 c=2"
                        "longoverlay e=incrmn01 m=incrm072 c=0")
                        "os copy runof072.map runof071.map"
                        "os copy moist072.map moist071.map"
                        "os copy incrm072.map incrm071.map"}


        x=(lineout(aud64jan.cmd,
                ":copying files for next month"
                "os copy Runof071.map R6401071.map"
                "os copy Moist071.map M6401071.map"
                ":deleting temporary  files"
```

```
                "os del *.rnd"
                ": producing data tables"
                "avgclass  m =r6401071 n =subcat07 w =00 r =r6401071 s =y p =n"
                "avgclass  m =m6401071 n =subcat07 w =00 r =m6401071 s =y p =n"
                ":initializing file for next month"
                "reclass  m =basef o =Runof071 w =00 b =y s =y f =Runof071 q =7"
                "reclass  m =basef o =Incrm071 w =00 b =y s =y f =Incrm071 q =7"
                "exec f=aud64feb"
        end
        exit

OS/2>EXECUTE REXX4
        /*AUTO.CFG file*/
        /*producing automation file in SPANS*/
        x=lineout(auto.cfg,"pmspans.mnu /*menu file*/
                            spansdll.dll /*language file*/
                                C:\UMCA\<data directory>")
        end
        exit

OS/2>start pmspans auto
        command mode
com>exec f=initial
```

Appendix F

Appendix F-1(a) Flow Data for Talawakele Sub Catchment (1964-1969)

	Measured	Observed	Deviation		Measured	Observed	Deviation
Jan	87.29	42.42	44.87	Jul	95.14	196.97	-101.83
	11.20	4.88	6.32		45.74	4.87	40.87
	78.15	33.99	44.16		72.85	72.76	0.09
	75.41	13.63	61.78		131.19	96.97	34.22
	20.45	18.47	1.98		333.27	238.14	95.13
	76.48	27.55	48.93		121.31	70.40	50.91
Feb	52.93	21.18	31.75	Aug	153.63	127.98	25.65
	32.01	12.82	19.19		151.95	122.29	29.66
	43.25	2.88	40.37		78.54	68.32	10.22
	59.90	31.09	28.81		98.91	41.67	57.24
	1.05	1.00	0.05		152.64	141.65	10.99
	45.06	8.10	36.96		87.24	28.27	58.97
Mar	40.63	10.76	29.87	Sep	180.65	184.35	-3.70
	19.34	20.61	-1.27		89.54	4.91	84.63
	51.55	52.91	-1.36		193.33	3.02	190.31
	59.16	66.14	-6.98		77.34	94.37	-17.03
	52.41	21.89	30.52		245.03	219.71	25.32
	36.67	9.00	27.67		182.92	68.88	114.04
Apr	30.18	26.81	3.37	Oct	81.83	123.19	-41.36
	74.01	194.20	-120.19		168.20	148.09	20.11
	55.14	180.64	-125.50		231.84	69.07	162.77
	46.27	68.61	-22.34		292.21	344.67	-52.46
	44.44	52.77	-8.33		208.25	229.01	-20.76
	72.73	185.52	-112.79		162.30	268.72	-106.42
May	29.43	44.41	-14.98	Nov	160.78	181.45	-20.67
	236.98	397.09	-160.11		137.65	129.98	7.67
	21.19	17.49	3.70		163.03	96.92	66.11
	47.96	26.29	21.67		211.66	248.52	-36.86
	90.60	93.92	-3.32		140.94	81.32	59.62
	126.23	263.68	-137.45		112.49	200.19	-87.70
Jun	33.84	32.46	1.38	Dec	95.69	27.05	68.64
	156.08	76.28	79.80		114.27	88.33	25.94
	56.25	10.49	45.76		95.03	36.37	58.66
	77.71	97.99	-20.28		101.20	94.07	7.13
	102.37	185.16	-82.79		106.13	80.94	25.19
	208.32	178.01	30.31		141.15	215.02	-73.87

Appendix F-1(b) Flow Data for Kotmale Sub Catchment (1964-1969)

	Measured	Observed	Deviation		Measured	Observed	Deviation
Jan	96.96	33.91	63.05	Jul	518.70	341.69	177.01
	20.36	3.58	16.78		109.29	32.36	76.93
	77.45	14.39	63.06		126.40	76.55	49.85
	47.39	24.22	23.17		173.02	157.47	15.55
	16.18	8.51	7.67		534.68	466.44	68.24
	44.01	13.40	30.61		196.14	125.24	70.90
Feb	113.66	57.28	56.38	Aug	119.40	187.14	-67.74
	60.04	11.27	48.77		147.05	280.69	-133.64
	21.01	1.99	19.02		120.94	92.82	28.12
	30.93	30.57	0.36		126.50	149.51	-23.01
	19.85	1.00	18.85		333.77	292.77	41.00
	29.58	4.58	25.00		5.95	46.75	-40.80
Mar	71.23	31.85	39.38	Sep	352.60	313.00	39.60
	31.38	6.57	24.81		122.24	32.82	89.42
	100.48	31.71	68.77		192.88	17.53	175.35
	28.54	37.40	-8.86		80.26	152.94	-72.68
	22.36	14.13	8.23		379.29	448.23	-68.94
	2.92	8.45	-5.53		21.28	120.41	-99.13
Apr	79.42	30.68	48.74	Oct	278.96	172.10	106.86
	153.55	154.66	-1.11		260.19	197.39	62.80
.	100.54	171.39	-70.85		68.22	52.47	15.75
	16.37	26.32	-9.95		291.44	411.48	-120.04
	15.36	38.15	-22.79		320.31	222.88	97.43
	10.36	155.75	-145.39		209.10	243.48	-34.38
May	62.66	91.90	-29.24	Nov	396.14	279.50	116.64
	637.70	546.55	91.15		204.93	127.75	77.18
	8.89	3.33	5.56		222.46	163.65	58.81
	18.88	54.30	-35.42		249.61	215.80	33.81
	87.81	223.20	-135.39		147.24	106.11	41.13
	115.49	297.06	-181.57		106.27	172.13	-65.86
Jun	95.96	128.94	-32.98	Dec	72.33	18.74	53.59
	287.44	225.50	61.94		151.72	101.01	50.71
	16.32	93.65	-77.33		88.09	61.36	26.73
	99.53	225.08	-125.55		218.16	186.14	32.02
	259.95	430.52	-170.57		106.41	85.32	21.09
	578.00	334.07	243.93		135.87	174.45	-38.58

Appendix F-1(c) Flow Data for Peradeniya Sub Catchment (1964-1969)

	Measured	Observed	Deviation		Measured	Observed	Deviation
Jan	77.52	35.04	42.48	Jul	117.21	331.87	-214.66
	16.10	4.72	11.38		121.86	60.67	61.19
	58.19	8.01	50.18		121.12	97.43	23.69
	445.54	88.87	356.67		198.97	171.29	27.68
	36.75	12.51	24.24		457.75	453.80	3.95
	64.28	5.34	58.94		226.10	83.14	142.96
Feb	82.58	25.19	57.39	Aug	252.87	143.49	109.38
	51.01	15.71	35.30		274.00	297.61	-23.61
	15.02	3.21	11.81		140.87	127.01	13.86
	75.40	35.74	39.66		174.56	158.30	16.26
	54.03	2.35	51.68		170.32	220.70	-50.38
	38.53	13.22	25.31		216.35	81.35	135.00
Mar	115.50	18.51	96.99	Sep	263.02	307.81	-44.79
	39.71	21.70	18.01		183.27	62.58	120.69
	57.00	42.59	14.41		445.54	88.87	356.67
	78.82	60.86	17.96		90.55	162.92	-72.37
	63.95	27.28	36.67		246.61	429.90	-183.29
	48.31	7.59	40.72		247.43	82.71	164.72
Apr	87.22	59.58	27.64	Oct	172.90	222.22	-49.32
	128.75	188.65	-59.90		482.68	296.38	186.30
	32.32	222.06	-189.74		140.00	112.95	27.05
	97.80	59.31	38.49		426.23	449.55	-23.32
	100.81	115.60	-14.79		243.33	229.87	13.46
	130.74	173.33	-42.59		83.54	311.12	-227.58
May	81.83	146.04	-64.21	Nov	305.68	323.76	-18.08
	296.45	566.39	-269.94		189.70	233.18	-43.48
	52.50	28.00	24.50		245.14	185.46	59.68
	63.48	77.82	-14.34		326.01	262.78	63.23
	228.59	233.77	-5.18		238.21	207.78	30.43
	248.19	396.18	-147.99		150.81	230.02	-79.21
Jun	72.82	163.66	-90.84	Dec	62.26	24.56	37.70
	257.84	245.76	12.08		204.10	139.37	64.73
	77.25	114.79	-37.54		122.94	76.72	46.22
	195.92	281.27	-85.35		199.94	165.73	34.21
	253.79	434.94	-181.15		132.37	79.93	52.44
	438.37	266.13	172.24		164.23	235.86	-71.63

Appendix F-1(d) Flow Data for Victoria Sub Catchment (1964-1969)

	Measured	Observed	Deviation		Measured	Observed	Deviation
Jan	196.60	176.36	20.24	Jul	67.90	70.16	-2.26
	47.67	33.80	13.87		15.10	1.61	13.49
	29.53	49.12	-19.59		9.78	3.18	6.60
	44.90	53.63	-8.73		34.48	31.11	3.37
	128.56	126.75	1.81		116.99	159.66	-42.67
	50.06	62.12	-12.06		89.02	3.64	85.38
Feb	195.75	150.91	44.84	Aug	77.14	47.62	29.52
	162.22	149.40	12.82		55.85	91.95	-36.10
	7.53	4.82	2.71		1.74	5.69	-3.95
	108.34	105.43	2.91		7.30	5.91	1.39
	20.80	4.33	16.47		42.29	43.85	-1.56
	18.69	12.42	6.27		95.03	27.83	67.20
Mar	94.16	26.47	67.69	Sep	82.98	72.71	10.27
	5.64	6.26	-0.62		7.44	3.57	3.87
	71.82	28.69	43.13		3.93	1.00	2.93
	39.56	35.07	4.49		13.50	19.07	-5.57
	21.14	28.11	-6.97		103.75	138.13	-34.38
	2.98	1.12	1.86		139.75	4.78	134.97
Apr	38.00	22.59	15.41	Oct	60.72	107.05	-46.33
	169.10	165.94	3.16		96.50	140.64	-44.14
	108.16	68.81	39.35		66.37	19.54	46.83
	27.91	67.77	-39.86		102.42	282.00	-179.58
	36.62	32.77	3.85		158.03	180.67	-22.64
	56.06	82.44	-26.38		333.59	274.20	59.39
May	64.62	80.43	-15.81	Nov	205.46	219.56	-14.10
	127.68	141.03	-13.35		238.39	265.37	-26.98
	7.64	1.76	5.88		157.71	96.26	61.45
	13.52	5.33	8.19		92.14	334.57	-242.43
	56.81	31.51	25.30		159.51	161.64	-2.13
	56.54	95.27	-38.73		293.49	247.50	45.99
Jun	10.76	7.76	3.00	Dec	195.87	115.90	79.97
	40.35	35.09	5.26		214.21	152.29	61.92
	4.56	5.64	-1.08		91.38	83.19	8.19
	37.75	42.41	-4.66		357.55	275.83	81.72
	28.44	51.83	-23.39		93.97	123.19	-29.22
	101.42	51.81	49.61		331.36	251.43	79.93

Appendix F-1(e) Flow Data for Randenigala Sub Catchment (1964-1969)

	Measured	Observed	Deviation		Measured	Observed	Deviation
Jan	385.07	358.92	26.15	Jul	57.40	23.54	33.86
	161.95	123.40	38.55		14.40	1.00	13.40
	267.51	206.75	60.76		19.79	2.68	17.11
	131.36	113.06	18.30		18.59	6.26	12.33
	128.96	122.19	6.77		95.37	43.84	51.53
	198.53	180.69	17.84		11.40	2.89	8.51
Feb	355.74	348.11	7.63	Aug	66.58	18.62	47.96
	325.59	392.72	-67.13		110.96	40.48	70.48
	34.13	21.27	12.86		12.60	2.24	10.36
	247.04	230.49	16.55		12.00	2.31	9.69
	40.40	41.56	-1.16		33.59	18.38	15.21
	91.56	70.56	21.00		13.20	6.08	7.12
Mar	38.39	69.72	-31.33	Sep	78.36	29.56	48.80
	65.98	17.84	48.14		28.44	3.92	24.52
	22.19	73.32	-51.13		53.98	1.00	52.98
	143.35	71.96	71.39		69.65	2.64	67.01
	70.18	98.65	-28.47		89.39	34.77	54.62
	20.99	1.89	19.10		12.19	2.83	9.36
Apr	15.67	31.10	-15.43	Oct	92.37	28.65	63.72
	246.11	176.40	69.71		62.98	87.58	-24.60
	30.76	119.67	-88.91		50.98	12.36	38.62
	107.96	83.59	24.37		93.57	117.08	-23.51
	28.44	31.72	-3.28		247.12	89.15	157.97
	163.11	132.34	30.77		109.16	148.94	-39.78
May	71.38	54.92	16.46	Nov	166.01	121.16	44.85
	232.72	181.26	51.46		318.67	239.53	79.14
	13.20	5.60	7.60		264.10	123.62	140.48
	10.20	4.99	5.21		507.31	494.87	12.44
	17.39	22.90	-5.51		159.04	130.06	28.98
	62.98	56.03	6.95		307.06	401.36	-94.30
Jun	14.51	1.59	12.92	Dec	195.53	230.21	-34.68
	19.15	7.42	11.73		345.48	284.44	61.04
	4.64	1.66	2.98		236.92	146.39	90.53
	51.66	8.58	43.08		126.56	241.78	-115.22
	17.99	24.47	-6.48		325.09	287.73	37.36
	35.99	17.26	18.73		347.28	445.72	-98.44