DOCTOR OF PHILOSOPHY

The effects of selective logging methods on hydrological parameters in Peninsular Malaysia.

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Award date:
1990

Awarding institution:
Bangor University

THE EFFECTS OF SELECTIVE LOGGING METHODS
ON HYDROLOGICAL PARAMETERS IN PENINSULAR MALAYSIA

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A thesis submitted in fulfillment for
the requirements for the degree of Philosophiae Doctor
in the University of Wales

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April 1990

ABSTRACT

An experimental forest watershed, consisting of three small catchments at Berembun, Negeri Sembilan, in Peninsular Malaysia has been monitored from 1979 to 1987. Adequate instruments were installed for continuous collection of hydrologic and climatic data. The calibration and post-treatment phases lasted for three and four years respectively. Two types of treatments were imposed -namely commercial selective logging and supervised selective logging in catchment 1 and catchment 3 whilst catchment 2 remained as a control.

Pertinent logging guidelines were prescribed and assessed in C3 in terms of hydrological responses. Significant water yield increases were observed after forest treatment in both catchments amounting to 165 mm (70%) and 87 mm (37%) respectively in the first year; increases persisted to the fourth year after treatment. Magnitude and rate of water yield increase primarily depended on the amount of forest removed and the prevailing rainfall regime and the increase was largely associated with baseflow augmentation.

Interestingly, both types of selective loggings produced no significant effect on peak discharge while the commercial logging resulted in a significant increase in stormflow volume and initial discharge. Such responses can be explained by the extensive nature of selective logging which normally left a substantial area of forest intact and minimal disturbance to flow channels. Thus, conservation measures introduced in this study - the use of buffer strips, cross drains, an appropriate percentage for the forest road network,- were found to be effective and beneficial in ameliorating the hydrological impacts.

ACKNOWLEDGEMENTS

IN THE NAME OF ALLAH, THE MOST GRACIOUS, THE MOST MERCIFUL

Apart from being time consuming and costly, this catchment study has involved many individuals and personnel since its inception whose help and assistance I would like to acknowledge.

I wish to extend my utmost thanks to my supervisor and personal colleague, Dr. Don Harding for his generous help, constructive comments and advice during the course of this study. His understanding and approachable manner has made the writing task a pleasant and rewarding undertaking. A special acknowledgement is conveyed to Associate Prof. Dr. Low Kwai Sim of University Malaya for her invaluable advice and comments on the outline of this thesis. I am most grateful to Prof. Larry Roche and Dr. John Hetherington for making available facilities needed while at the University of Wales. To Mr. Tom Jenkins, departmental statistician, I am thankful for his useful comments on statistical presentation of this study.

I wish to express special thanks to Forest Research Institute Malaysia for awarding a part-time scholarship and study leave towards the completion of this study and particularly to Director General, Dato' Dr. Salleh Mohd. Nor for his personal interest in my study progress. Sincere appreciation is extended to all research assistants, foresters, and staff of the Hydrology Section FRIM, who have skillfully and religiously serviced hydrological equipment at the study site even during odd hours of the day. To my colleagues hydrologists, Baharuddin, Zulkifli, Saifuddin and Azman, I am deeply indebted for their generous cooperation, invaluable help and at times stimulating discussions.

Close cooperation and support rendered by the Forestry Department of Peninsular Malaysia during implementation of this study is gratefully acknowledged. The efficient computer services provided by the Drainage and Irrigation Department in the processing of hydrographs are deeply appreciated.

I am cordially grateful to all colleagues in Bangor for their gracious company, particularly Jalaluddin and Aminuddin who have brightened up my sojourn at Bryn Haul and in Bangor.

I wish to express profound appreciation to my wife, Sharifah Norul Akmar of University Malaya, for her continuous encouragement and forbearance during my study leave here and to my three children, Luqman, Salwa and Asma for their affection and source of inspiration. I am deeply obliged to my mother and family. May Allah s.w.t. showers them with blessings.

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The protective role of tropical rainforests in maintaining environmental and climatic stability has received great attention worldwide in the wake of present environmental concerns. Furthermore, the dwindling resource of the tropical rainforests has heightened awareness of such environmental problems. While rainforests are considered to be crucial elements in the protection of watersheds from erosion, the preservation of water quality and in climatic regulation, the growing population in tropical areas is forcing continued exploitation of this very resource for agricultural expansion, the increased world timber trade and in domestic fuelwood demand (UNESCO, 1989). Deforestation in tropical countries has reached devastating proportions amounting to 11 million hectares per year particularly in the Amazon Basin (Lanly, 1990). It is expected that 40% of the remaining *closed* forest within this developing world will disappear by the year 2000.

The potential problems of watershed degradation and subsequent hydrological impacts have long been recognized in many tropical countries. The World Resource Institute (1985) has estimated that more than 160 million ha of upland watersheds in the three humid tropical zones have been seriously affected especially in Latin America. Rapid population growth and the search for food, fuel and fodder have been associated with the above intrusions and have led to watershed degradation. Further, the recent UNESCO International Colloquium on the Development of Hydrologic and Water Management

Strategies in the Humid Tropics has expressed its strong concern regarding the hydrological impacts of the rapid rate of natural resource exploitation in countries of this region (UNESCO, 1989):

> "...the humid tropics play a pivotal role in the maintenance of the global hydrological cycle which to a great extent determines the capacity of the world to continue to support the agriculture, industry and infrastructures required to enable all countries to meet the expectations of their people..."

The humid tropics as defined by Chang and Lau (1983) and adopted by the Colloquium, exhibit special characteristics unique from other climatic zones. Amongst factors of relevance are intense and highly variable rainfall in space and time, climatic, vegetation and soil conditions which are markedly different from temperate zones, and unplanned land use conversions, often following major deforestation from logging operations, which have led to many serious problems of erosion and sedimentation and to the destruction of the natural ecosystem. Thus, there is an urgent need to bridge the information gap in the understanding of pertinent issues relating to the sustainability of hydrological systems in this region.

Malaysia is one of the countries located in the above region extending between latitudes 0° 40′ and 7° 49′ and longitudes 98° 40′ and 119° 35′ East with a total land area of 33 million ha. It consists of Peninsular Malaysia (13.2 m ha) having a frontier with Thailand in the north and East Malaysia consisting of Sabah (7.4 m ha) and Sarawak (12.4 m ha), which lie to the north of Kalimantan, Indonesia. Malaysia is a developing country with a population of 16.5 millions distributed in Peninsular Malaysia (13.7 m), Sabah (1.3

m) and Sarawak (1.5 m) with an estimated growth rate of 2.5 % per year (Ministry of Primary Industries, 1988). Malaysia has been fortunate to be endowed with vast natural resources notably tropical rainforests which not only provide timber for domestic use and for export purposes but also provide vital environmental functions. Nevertheless, being a developing country, a rapid rate of natural resource exploitation is often necessary for socio-economic development in addition to providing income. In the process, a large area of lowland forests has been systematically transformed to other land uses namely agriculture, urbanization, reservoir construction and other rural development activities. Over the past two decades, more than 1.5 million ha of lowland forests have been converted for this purpose primarily to rubber, oil palm, coconut and cocoa which together occupy 3.9 million ha. Despite this economic necessity, this policy at the same time hastens the process of forest resource depletion.

The tropical rainforest of Malaysia is one of the most complex and species-rich ecosystems in the world (Ashton, 1969; Whitmore, 1975). In Peninsular Malaysia alone, about 2900 tree species reach a girth of 30 cm or a dbh of about 10 cm of which 677 species reach 'timber size' of at least 40 cm dbh (Kochumen, 1973). The total forest area of Malaysia is 20.1 million ha or 61.1 % of the total land area. Of the total forested land, 17.4 million ha are dipterocarp forests while the remaining 2.1 million ha and 0.6 million ha are freshwater swamp and mangrove forests respectively. The dipterocarp forests which represent 86.6% of the total forested land are characterised by the predominance of the plant family of Dipterocarpaceae and form the main source of Malaysia's commercial hardwoods. Subsequently, the forestry sector has contributed significantly towards the overall economic development of the country. Currently, the forestry sector contributes about 13.2% of export earnings while providing about 3.0% of the total employment in the country (Ministry of Primary Industries, 1988).

The forest resources in Peninsular Malaysia have been adequately managed since the beginning of this century and are still managed today under the ambit of the National Forestry Policy adopted in 1978 and the National Forestry Act of 1984. The policy was formulated to ensure a fuller utilization of resources on a sustained yield basis whilst ensuring environmental stability. To this end, the policy calls for classification of forest areas into productive forests, protective or amenity forests and national parks and wildlife reserves.

Traditionally, the forest resources of Peninsular Malaysia have been managed under the Malayan Uniform System or MUS which involved removing the mature crop in one single felling of all species in lowland forests (Wyatt-Smith, 1963). As logging activities increasingly encroached into hill forests, a new system was introduced in the late 1970s called the Selective Management System or SMS as the earlier system had been found to be unsuitable in the hill dipterocarp forests (Thang, 1986). The SMS endeavours, among other things, to optimise the goal of efficient timber utilization, conservation of the genetic and other non-wood natural resources, and maintenance of environmental stability and quality, particularly in sensitive watersheds (Mok, 1989). An important pre-requisite of this system is the use of inventory data instead of an arbitrary prescription in the formulation of selection or felling regimes. In this context, sustainable forest management requires technical and managerial expertise and skills which tend to be inadequate in the forestry service of Malaysia. It also requires up-to-date information and appropriate strategies, normally derived from forestry related research projects, to optimise resource utilization.

As water is one of the most important watershed resources, the demand for adequate quantities of water of an acceptable quality at the right place and time is increasingly becoming a major problem in Malaysia. The National Water Resources Study has identified the main water user sectors as irrigated agriculture, domestic and industrial water supply and hydro-power (Economic Planning Unit Malaysia, 1982). About 53% of the rice production in the country is served with some irrigation facilities that invariably permit a double cropping programme. With the expansion of irrigated areas, the water demand for irrigation will increase from 9.0 billion m^3 in 1980 to 10.4 billion m^3 in 2000 (Sieh, 1984).

The domestic and industrial water demands are expected to increase from 1.3 billion m^3 in 1980 to 2.6 billion m^3 in 1990 and 4.8 billion m^3 in the year 2000. At the present level of utilization, 71% of the total population is served with public water supply with a service factor for the urban areas of 93% with that for the rural areas being 57%. The annual demand growth rate is estimated at 12% (Sieh, 1984). Hence, the aggregate total water demand is estimated to be 11.6 billion m^3 in 1990 and 15.2 billion m^3 in 2000 - an almost two fold increase from 1980 (Lim, 1989). Nevertheless, the projected demand of the year 2000 represents only 3% of the estimated annual surface runoff. Despite the copious amounts of water available as compared with demand, significant water shortages have already occurred in some areas. This is mainly due to variability of rainfall from region-to- region and year-to-year which ultimately leads to uneven distribution of water resources. In some areas of growing demand, the lowflows that occur during the dry season are insufficient to meet all demands. Conversely, during the wet season, for example the north east monsoon, flooding frequently occurs and large quantities of water flow to the sea unutilized.

In addition to the above problems, the water quality of some rivers has progressively deteriorated (Environment Department Malaysia, 1985) Developmental activities in upstream or headwater regions have often rendered water unfit for use mainly due to chemical pollution. The main sources of this pollution are domestic and industrial sewage, effluent discharge from palm-oil mills and rubber factories, and effluent from tin mines. On the other hand, land conversion to agriculture, forest logging activities, housing and urban development and mining operations are major causes of high concentrations of suspended sediment in the same rivers. Recognizing the importance of water resources in terms of their quality and quantity, the Department of Environment (DOE) of Malaysia has recently formulated the Water Quality Criteria and Standards to be enforced under the aegis of the Environmental Quality Act 1974.

Sound watershed management implies a rational utilization of all watershed resources such as forest, soil, water, fisheries and wildlife for optimum and sustained production by society (FAO, 1983). It includes development as well as conservation of all the above resources against all forms of deterioration. Although the concept of watershed management in the context of development in Malaysia is relatively new, it is beginning to gain support from policy makers and planners as reflected in the National Forest Policy and National Forestry Act, 1984. However, in Malaysia, effective management of watershed resources has been plagued by a number of limitations largely depending on socio-economic factors, and to a certain extent, the inherent physical factors of the country. Subsequently, this leads to conflicting uses of these watersheds. Because the Malaysian economy is agriculture-based, the development of forest lands for agricultural crops and agriculture-based industries has been an important socio-economic strategy. Thus problems facing watershed managers include the large scale conversion of forest land, commercial forest logging, mining activities, shifting cultivation, urbanization and highway construction (Abdul Rahim, 1985).

Under undisturbed conditions, forest cover maintains an acceptably low erosion rate and consequently high quality of water as forests provide the most natural protection for streams. Accordingly, forest catchments become the main source of Man's supply of fresh water. In Malaysia, approximately 97% of water supplies for domestic and agricultural uses come from surface water (Talha, 1986). As most of these catchments are situated in hilly areas of more difficult terrain, the present mechanical logging operations are approaching into these sensitive areas. Furthermore, the traditional limit of 20° or 36% slope for agricultural land use has been exceeded in some agricultural development schemes (Salleh, 1987).

Associated with forest harvesting are activities such as canopy opening, road construction, skidding and extraction of logs which have a great potential for accelerating soil erosion and sediment transport, ultimately leading to deterioration of water quality downstream. Evidence from other places, though mostly from temperate areas, has shown that substantial changes in hydrological responses ensue proportional to the magnitude of forest disturbances. Nevertheless, there is a dearth of information on the hydrologic characteristics of tropical forest ecosystems, particularly on the effect of logging activities on water attributes and sediment. In recent summaries on the state-of-knowledge of the hydrological functioning of more or less disturbed tropical ecosystems, Hamilton and King (1983), reported that there is surprisingly little 'hard' data available on which rational watershed management is to be based. Information on hydrological responses of forested watersheds to the alterations imposed upon them, is crucial in watershed management and can only be obtained by conducting rigorous research in forested watersheds.

Realising the importance of watershed research, several agencies in Malaysia have initiated a network of representative and experimental watersheds since 1973. Amongst agencies actively involved in such endeavour are the Drainage and Irrigation Department (DID), Federal Land Development Authority (FELDA), Department of Agriculture (DOA), Department of Forestry (DOF), Department of Environment (DOE), Forest Research Institute Malaysia (FRIM), University of Malaya, Agriculture University of Malaysia (UPM) and the Sabah Foundation which altogether manage eight experimental watershed research projects throughout Peninsular Malaysia (Abdul Rahim, 1987b; Douglas et al., 1990). The Sg. Tekam Experimental Basin (STEB) headed by DID is an example of a multi-disciplinary research approach in which most of the above agencies participate and which has culminated in several research reports on the effects of forest conversion to agriculture land use (DID, 1982; 1986; 1989). FRIM, with the cooperation of the Forestry Department has initiated and maintained three experimental catchment research projects since 1979 namely the Berembun Watershed in Negeri Sembilan, Jengka Watershed in Pahang and Bt. Tarik in Selangor; each site is underlain with a different geological formation. The two former watersheds were located initially in undisturbed forests whilst the latter is covered by a logged-over forest. All watersheds are adequately equipped with necessary instruments for continuous monitoring of hydrological and climatic parameters. Essentially, studies initiated in these watersheds represent FRIM's integrated hydrological research programme involving research activities in the field of descriptive hydrology and climate, sedimentation and water quality. Information generated from well-designed catchment research will be useful in the formulation of appropriate strategies and guidelines for sound management of watershed resources. Up to now, broad-based proposals and guidelines to reduce negative effects of logging have been compiled by Pearce and Hamilton (1986) while similar preliminary guidelines have been proposed by the Forestry Department Peninsular Malaysia (1988). Hopefully, results derived from the present study located at Berembun Watershed coupled with other related studies of FRIM, can provide pertinent information in improving these broad-based guidelines and thus eventually may lead to a formulation of sound watershed management strategies that aim at reducing watershed deterioration (Abdul Rahim and Harding, 1990).

In order to fulfill the above applied needs, some basic information on hydrological processes operating under the forested environment of the humid tropics must be obtained. Further, catchment responses upon forest harvesting, particularly in terms of hydrological changes and trends, ought to be quantified and statistically assessed for making inferences concerning the effects. When relevant, comparisons with similar studies conducted either locally or at other locations in the tropics will be made to stress amongst other things the influence of inherent physical factors and climatic variations.

1.2 Specific Objectives of the Study:

The specific objectives of the present study are as follows:

1. to characterize various hydrological input and output components based on a paired-catchment approach,
2. to quantify the hydrological effects of two selective logging methods on selected parameters and to predict water yield changes resulting from the above activity,
3. to determine the stormflow response resulting from selective logging methods, and
4. to test the effectiveness of preliminary logging guidelines as introduced by the Forest Department on hydrological parameters.

CHAPTER 2

LITERATURE REVIEW

2.1 Development of Watershed Research

Paired watershed research has been widely adopted in many places as an acceptable approach to conducting hydrological research, particularly to determine the effect of land use changes. This is so because, theoretically, a catchment or drainage basin can be envisaged as the most fundamental spatial unit in which biotic, geomorphic and hydrologic processes operate and interact and tend to evolve an energy balance or quasi equilibrium state (Douglas, 1969; Ward, 1971). In a properly delineated watershed, a balance can be struck between inflow and outflow of water and energy through various structural elements in the ecosystem. Even biologists and ecologists have turned to using the drainage basin as an ideal unit in which to develop an ecosystem approach to their studies (Ffolliott, 1981). In a broad sense, a watershed can also be considered as a unit for development purposes because, within it, biophysical, natural, and social processes are interlinked in a logical and quantifiable pattern (Hamilton and King 1983; University of Minnesota, 1988).

The paired watershed or control watershed method requires two or more catchments located adjacent to each other having similar physical characteristics such as soil, geology, vegetation, slope and catchment characteristics (Ward, 1971; Reinhart, 1965). On such a watershed system, there is a deliberate attempt to modify and manipulate one or more of the physical attributes. Subsequently, the effect of such modification and treatment will be evaluated and quantified in comparison with a control catchment (Reigner, 1964; Toebes and Ouryvaey, 1970).

2.1.1 Research in temperate countries

The first documented watershed research experiment was initiated at the Emmental Valley of Switzerland on two catchments, one fully forested and one lightly forested (Engler, 1919). Amongst the objectives of this study was to compare the streamflow regimes of the two catchments with different cover intensity. Although a pair of basins were instrumented, and have been operated ever since, there was no 'control' basin nor 'calibration' period because the land was partly in private ownership (Hewlett, 1970). Another historical catchment study was conducted at Wagon Wheel Gap, Colorado, USA by the Weather Bureau of the United States (Bates and Henry, 1928). In this experiment, started in 1909, two similar watersheds were calibrated for eight years and followed by a treatment on one of them. Streamflow measurement continued for another seven years after treatment.

Since then, many other research studies have been conducted worldwide, particularly those undertaken in the United States by the Forest Service to evaluate the effect of forest and grazing practices on hydrological parameters (Hewlett and Hibbert, 1961) and also by the Tennessee Valley Authority (TVA) to study the effect of changes in vegetational cover on runoff (TVA, 1961). The well-known research at the Coweeta Hydrologic Laboratory started in 1933 and has provided much information on catchment hydrology. The unique set-up at Coweeta afforded scientists comprehensive and long-term research on the effect of forest cover on hydrology (Dils, 1957; Douglas, 1983; Hewlett and Hibbert, 1961). Other reputed experimental catchments were at the Fernow Experimental Basin, West Virginia (Reinhart, et at., 1963). Fraser Experimental Forest, Colorado (Goodell, 1958), Hubbard Brook (USDA For. Ser., 1964) and H.L. Andrews (Rothacher, et al., 1967). Anderson et al., (1976) condensed and summarized the results of more than 100 years of collective experience in watershed research in the US, particularly the effect of forestry practices on water resources.

Considerable research effort has taken place in Britain but not until after Frank Law's (1956) controversial study on the role of forested catchments. Before this time, however, a few isolated yet important studies had been conducted such as those of McLean (1927, 1935) and Penman (1950-1955). The establishment of the Institute of Hydrology in 1961, saw the start of rigorous studies in catchment research of which the Plynlimon studies deserved a special mention (Howe, et al., 1967; Newson, 1978, 1979; Harding, 1977). Between 1975-80, 73 watershed research projects were underway in the U. K. with an initial emphasis on changes in land use in upland catchments and further these were extended to understand the role of physical and chemical processes in hydrology (Douglas, 1987; Institute of Hydrology, 1988).

An upsurge of interest in catchment research developed in other countries as well including Australia (Boughton, 1970; Costin and Slatyer, 1967), New Zealand (Morris, 1967), Japan (Nakano, 1971; Ogihara, 1967), Sweden (Troedsson, 1967) and in Africa (Pereira, 1967; Wicht, 1967). In Australia, a large network of research catchments has been established by various working groups, each with slightly varied objectives (Cassells, 1987). In 1974, there were more than 100 catchments being monitored throughout Australia with the aim of detecting hydrological responses to land modification (Dunin, 1974). Findings of most of these studies were documented in the proceedings of the First National Symposium on Forest Hydrology which elicited much useful information on the state-of-the-art of forest influence research in Australia so far (O'Loughlin, 1982).

Similar trends developed in New Zealand where catchment research began as early as 1950 (O'Loughlin, 1984; 87). Since then, more than 100 small catchments have been maintained using three main study techniques - experimental catchment, observation and the before-and-after approach. Evidently, the most successful and useful studies utilised the experimental approach while information from the other two techniques did not generally stand up to close scientific scrutiny.

2.1.2 Research in humid tropical countries

As catchment research is generally long-term, expensive and requires a high degree of technical competence, most research evidence to date comes from the temperate countries, mainly due to their early start as well as the availability of qualified researchers (Hamilton and King, 1983). However, the situation has changed in the last two decades in which many countries in the tropics have embarked on this type of research. Coincidentally, the last two decades have seen a rapid increase in natural resource exploitation, especially forest vis-a-vis population growth in the tropics (World Resources Institute, 1985; FAO, 1986). Among the early research efforts in the tropics were those in East and Central Africa (Pereira et al., 1962; Edwards and Blackie, 1981), Taiwan (Sheng and Koh, 1967) and Queensland, Australia (Gilmour, 1977). Quite recently, similar studies are being undertaken in tropical

South America such as in French Guyana (Roche, 1981; Fritch, 1983 as quoted by Bruijnzeel, 1989c). Within the last decade or so, a number of paired catchment studies have been established in Tropical Asia albeit with varied objectives. Research has begun in Malaysia (Rahmid and Blake, 1979; DID, 1982), Indonesia (Bruijnzeel, 1983, 1986), the Philippines (Baconguis, 1989) and Thailand (Kasertsat University, 1986). In Malaysia, hydrological activities can be traced back to the late 19th Century when the first rainfall station was set up by the Drainage and Irrigation Department (Teh, 1982). The rainfall data at that time were mainly used for agricultural purposes. A diverse range of studies on agricultural development and forest influences in relation to hydrology has appeared in the last four decades. Essentially, these studies were initiated either by the foresters' insight on the forest influences on watersheds (Berry, 1956; Anderson, 1958), or studies on the effect of agricultural practices (Allen and Haynes, 1953) or special studies on reservoir and dam construction in a particular river basin (Shallow, 1956). Nevertheless, most of these studies did not attempt to use watershed areas as an integral unit of the ecosystem designed to document the input and output processes (Abdul Rahim, 1987b).

Detailed hydrological and geomorphological research which examined the processes involved and quantified each of the processes only appeared in the early 70s or mid 70s. The catchment area has been deliberately used as the quantifying unit in some of these studies and has proved to be useful in formulating water resources projects. Among the themes studied include the erosion and runoff rates from river basins of different vegetation types, (Douglas, 1967; 1968), the deterioration of water quality resulting from forest logging and land clearance (Burgess, 1971; Ho, 1973), and rigorous studies on rainfall-runoff relationships of forested and partially altered catchments (Low, 1971; Goh, 1972; Low and Goh, 1972). The first paired catchment study ever initiated in Malaysia was at Sg. Tekam Experimental Basin, Pahang in 1973 by the Drainage and Irrigation Department (DID) and Federal Land and Development Authority (FELDA) (DID, 1982). Subsequently, the Forest Research Institute Malaysia (FRIM) and Forest Department of Peninsular Malaysia established another two sets of catchment studies (Rahmid and Blake, 1979). By 1986, a total of eight catchment studies had being established with areas ranging from 4-500 ha (Abdul Rahim, 1987b).

2.2 Forest Logging and Water Yield Changes

The specific influence of forests on rainfall, water yield and floods was the subject of intermittent controversy between foresters and others until Kittredge (1948) documented and redressed the issues into a standard text. Other earlier works on forest influences included Brown (1877) and Zon (1927); the latter summarized the relevant scientific literature covering a period of more than 150 years. Interest in forest influences and hydrology increased dramatically in the 19th century particularly in terms of effects on water yield. Subsequently, small catchment studies were initiated in Switzerland and in the United States in trying to quantify forest influences (Burger, 1943; Bates and Henry, 1928). The most comprehensive document assembled to date on the subject of forest hydrology, albeit a little outdated now, is the proceedings of a symposium held at Pennsylvania State University, USA in 1965 (Sopper and Lull, 1967). Subsequently, several other important proceedings were published, partly designed to update information with new findings and approaches in hydrological research including the Proceeding of the FAO/USSR Symposium on Forest Influence and Watershed Management (Rakhmanov, 1970), the Canadian Hydrology Symposium (National Resource Council, 1982), the National Symposium on Forest Hydrology in Australia (O'Loughlin and Bren, 1982) and the Hamburg Hydrology Symposium (Keller, 1983).

A common perception about the role of forests is that the complex of forest soils, roots and litter acts as a sponge soaking up water during wet periods and releasing it during dry periods. However, most of this water is utilised again by the forest to satisfy its physiological needs rather than being used to sustain streamflow (Bruijnzeel, 1986). Furthermore, appreciable quantities of rainfall are intercepted by forest canopies (Helvey and Patric, 1965; Zinke, 1967) and evaporated back into the atmosphere (Stewart, 1977; Calder, 1979; Calder and Newson, 1979; Gash, 1979; Pearce, et al., 1980).

2.2.1 Water yield changes in temperate areas

The question of water yield changes upon forest removal has been extensively studied in many parts of the world, particularly in temperate areas and to a small extent in the tropics. Bosch and Hewlett (1982) reviewed results of almost a hundred paired-catchment experiments throughout the world, updating the earlier compilation of 47 studies by Hibbert (1967). The main thrust of those studies was to determine the effects of vegetation and natural cover removal or modification on water yield.

Swank and Douglas (1974) documented that the highest annual change in water yield resulting from cover manipulation amounted to

662 mm/yr, based on experimental catchment 17 at Coweeta, North Carolina, USA. The change in water yield occurred after the site (14 ha) was totally planted with pines; the site had been clearcut 15 years earlier and was previously covered by mixed hardwoods. On the other hand, the actual effect of forest cover removal was observed in Maimai, New Zealand where an increase in yield of some 650 mm was documented in the first year after treatment (Pearce et al., 1980). In this study complete removal of mixed beech forest was followed by burning. A similar pattern of water yield increase was observed in other studies as well, such as at Fernow Experimental Watershed, West Virginia (Reinhart, et al., 1963), at H.L. Andrews (Rothacher, 1970; Harr, 1976) and at Hubbard Brook, New Hampshire (Hornbeck, et al., 1970). While almost all catchment studies reported increases in water yield after removal of forest cover, some studies showed non-significant change or non-detectable change following similar kinds of treatment (Harr, 1976; Harr 1980; Johnson and Kovner, 1956). The only study that partly contradicts the general trend of water increment was reported by Langford (1976). Langford concluded that there was no significant increase in water yield immediately after a stand of Eucalyptus was burnt down and, in fact, a reduction in streamflow for 3 to 5 years after the burn was observed. It can however be concluded that almost every well-designed experiment has shown increases in water yield as a response to forest cutting and in general the increase is proportional to the amount of canopy removal. Bosch and Hewlett (1982) even suggested some predictive generalisations as follows:

(i) Coniferous and eucalypt cover types have approximately a 40 mm increase in water yield per 10 % reduction in cover.

(ii) Deciduous hardwoods have approximately a 25mm increase in yield per 10% reduction in cover.

Most of the present information regarding water yield changes resulting from forest logging is based on experiments usually conducted on relatively small watersheds of less than 250 ha in size (Harding, 1986). This is so because, as pointed out by Hewlett (1971) it was almost impractical to instrument and continuously monitor watersheds larger than 1000 ha. Nevertheless, there are a few published studies of effects of forest harvesting on discharge of streams draining larger watersheds (> 1000 ha) (Patric, 1974; Helvey and Tiedeman, 1978; Cheng, 1989). Even some of these studies, however, essentially dealt with streamflow changes resulting from deforestation caused by fire or insect attack rather than actual clear cutting (Riekerk, 1989).

2.2.2 Water yield changes in the humid tropics

There has been an upsurge of interest in the effects of tropical forests on catchment hydrology, especially on water yield. This is partly because of the alarming rate of tropical forest exploitation and conversion to other land uses in the last two decades (FAO, 1986). Estimates of the areal extent of forest land in the humid tropics and the rate at which these forests are disappearing vary considerably between workers (Myers, 1980; Sommer, 1976; Lanly, 1982). Whatever rates are quoted, the exploitation and disappearance of tropical rain forests may cause a major problem not only to the environment at large but also specifically to its hydrological functions.

Obviously tropical forests are different from temperate forests. However, are they so different in their hydrological characteristics and responses (Hamilton and King, 1983)? Although most scientific evidence indicates that differences are more in degree than in kind, more convincing data are needed to confirm this.

Relatively limited information is available to date quantifying the effects of forest cover removal and/or forest logging on water attributes in the humid tropics. Although a number of tropical paired-catchment studies have been initiated during the last decade, for example, in French Guyana (Roche, 1981), Indonesia (Bruijnzeel, 1986), and Malaysia (Abdul Rahim, 1987b), most of these experiments are still in progress. However, based on the available data, Hamilton and King (1983), Bruijnzeel (1986) and Oyebande (1988) have compiled and summarized some of the results of studies initiated so far. In these surveys, the authors were dismayed at the paucity of reliable data.

Studies in tropical countries on conversion and removal of forest cover to other land uses in Australia (Gilmour, 1977), Tanzania (Edwards, 1979), Kenya (Blackie, 1972) French Guyana (Fritsch, 1983) and Taiwan (Hsia and Koh, 1983) characteristically revealed increases in water yield. In Tanzania, East Africa, the Mbeya catchment study commenced in 1958 produce an average increase of 220 mm per year after the conversion of evergreen montane forest to an agricultural land use. Most of the increase occurred during the dry-season while overland flow contributed very little due to a remarkably high infiltration capacity of its volcanic soil. Clear cutting of mixed evergreen hill forest in Taiwan with extraction prohibited saw a greater increase of 448 mm/yr. In this study, the surface disturbance was kept to a minimum as skyline logging was employed; roads were constructed around the basin periphery, away from the stream (Hsia and Koh, 1983).

Logging of lowland rain forest in Babinda, Queensland, an area of high mean annual rainfall (circa. 4035 mm) produced little detectable change, but a clearing operation produced a 7.0% and 13.4 % or 264 and 323 mm increase in yield in the first and second year following clearing (Gilmour, 1977). It was also observed that soil moisture levels remained higher because of reduced transpirational demand; soil moisture deficits were therefore critically reduced. Clearcutting of a primary lowland rain forest in French Guyana, under a rather high prevailing rainfall, produced a first year increase of 408 mm or about 26% (Fritsch, 1983). However, the size of the catchment used, about 1 ha, was quite small for a detailed evaluation of water yield changes in a paired watershed study.

The highest increase in yield ever reported resulting from rain forest clearance was observed at Sg. Tekam, Malaysia (DID, 1986; Abdul Rahim, 1988). After the dipterocarp forest was completely cleared and converted to oil palm plantations, the water yield increase was 822 mm/yr but the average annual increase over a four year period only amounted to 314 mm. In this regard, it is worth noting that the area received on average some 1730 mm of rain per year, about 200 mm below the country average. In fact, this area is located in a relatively low rainfall region according to the classification of hydrological regions in Malaysia (Law and Ahmad, 1989).

It has been well documented that following clearance of forest cover and conversion to other types of land use, there is an initial increase in total streamflow both in temperate areas (Bosch and Hewlett, 1982; Hewlett, 1982) and in the tropics (Bruijnzeel, 1986; Abdul Rahim, 1988; 1989). This increase may be permanent when converting tall forest to grassland or shallow rooted agricultural crops or temporary in the case of conversion to tree plantations.

2.3 Forest Logging and Stormflow Response

As indicated earlier, there has been a protracted debate regarding the role of forests within catchments and what exactly happens when forests are cleared from the land (Hewlett and Helvey, 1970; Pereira, 1973; Lee, 1980; Ward, 1984; Bonell, 1989). Among controversial questions are, for example, whether the perceived increase in flooding that follows forest clearing is due to the removal of tree cover itself or due to abusive land use. Further, are both upstream and downstream flooding affected, does the peak discharge increase and does it also increase the total volume of floodwater released?

Controversy has occurred mainly because there have been few research results available to relate different types of clearing to different aspects of the flood problem. Lull and Reinhart (1972) offered a set of conclusions based on existing knowledge in the Eastern United States that the extent and frequency of forest cutting offered no flood hazard. A decade later, Hewlett (1982) examined the evidence worldwide from forest watershed research and reported that there was no cause-effect relationship between forest cutting in headwaters and floods in the lower basin. However, often a substantial part of stormflow and/or peakflow effects on small basins is due to improper logging methods (Hamilton and Pearce, 1985), all of which speed water off-site. Major floods occur because too much rain falls in too short a time, or covers too long a time. In either case, rainfall exceeds the capacity of the soil mantle to store water or the stream to convey it (Hamilton, 1988).

2.3.1 Stormflow volume and peakflow rate responses

Over the last decade or so, numerous well-designed catchment experiments have been conducted in which quantitative effects of deforestation or forest logging on both stormflow and peakflow were assessed. Hewlett and Helvey (1970), working on a 42-ha catchment of deep-soil and heavy annual rainfall reported a possible 6% increase in mean flows and an approximately 11% increase in stormflow, where a complete clear-felling of all trees and shrubs was permitted. In this case, season did not seem to be an important factor in determining the increase. On the other hand, Hornbeck (1973) using an equally-controlled catchment experiment on a shallow soil reported a 30% increase in stormflow across the year, with a larger absolute increase in summer than winter. No harvesting or roading was allowed but vegetation was leveled with chemicals. Reinhart (1964) also observed that a greater increase occurred in the growing season (c.24%) as compared with only 2.5% during the dormant period. Harr, et al.(1975) while drawing partly on the work of Rothacher (1973) and Harris (1977) in Oregon, reported about a 10% increase in quickflow or stormflow volume resulting from forestry activities, such as skidding, high lead logging and some burning.

Increases in stormflow volume were also observed following silvicultural treatments preceded by clear-cutting operations or different harvesting systems. Response was greater when soil was dry as compared with wet conditions (Hewlett and Doss, 1984). In addition, a greater response was observed during small storm events as compared with larger ones (Pearce, et al., 1980). On the other hand, Miller et al., (1988) reported that overall stormflow did not respond positively to either clear-cutting or selection cutting and he suspected that some degree of leakage might have taken place. Swindel et al. (1983) attributed the increase in stormflow volume upon clearcutting, regardless of logging techniques used, to the following factors:

a. decreasing evapotranspiration removal of water stored in the soil

b. interrupting the infiltration process

c. mechanically increasing the extent of source area of runoff

However, in silvicultural practice, (a) and (b) tend to be transitory and their effect on stormflow diminishes upon revegetation and stabilization of the soil surface.

The other major concern of the effects of forest activities on the stormflow hydrograph is peakflow discharge. In this instance, peakflows are largely a channel process and thus have their main source in the surface channel and its storm period extension (Hewlett and Doss, 1984). It is a sensitive parameter that is likely to be increased by practice that increases the source area of runoff. Most workers recorded increases in peakflow rates following clear-cutting and silvicultural practices (Harr, et al., 1975; Pierce et al.,1970; Rothacher, 1973; Golding, 1987). Peakflow may have increased up to 100% when soils were wet; however, results were often variable. Based on a quite large watershed, c. 424 ha in northern California, Ziemer (1981) observed an average increase of peakflows of 5% after tractor logging in the Fall. However, Hewlett (1982) questioned his technique of calculating the volume dimension of peakflow. A rather contrasting result was observed in British Columbia, Canada in which an average 22% reduction in peakflow following clearcutting as well as several hours delay in time-to-peak was observed (Cheng, et al.,1975). They attributed the above ramifications to the degree of ground disturbance and different stormflow generation mechanisms. Contrary results were also observed by Harr et al., (1979) in Oregon and Miller et al.,(1988). However, in the latter study, as in the case of stormflow volume, some degree of leakage was suspected.

2.3.2 Effect of afforestation activities on stormflow response

In addition to studies on the effect of forest cutting activities, some studies have also documented the effect of afforestation practices on the stormflow responses, particularly in the United Kingdom. In this context, Bosch and Hewlett (1982) and Trimble and Weirich (1987) assumed that changes of forest cover affect hydrological parameters identically in both directions: reductions of forest cover increase water yield and vice versa. In the United Kingdom, one such study has been conducted by the Institute of Hydrology (IOH) at the Coal Burn catchment, Cumbria. Based on the provisional results of the above study, Newson (1979) reported that prior to afforestation, peak flows were increased by drainage ditching whilst time to peak decreased by half. Similarly, Robinson (1980) reported that ditching of the entire area of a small upland basin, as part of normal practice prior to afforestation, produced an increase in unit hydrograph peak flow of 40% and halved the time-to-peak. Some years after planting, the basin showed a decrease in peakflows compared with that in the year following drainage. He attributed this to the establishment of young trees and to the degradation of ditches. In another recent study in the Southern Uplands of Scotland, Acreman (1985) observed that ploughing and planting of the lower part of the basin resulted in lower flood peaks. However, similar practice in the upstream section of the basin was followed by an increase in peak flow of 37% and a decrease in time-to-peak; he suggested that the reason for the above opposing results could be that certain sections of the basin may be more important in terms of their contribution to quickflow components of the hydrograph. The effect of agricultural activities on the stormflow response has also being documented as a case study (Newson and Robinson, 1983).

2.3.3 Stormflow response in the tropics

Stormflow volume and peakflow changes as documented in many studies in temperate countries mainly occurred during the growing season with minimal changes during the dormant season. The question is whether similar mechanisms operate in the humid tropics which obviously does not have distinct seasons as such.

Up to now, very limited work has been conducted in the tropics to quantify the effects of forest activities on stormflow response except for the pioneer work of Gilmour (1977) in Australia, Hsia (1987) in Taiwan and research in the Sg. Tekam Experimental Basin in Malaysia (DID, 1986). Nevertheless, there has been no study as yet to document the effect of the selective forest logging method on stormflow response despite the fact that this forms the most common method of harvesting in South-east Asia. Results from the Babinda catchment in the tropical north-east of Australia showed that peak discharges increased slightly following logging and clearing, although the statistical evidence for this is rather weak. Gilmour (1977) concluded that in the context of his study:

> "...logging caused virtually no detectable changes in streamflow regime, a fact he ascribed to the rather extensive character of the type of logging practice which leaves a fair amount of canopy intact...".

The Taiwan study indicated that neither the stormflow volume nor response factor (ratio of stormflow volume to the gross precipitation) had been affected after clearcutting, although peakflow discharge increased by 48%. Similarly, the Sg. Tekam study showed no significant change in stormflow volume following clearcutting. However, peak specific discharge somewhat increased whilst time-to-peak decreased considerably. Fritsch (1983) as quoted by Bruijnzeel (1989) reached similar conclusions through a paired catchment study involving mechanical clearing of rain forest in French Guyana.

Drawing observations from studies in the United States and in particular those in the Piedmont Region, USA, Hewlett et al., (1984) concluded that peakflows were consistently increased following forest clearcutting and silviculture practices, whilst stormflow volume was quite variable, in amounts that may have local effects, but rarely, if ever, a significant effect on downstream flooding. They further suggested that:

> "...there is a need for regional verification of the above conclusion as hydrologic response too often varies spatially and temporally...".

2.3.4 Low flow response in the tropics

It is obvious from the earlier review on catchment studies in the tropics that total water yield increases substantially following forest clearance and conversion to other types of land use (Hamilton and King, 1983; Bruijnzeel, 1986; Oyebande, 1987). However, the evidence with respect to the effect of forest clearing on dry-season flow rate (baseflow) in the tropics seems contradictory (Bruijnzeel, 1989c). On the one hand, reports of greatly diminished flows abound (Daniel and Kulasingam, 1974; Hardjono, 1980), but significant increases have been observed as well (Gilmour, 1977; DID, 1986 and 1989; Abdul Rahim, 1988). Even the results from the Mbeya catchment in Tanzania, underlain by volcanic soils of a highly permeable nature, seem to support the latter observation (Edwards, 1979). In fact, contrasting results are not contradictory when one takes into account the prevailing climatic, pedological and hydrological setting of the area as well as the way in which conversions and subsequent land use changes were carried out (Bruijnzeel, 1989c; Bonell, 1989). They suggested that the apparently conflicting evidence can be resolved by taking into account:

> "...the net effect of changes in infiltration opportunities and evapotranspiration associated with the respective land use type: if infiltration opportunities after conversion decrease to the extent that the increase in volumes of stormflow exceed the increase in baseflow associated with reduced evapotranspiration, then dry season flow will decrease and vice versa..."
> (Bruijnzeel, 1989c).

In spite of the above observation, quantitative data sets pertaining to low flow responses in the tropics are still limited, thus emphasizing the need for further rigorous research to be carried out.

2.3.5 Stormflow Response Modelling

The basic hydrological concept states that both peak and storm flow volume discharge will increase in proportion to increased rainfall intensity (Chow, 1964; Ward, 1967). If this hypothesis is correct, then the volume of storm water discharge by source (headwater) area should vary directly with hour-to-hour changes in rain intensity (Hewlett and Bosch, 1984). Nevertheless, this hydrological concept had not been rigorously investigated, particularly in a small forested catchment, mainly due to scarcity of needed data, until

Hewlett et al. (1977) attempted to test the hypothesis. Throughout the analysis, hydrograph separation was carried out using the standard method as proposed by Hewlett and Hibbert (1967).

Consequently, based on analysis of a 30-year record of rainfall and streamflow events of forested catchments, Hewlett et al., (1977) concluded that:

> "...for all practical purposes, hourly and minutely rainfall intensities during storms had no effect on storm flow volumes delivered by the basin..."

Accordingly, the four important variables in explaining the variation of stormflow volume were gross rainfall, antecedent flow, season (winter or summer) and duration of rainstorm. Hewlett et al., (1984) provided further evidence based on 4094 storm events representing 15 basins that hourly rainfall intensity has no effect on storm flows and only a small effect on peak flows. As this finding apparently was at variance with the prevailing concepts, Lee and Tajchman (1977) questioned the validity of the former claim by pointing out the anonymity of the expression used for mean storm rainfall intensity and criticized the use of data from one rain gauge located near the centre of the basin. Since the pioneer work of Hewlett et al., (1977), there have been a few other studies attempting to verify the former claim at different sites and regions. Evidently, similar results were observed by other workers who employed similar methods of analyses in New Zealand (Taylor and Pearce, 1982), in Australia (Bren et al., 1987), and in South Africa (Hope, 1983; Hewlett and Bosch, 1985). While confirming the conclusion of Hewlett et al., (1977), Taylor and Pearce (1982) added that:

> "...rainfall intensity is not an important variable in controlling quickflow responses of the study catchments, at least in events with return periods of two years of less..."

The work of Hsia (1987) in Taiwan probably represents the only study in tropical Asia to investigate the above claim. His result corresponds with most of the other studies in temperate regions in that the intensity of rainfall did not present any significant contribution to the generation of stormflow. Conversely, the results of the Babinda study in the tropical part of Australia showed the importance of rainfall intensity in the generation of saturation overland flow and sub-surface flow, especially within the top 0.25 m, below which there is a 'throttle' or impeding layer (Gilmour et al., 1982; Bonell, 1989). In this context, it is worth noting that the mean annual rainfall of this area is 4009 mm with 45% of gross storm rainfall appearing as quickflow (storm flow).

2.4 Forest Evapotranspiration

Evaporation is a physical process of converting liquid to the vapour state. Essentially, it involves the transfer of both energy and mass, thus it can be evaluated in terms of an equivalent energy flux or mass flux per unit area (Lee, 1978). The forest canopy shields the underlying surface from the effects of solar radiation, the main source of energy, and raises the level of the active surface above the level of water concentration in the soil. Therefore, evaporation from the forest environment is not only controlled by weather factors but also physiological factors (Monteith, 1965; Stewart, 1977; Halladin, et al., 1984/85).

Evaporation from grass and short crops can be satisfactorily estimated from several methods using routine meteorological observations (Stewart, 1977; Shuttleworth, 1979). However, the process of evapotranspiration from forests tends to be more complex, in part due to its greater dependence on physiological and surface factors.

There have been significant developments in evaporation calculation in the last four decades, notably by Penman (1948) on the combination method; lysimeter studies by Harrold and Dreibelbis (1958; 1967); the pan method and catchment studies.

The present available methods of prediction can in fact be classified conveniently based on the underlying principles in the methods. Shuttleworth (1979), in reviewing the evaporation process and measurement methods, has classified them into eight categories namely:

(i) Simulation models
(ii) Single source model
(iii) Intermediate model
(iv) Energy balance model
(v) Radiation model
(vi) Humidity models
(vii) Temperature models
(viii) Direct model

For each of the categories, an example of the method was given together with the most likely application. In another review, Saxton (1982) classified the established methods into seven categories, but essentially covered the same models as discussed by Shuttleworth (1979), as did Stewart (1984).

As all these models were developed in the temperate countries, little detailed information was available on their validity and accuracy in the tropical environment except for a few studies (Brutsaert, 1965; Edwards and Blackie, 1981; Bruijnzeel, 1983; 1989). Doorenbus and Pruit (1977) recommended a method for irrigation purposes. However, all studies employed the Penman (1948) method (with some modifications) in their studies simply because it is widely used and accepted in other places and provides satisfactory results.

De Bruin (1983) argued that the Priestly-Taylor or P-T (1972) method has a greater advantage in terms of simplicity whilst the method itself was a simplification of the Penman Equation. Furthermore Gunston and Batchelor (1983) compared the P-T method and the old Penman and obtained 'good' agreement in monthly values using 30 selected stations in 30 countries. De Bruin (1983) verified the above finding in 60 tropical stations of less than 600 m in altitude. Commenting on the Penman method, De Bruin (1983) put forward two drawbacks from a practical point of view.

(i) it requires a lot of data

(ii) there are too many versions and calculation schemes.

Although the P-T method has received increasingly popular usage (Shuttleworth, 1979) and might provide useful estimates of potential evaporation, it should be considered as a means of estimating actual evapotranspiration except for short green crops. Further, Shuttleworth and Calder (1979) has cautioned on the indiscriminate use of the P-T equation in estimating actual evapotranspiration for forest vegetation.

2.5 Conclusion

It is evident that well-designed research into the effects of forest activities on hydrological responses has been widely carried out in temperate countries and is still on-going, notably in the United States, United Kingdom, Australia and New Zealand. Results of these studies clearly show that significant changes have been observed in water yield, stormflow volume and peakflow rate resulting from forest cover manipulation, although a few studies indicate otherwise. Upsurge of interest in catchment research in the humid tropics has been shown particularly in the last ten years or so. In fact some studies are still at an early stage or are on-going. While research in temperate regions enters into the 'hydrological processes-type of study' and the impacts of various land use practices, research in the tropics mostly deals with the input-output relationships of the hydrological cycle and the effect of forest clearing operations on water yield, soil erosion and sedimentation. Thus, certain aspects of hydrological processes have yet to be documented. Moreover, the present logging practice in many countries in the humid tropics employs some kind of selective logging in response to great pressure on the issue of deforestation. Therefore, the present study located at the Berembun Experimental Watershed attempts to quantify such activities in forested catchments and ultimately to bridge the gap in the understanding of the cause-and-effect relationship of hydrological responses.

The selection and location of the above experimental watershed based on several criteria will be discussed in the following chapter. The chapter also describes in detail the characteristics of selected catchments in terms of soil, geology, geomorphic properties, vegetation cover and climatic condition.

CHAPTER 3

DESCRIPTION OF STUDY AREA

3.1 Selection of Study Area

Site selection for a watershed research study requires proper planning from the very beginning of the study phase. It is in fact the most important and difficult phase in the preparation of such a research undertaking. Improper site selection may drastically affect the quality of data collected, and render the whole research effort useless. If that happens, then the investment in terms of manpower, time and finance in the development of the research project could be wasted.

Site selection is further constrained by the specific requirements of the watershed research study, and whether or not the aim is to set up representative, experimental or benchmark types of watershed. The basis and choice of experimental design for this study will be discussed in detail in Chapter 4.

During the site selection phase, a number of factors have been considered, namely:

a. Uniformity of soil and geological features of the site
b. Single land use or vegetation type of the site
c. General understanding of physical make-up of the site
d. Reasonable information on the climate of the area and its surroundings
e. Accessibility and logistics of the site
f. Adequate funding available
g. Manpower capability

i. Whether pertinent equipment is available

In addition to the above factors, there were two other important criteria considered as to the choice of the site that ultimately relate to practical implications of this research. Firstly, the selected site should be a virgin forest that falls within the current management unit of the State Forestry Department of Malaysia so that an appropriate time schedule could be planned with regard to the logging operation as well as the institution of relevant guidelines. Secondly, the site should be located on elevations that represents the present logging practice which is largely encroaching into the hill forests. This is pertinent because the current method of logging, the Selective Management System (SMS), is normally employed in hill forests (Ministry of Primary Industries, 1988).

3.2 Location of Study Area

The site in Malaysia that meets the above criteria is located in the Berembun Forest Reserve in the State of Negeri Sembilan, approximately 70 km south-east of Kuala Lumpur, the capital of Malaysia (Figure 3.1). Subsequently, this study area is called the Berembun Experimental Watershed or in short BEW. This site is situated at about $2^{0}\ 50'$ latitude and $102^{0}\ 10'$ longitude, 55 km east of the Straits of Malacca and 150 km west of the South China Sea. Logistically, Kuala Pilah is the nearest town with a population of 20,000 at about 15 km to the east whilst Seremban (population-150,000) is about 30 km to the west. There is a forest road linking this site to the main highway which passes the two towns mentioned above.

The Berembun Experimental Watershed comprises three small catchments, Catchment 1 (C1), Catchment 2 (C2) and Catchment 3 (C3) located

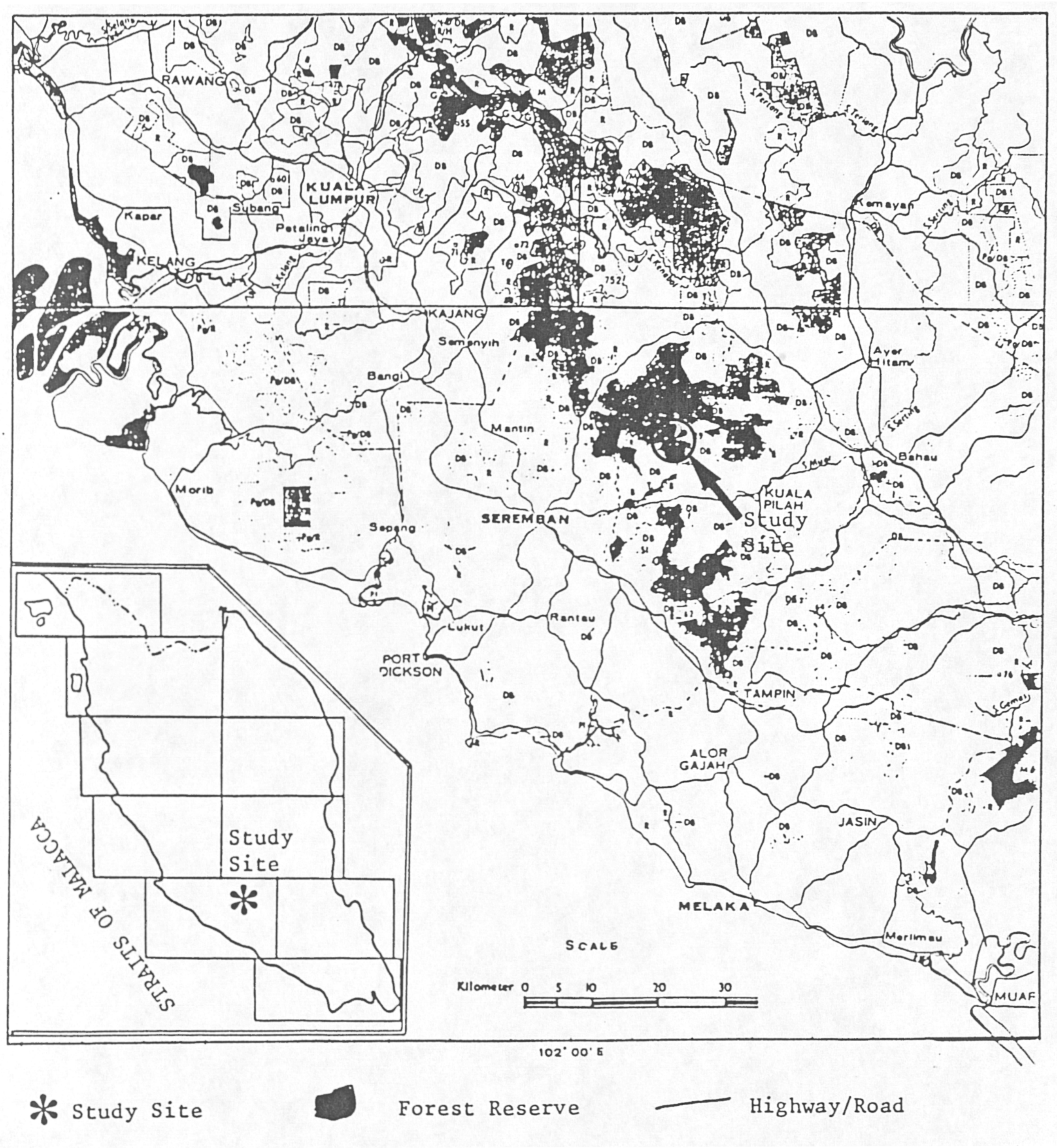


Figure 3.1 Location of Berembun Experimental Watershed (BEW) in Peninsular Malaysia

adjacent to each other occupying areas of 13.3, 4.6 and 30.8 ha, respectively, giving a total area of 48.7 ha (Figure 3.2).

3.3 Soil and Geological Setting

Detailed soil survey was carried out in this watershed following the standard soil survey practice in Malaysia (Adzmi and Ghazali, 1988). According to this survey, the soil is classified as of the clayey kaolinitic-isohyperthemic family of the Typic Paleudult. The A-horizon can be described as thin with thickness varying from 3 to 7 cm and coarse sandy clay loam in texture. Its colour ranges from 10YR, 5/8 to 10YR 6/8. The B-horizon is relatively deep with uniform brownish yellow to yellowish brown (10YR 6/6, 6/8) and occasionally becomes a strong brown (7.5YR 5/6 to 7.5YR 5/8). Its texture is similar to the A-horizon except that there is a slight increase in clay content with depth. Structurally the soils have a moderately developed medium sub-angular blocky and friable consistency which is largely derived from a granitic parent material. The survey has also reidentified the soil series of this area as belonging to Berembun series, a new series named after this place, although it has been quoted as belonging to the Rengam and Beserah series previously (Abdul Rahim, 1983). The present series differs from that of previous series in terms of clay and silt contents. Average clay content ranges from 21% to 29% whilst that of silt between 10-13 %.

Soil pH is 4.5 which is expected of forest soils. The concentration of N and P is quite low while exchangeable Ca, Mg and soluble K shows a higher concentration in the top soil decreasing with depth.

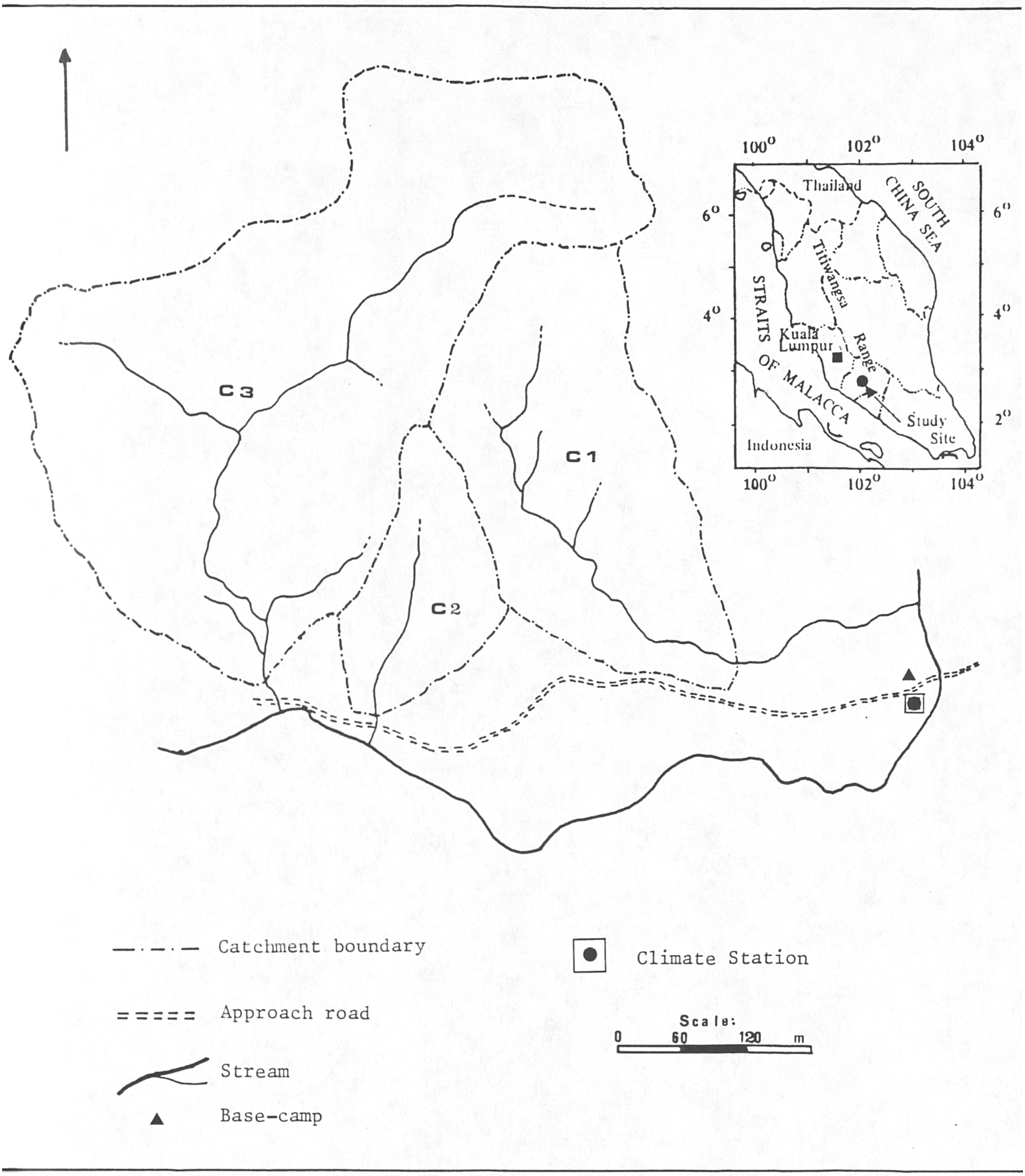


Figure 3.2 Three catchments at Berembun Experimental Watershed, Kuala Pilah, Negeri Sembilan, Peninsular Malaysia

Detailed analytical results of soil in each catchment are given in Table 3.1. A general description of soil profiles representative of each catchment is given in Appendices 3.1, 3.2 and 3.3.

Although a detailed geological survey has not been carried out, some prominent features of the geology have been established by the Geological Survey Department of Malaysia as well as during the soil survey exercise. Geologically, this area is underlain by a single granitic body known as the Senaling granite which generally forms the southern portion of the Main Range Granite (Khoo, 1973) (Figure 3.3). The rocks consist of medium to coarse-grained porphyritic biotite granite with both quartz and felspar as phenocrysts. Granitic dating of samples taken from the nearby area showed that they belonged to the isochron age of middle to upper Triassic (Bignell and Snelling, 1972).

3.4 Morphometric Characteristics of the Study Area

Morphometric properties of the watershed which are very important in understanding hydrological processes operating in a particular drainage basin, will be described according to three categories as expounded by Chorley (1969):

a. Linear aspects of the watershed

b. Areal aspects of the watershed

c. Relief aspects of the watershed

In addition, a 3-dimensional plot of the watershed can provide an alternative way of appreciating various morphometric properties of catchments (Figure 3.4). This 3-D plot was drawn based on field data collected during the topographical survey.

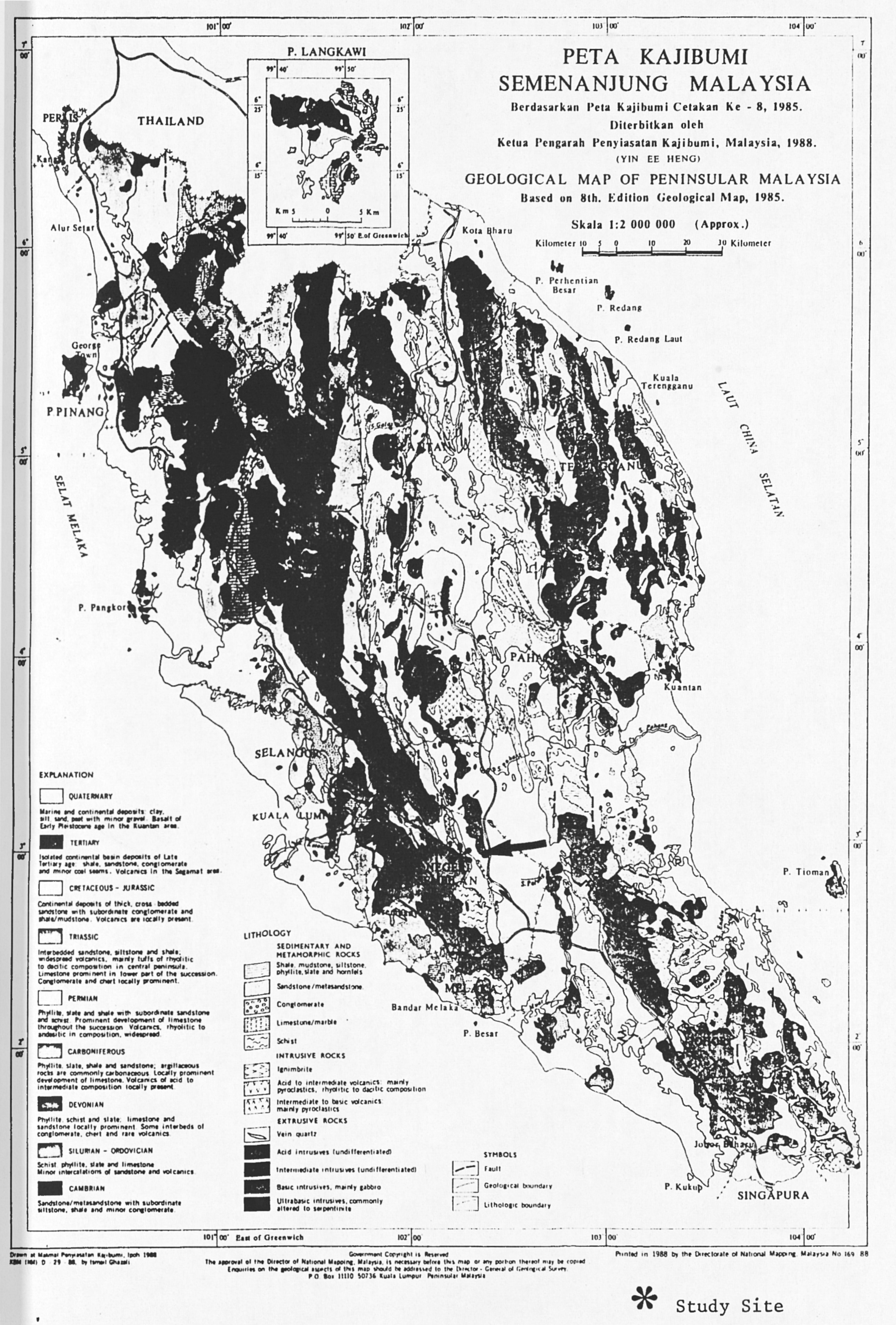


Figure 3.3 Geological map of Peninsular Malaysia

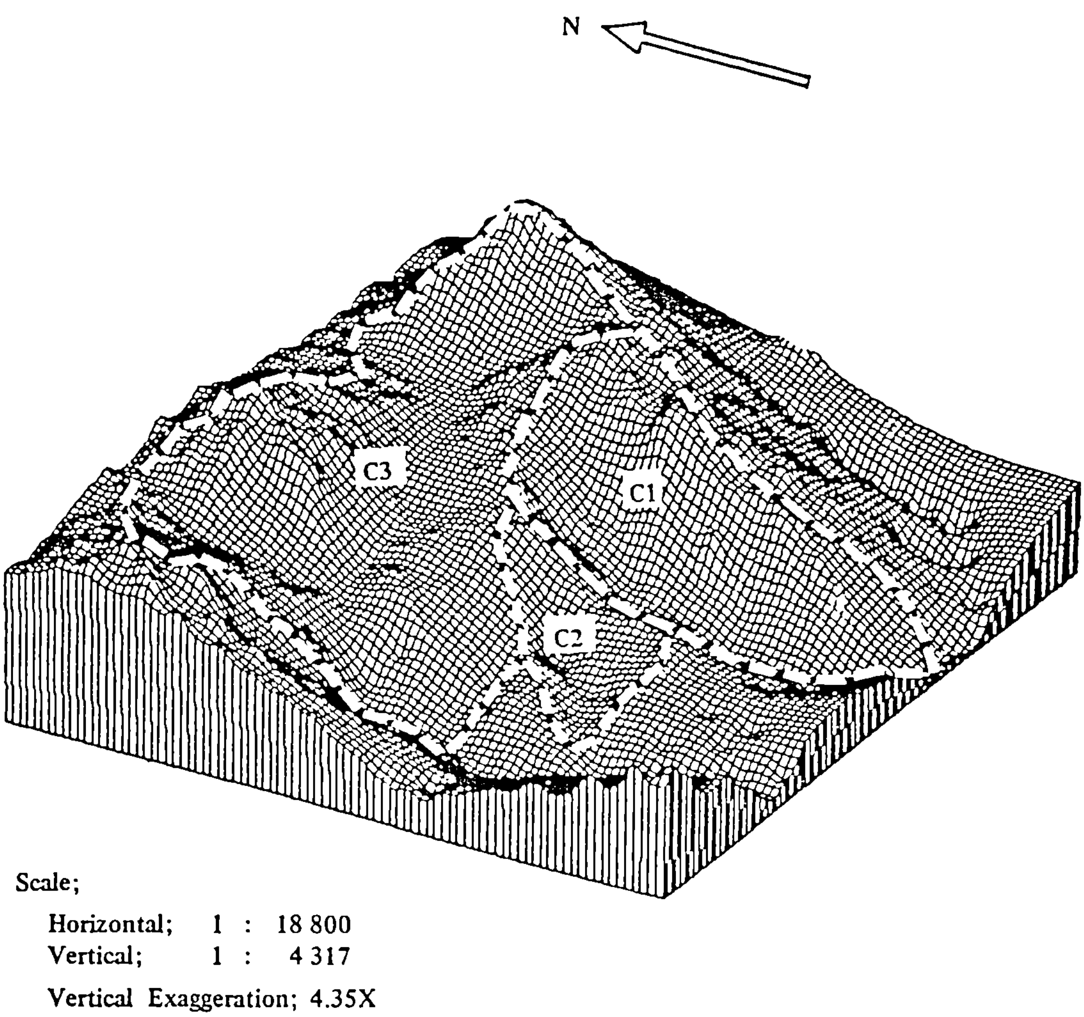


Figure 3.4 Three Dimensional View of Berembun Experimental Watershed

Table 3.1 Analytical Results of Soils in BEW

Catchment 1

Horizon	% Clay	% Silt	% Fine sand	% Coarse sand	pH	% Carbon	% Nitrogen	Avail. P (ppm)	$Sol.K^+$ (ppm)	Exch. Ca[1]	Exch. Mg[1]
A	8.2	15.9	44.6	34.3	4.5	3.04	0.52	7.1	85.0	1.407	2.386
AB	22.0	8.3	21.8	44.0	4.5	1.44	0.35	2.9	33.6	0.374	0.692
B21t	18.1	7.3	31.4	40.3	4.7	0.60	0.17	0.9	20.0	0.357	0.692
B22t	25.5	3.0	30.6	40.3	4.6	0.41	0.16	0.4	16.5	0.222	0.375
B23t	30.7	13.0	26.6	35.9	4.6	0.37	0.15	0.4	25.5	0.110	0.250

Catchment 2

Horizon	% Clay	% Silt	% Fine sand	% Coarse sand	pH	% Carbon	% Nitrogen	Avail. P (ppm)	$Sol.K^+$ (ppm)	Exch. Ca[1]	Exch. Mg[1]
A	28.0	9.2	22.3	47.0	4.3	1.56	0.43	2.95	112.5	0.250	1.316
AB	19.6	8.5	26.0	39.9	4.5	0.49	0.21	1.20	44.5	0.128	0.247
B21t	26.1	24.6	20.7	35.6	4.5	0.45	0.15	0.30	46.0	0.203	0.357
B22t	31.0	9.1	25.6	39.2	4.7	0.37	0.13	0.00	44.5	0.193	0.332
B23t	26.5	11.3	26.5	42.5	4.6	0.31	0.14	0.30	14.0	0.199	0.416

Catchment 3

Horizon	% Clay	% Silt	% Fine sand	% Coarse sand	pH	% Carbon	% Nitrogen	Avail. P (ppm)	$Sol.K^+$ (ppm)	Exch. Ca[1]	Exch. Mg[1]
A	26.0	10.9	39.9	20.0	4.2	3.87	0.54	4.45	63.0	0.345	1.438
AB	24.4	14.7	27.0	34.4	4.7	0.91	0.21	1.15	14.5	0.189	0.453
B21t	34.4	5.1	25.6	41.9	4.7	0.86	0.13	0.35	8.5	0.192	0.285
B22t	19.1	16.4	15.5	36.4	4.6	0.41	0.12	0.20	7.5	0.208	0.285
B23t	40.2	6.9	27.8	15.6	4.7	0.23	0.08	0.00	5.5	0.304	0.424

[1] meq/100g

3.4.1 Linear aspects of the watershed

Based on Strahler's (1957) scheme of stream ordering, C1 and C3 are second-order whilst C2 is first-order only. As expected, such small headwater catchments are normally present in the undisturbed forests which constitute the current forest management unit administered by the State Forestry Department. Accordingly, the length of the main stream is longest in C3 (1000 m), followed by C1 (647 m) and the shortest is in C2 (247.5 m). The three catchments share a common southerly aspect (Figure 3.5).

3.4.2 Areal aspects of the watershed

The catchment areas follow a similar pattern to that of the stream length in which C3 is the largest, 30.8 ha and C2 is the smallest, being only 4.6 ha (Table 3.2). The relationship of stream length to catchment area is important because it may give an idea of the pattern of runoff out of the basin. Another more sensitive but often variable parameter is the **drainage density**, the largest being C1 (6.18 km/km^2), followed by C2 (5.37) and the smallest being C3 (4.67). Normally this parameter exhibits quite a wide variation, in part reflecting the physical features of a particular basin. For example, drainage basins of headwater catchments at Jengka Experimental Watershed, Pahang underlain by sedimentary rocks, range from 6.7 to 10.0 km/km^2 (Abdul Rahim, 1983).

Despite some differences in stream order, the three catchments maintain relatively similar shape in terms of **form factor** which ranged from 0.377 to 0.330. On the other hand, C3 seems quite different in **catchment circularity** as well as being **lemniscate** as compared to the other two catchments C1 and C2 whose values are about the same. According to Chorley (1969), drainage basins differ

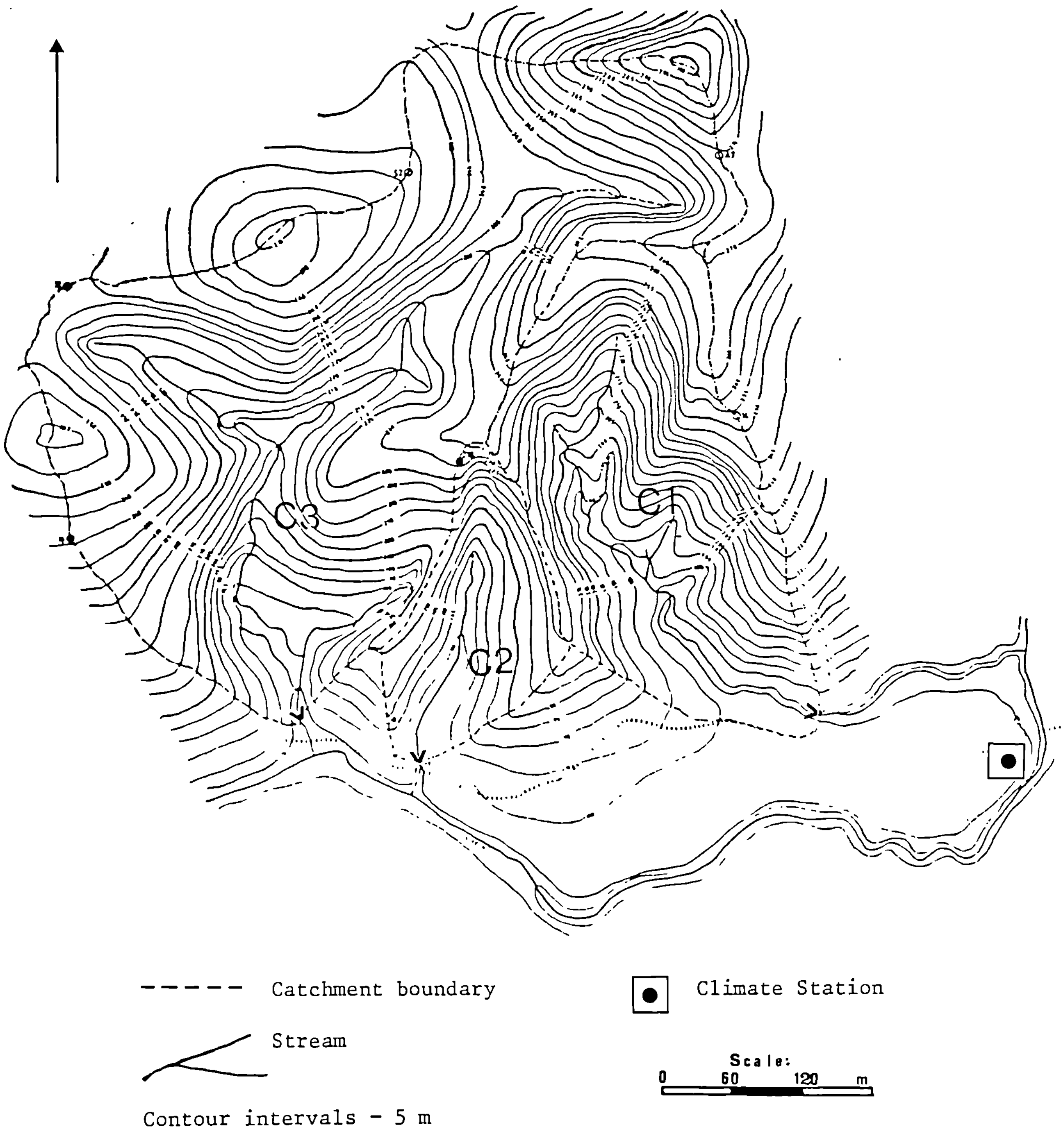


Figure 3.5 Topographical Map of Berembun Experimental Watershed

relatively little in shape, unless pronounced structural control is present, although basins tend to become more elongate with strong relief or steep slope.

3.4.3 Relief aspects of the watershed

C3 indicates the highest elevation, 302 m.a.s.l, whilst C2 is the lowest (272 m.a.s.l). Similarly, C3 has the largest relief range (131 m) while the smallest is C1 (101 m). Another important factor under this category which has much influence over the magnitude of the runoff peak is slope. There are a number of ways to express slope factor but in the present analysis, the Ouryvaey method was employed (Toebes and Ouryvaey, 1970). C2 has the highest slope, 47% and that with the lowest is C3, 34%.

Table 3.2 provides a summary of morphometric properties of the three catchments:

	C1	C2	C3
A. Linear aspects			
1. Length of main stream (m)	648	248	1000
2. Stream order	2	1	2
3. Aspect	S	S	S
B. Areal aspects			
1. Area (ha)	13.3	4.6	30.8
2. Drainage density (km/km^2)	6.17	5.37	4.68
3. Form factor	0.34	0.33	0.37
4. Elongation ratio	0.66	0.65	0.69
5. Circularity ratio	0.69	0.71	0.68
6. Lemniscate	0.73	0.76	0.66
C. Relief Aspects			
1. Elevation (m.a.s.l)			
Max	289	272	302
Min	171	175	171
2. Mean slope (%)	42	47	34
3. Relief (m)	101	114	131

3.5 Vegetation Cover

A botanical survey and a pre-felling inventory have been carried out in this watershed with the intensities of 100 and 10 %, respectively. In the former, all trees equal to or greater than 10 cm dbh in six 1 ha survey plots were enumerated while in the latter all tree species of 5 cm and above, categorised into different size classes, were enumerated into timber groupings. The pre-felling inventory is actually a routine part of forest management to provide reliable estimates of stocking and volume of the area (Yusuf et al., 1987).

The forest type of this area can be classified as 'Red-Meranti-Keruing Forest' according to Wyatt-Smith's (1963; 1987) classification. The forest is typical of the Lowland Dipterocarp Rain Forest with a great species diversity characterized by multi-tier canopy and dense stocking. The Lowland Dipterocarp Forest of Peninsular Malaysia is characterised by family dominance of the Dipterocarpaceae. It may be regarded as composed of three tree layers: the emergent layer trees, usually with spreading crowns nestling above but in contact with those of the main canopy; the main-storey trees forming the continuous canopy 20 - 30 m in height, and the understorey trees below the main canopy. This forest is a reasonably rich forest with a high percentage of commercially important species of *Shorea* in the emergent and main storey level; the main species are *Shorea leprosula* and *S. acuminata*. Other common large tree species are *Koompassia malaccensis* and *Intsia palembanica*.

Frequency of *Dipterocarpus* species is surprisingly low, mainly represented by *Dipterocarpus baudii* and *D. sublamellatus*. *Shorea laevis* is quite abundant and forms a main group of the emergent level of the canopy. With the presence of this species, which normally occurs on the upper slope, this forest, to a certain extent, is characteristic of a hill dipterocarp forest.

The main storey comprises smaller trees of the emergent species and also other species such as Dillenia spp., Eugenia spp. and Burseraceae spp. Another characteristic feature of this forest is the comparatively poor representation of the middle size classes of the large, upper storey and important forestry species; this can possibly be explained by the fact that these species are in general strong light demanders and pass through the middle size classes very quickly in the gap phase of the forest regrowth cycle. The understorey is moderately dense consisting mainly of Temin (Streblus taxoides) and Minyak berok (Xanthophyllum spp).

The mean basal area of the forest for the entire watershed inclusive of all species groups is 26.9 m^2/ha which indicates that the forest is quite well-stocked. A similar type of forest located 50 km away is Pasoh F. R., Negeri Sembilan having a mean basal area of 25.2 m2/ha based on a 40 ha sampling of all trees of 10 cm dbh and above (Manokaran, 1988).

The full list of tree species surveyed in BEW is given in Appendix 4, and is arranged according to species grouping as well as marketability of each group.

3.6 Climatic Description

The general climatic condition of the experimental watershed has been described by Abdul Rahim (1983). Climatic data for this watershed are taken from the climate station located at the base camp which has been continuously monitored since the establishment of this study (Figure 3.2). Detailed descriptions of equipment used and related procedures will be covered in chapter 4.

3.6.1 Rainfall

The annual rainfall total ranges from 1442 to 2611 mm, with a mean of 2126 mm. Monthly rainfall distribution exhibits a two-maxima pattern which normally coincides with the North-east Monsoon and the transitional period (Figure 3.6). The two maxima occur in the months November and April. The average number of raindays per year is 163 and the highest number per month is 20 which normally occurs in the months of the North-east Monsoon (October - January). The bulk of rain mostly falls during the afternoon and late evening, this being characteristic of the convectional type of rainfall.

3.6.2 Air Temperature

Air temperature shows little variation throughout the year, with a monthly mean of 26.5°C and small annual temperature range (about 1.6°C). Daily mean maximum and minimum temperatures are moderate. The mean daily maximum is highest in March or April (35.4°C) and lowest in January (19.6°C) (Figure 3.7). The absolute maximum and minimum temperatures ever recorded were 37.0°C and 17.9°C, respectively. Based on the 24-hour variation of temperature in a nearby Pasoh Forest Reserve, 50 km away, the highest temperature usually is recorded at 1200-1400 hrs with the lowest at about midnight (Shahruddin, 1984). Temperature variation with height in that forest indicates that in the early morning, temperature in the crown area was higher than that at sites below. On the other hand, temperature was fairly constant within the forest until about 1000 hrs when it started to show a slight increase.

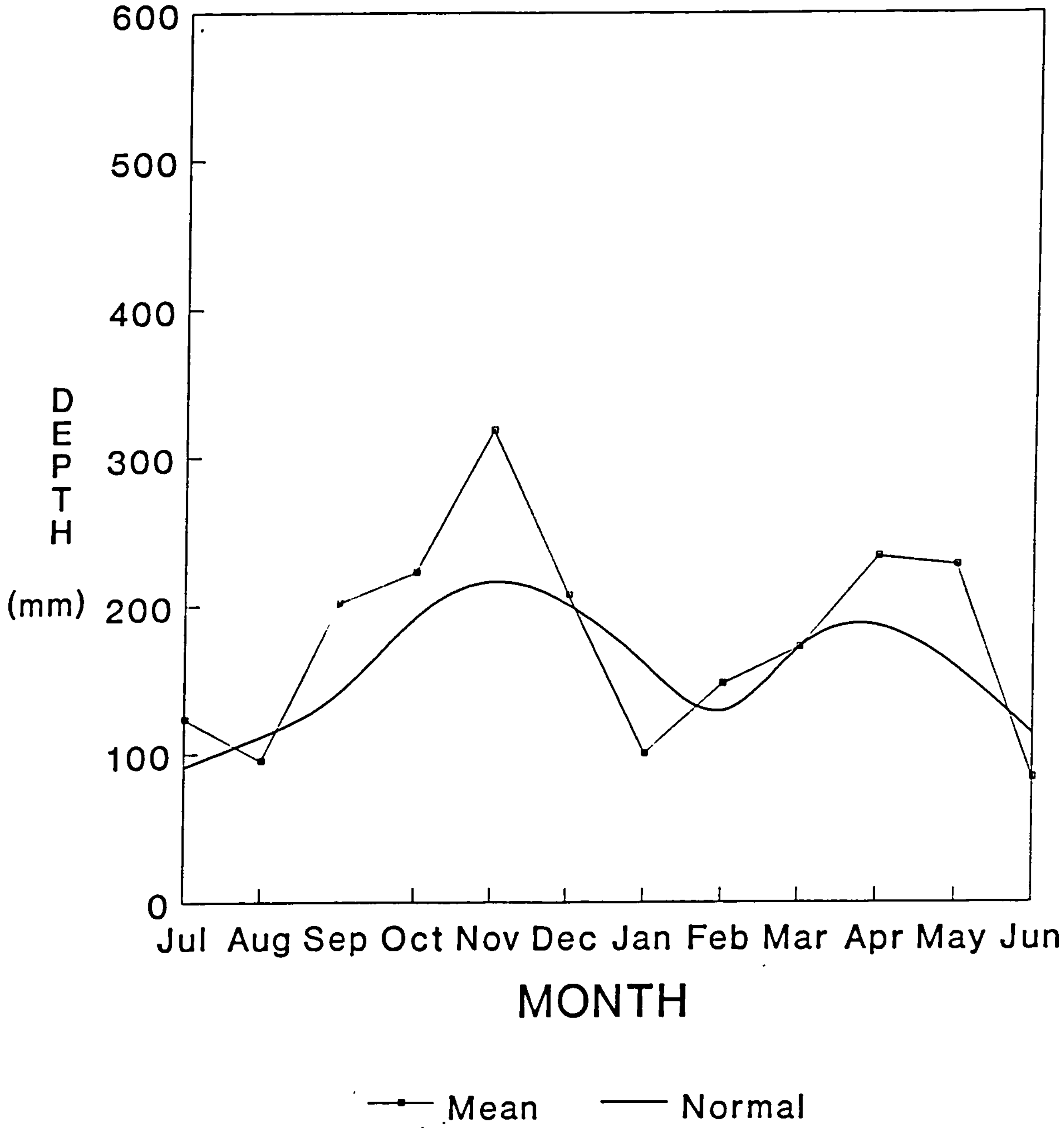


Figure 3.6 Mean monthly rainfall of BEW and normal rainfall of Kuala Pilah app. 15 km from the site

3.6.3 Relative Humidity

Another prominent feature of the humid tropics is invariably high relative humidity, as for example in BEW, it seldom drops below 75%. The daily maximum humidity can be as high as 98.8% with a minimum of 61.0%, giving a mean value of 83.6%. Although RH varies very little from month to month, apparently absolute RH during wet months (November - December) indicates slightly higher values (Figure 3.7). A similar pattern of RH was observed in Pasoh Forest Reserve (Soepadmo and Kira, 1981). The hourly trend of RH does fluctuate with most of the higher values observed in the early morning hours with a range of about 10% between the highest and the lowest values. As observed by Shahruddin (1984), the hourly variation of relative humidity with height was almost the reverse of air temperature.

3.6.4 Windrun

Windrun in terms of km per day inside the forest is relatively low compared with non-tropical countries. The highest daily windrun recorded at 2 m above ground is 29 km/day or about 0.80 m/sec with mean monthly values of 17.5 km/day. The mean monthly windrun for the months of May to October is about 15 km/day whilst in the other six months range is 17 to 24 km/day (Figure 3.8). A slightly higher mean monthly value, 21 km/day was recorded at the same height in another forested watershed at Jengka, Pahang, (Abdul Rahim et al., 1986).

3.6.5 Sunshine

Continuous daily recording of sunshine duration was carried out using the Campbell & Stokes Mk II Sunshine Recorder located at the

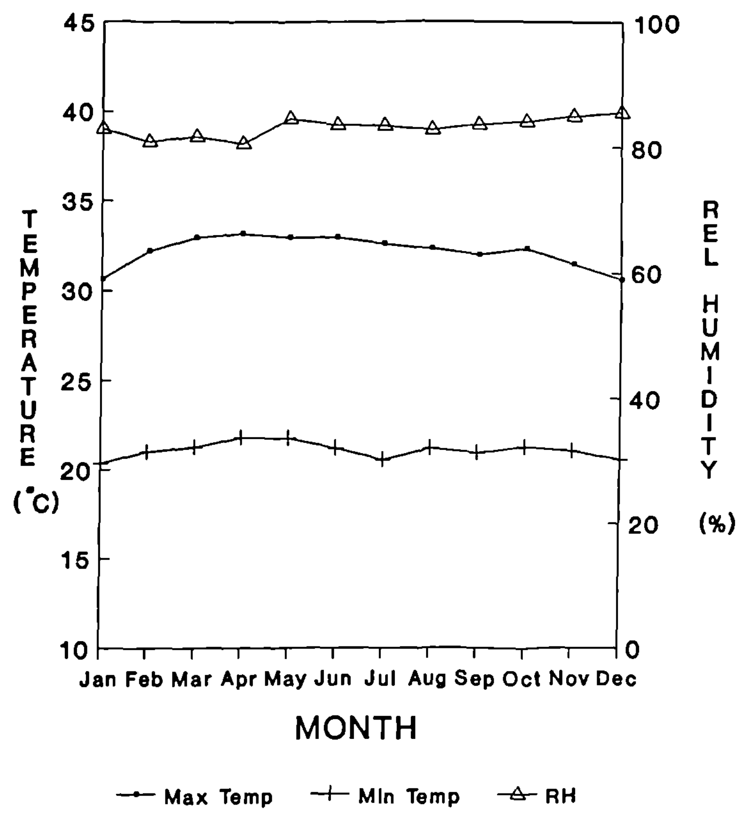


Figure 3.7 Mean monthly maximum and minimum of air temperature (C°) and relative humidity (%) of BEW (1980 - 1987)

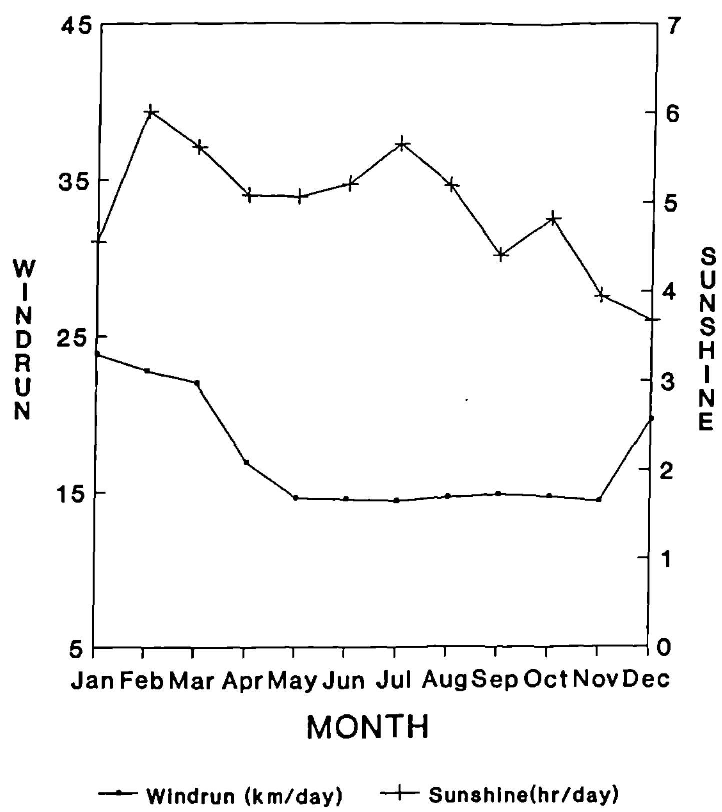


Figure 3.8 Mean monthly windrun and sunshine duration of BEW (1980 - 1987)

base-camp. The monthly sunshine duration ranges from 86 to 236 hrs/month, with a mean value of 147 hr/month. The corresponding values in hrs/day are 2.8, 7.6 and 4.9, respectively. Interestingly, minimum and maximum values were recorded in the months of December and February which coincide with wet and dry months (Figure 3.8).

3.6.6 Evaporation

Two methods are used to calculate evaporation rate in this watershed - the Pan Method and the Penman Method, both of which utilize data collected from the climate station. Evaporation in the humid tropics normally assumes a conservative figure and shows minimal monthly variations over the years. Mean daily evaporation computed by the Penman Method (4.1 mm/day) indicates a higher value than that of the Pan Method (3.5 mm/day) with corresponding yearly totals of 1471 and 1263 mm, respectively. Average evaporation of Peninsular Malaysia is about 1450 mm/year (Scarf, 1976)

Table 3.3 summarizes the general climatic condition of BEW based on a seven-year period (1980/81 - 1986/87)

Annual rainfall		2126 mm
No. of raindays		163
Air Temperature		
Mean		26.5^{0}
Mean Max		35.4^{0}
Mean Min		19.6^{0}
Relative Humidity		83.6 %
Windrun		17.5 km/day
Sunshine hours		147 hrs/month
	or	4.9 hrs/day
Evaporation		
US 'A' Pan		3.5 mm/day
Penman Method		4.1 mm/day

3.7 Conclusion

The three catchments situated at Berembun Forest Reserve, Negeri Sembilan obviously possess almost all criteria needed for a well-designed watershed study. They are located adjacent to each other, share a common soil series and geological setting, and have almost similar geomorphic properties and these are amongst the central characteristics required by an experimental watershed. More importantly, however, these catchments are still covered with undisturbed forests which fall under the purview of the State Forestry Department of Negeri Sembilan. As such, various logging prescriptions planned for different treatments can be easily imposed and managed with the cooperation of the staff of the latter agency.

The smaller size of the control catchment (C2), compared with the other two catchments can arguably been seen as disadvantage. However, size of a catchment is solely governed by the topographic divide prevailing at a particular location. Furthermore, it is not satisfactory to locate the control catchment away from the others as this may create other logistical problems later on, especially during the treatment phase.

While an ideal site for an experimental watershed study is invariably necessary, appropriate instrumentation forms another important pre-requisite for a successful watershed research programme. Hence, the following chapter describes the installation, operation and maintenance of various types of equipment installed in the above watershed. In addition, the chapter elaborates on the basis of experimental watershed design, the approach of calibration analysis and lastly, the treatment exercise undertaken upon completion of the calibration period.

CHAPTER 4

EXPERIMENTAL-DESIGN, INSTRUMENTATION, WATERSHED CALIBRATION AND TREATMENT

4.1 The Concept of the Experimental Watershed

A watershed, synonymous with catchment or basin, has more than one definition. Essentially, a watershed can be defined as a land area drained by a stream or river to a given point on a water-course usually delineated by a topographic divide (Ward, 1967; Pereira, 1973; Lee, 1980). A number of processes operate within a watershed including hydrologic, climatic, geomorphic, edaphic, and social factors that are interlinked in a quantifiable manner. Thus, a watershed offers an ideal unit in which to develop an ecosystem approach as opposed to the system approach that has been deeply entrenched in watershed research since the 1960s. To this effect, Gibb (1986) describes a watershed as a functional unit established by the physical relationship between physical attributes and cultural influences. With strong overtones of sustainable resource management in recent years, Hamilton (1986) further emphasized the importance of appropriate understanding of how the various inter-relationships and processes operate in the watershed if watershed resources are to be managed to derive optimum benefits from them.

4.1.1 Types of watershed research

The use of a whole watershed as an experimental unit can be traced back as far as an early effort in the Emmental Valley in Switzerland in 1893. Since then a great number of so called watershed research studies have emerged, but not all of them can be accurately defined as experimental watersheds as they conceivably suffered from two short-comings (Ward, 1967):

i. inadequate motivation or direction
ii. inadequate data collection

In essence, watershed research should have a specific objective to fulfill and the watershed itself should have been selected with care, pertinent instruments installed and followed by rigorous data monitoring, collecting and processing.

However, with a wide variety of objectives and sometimes different fields of study, to make comparisons of results is often difficult and unrewarding. In an effort to bring some measure of compatibility to results and conclusions, general guidelines on the research method were formulated by committees of the International Association of Scientific Hydrology (IASH) and the International Hydrological Decade (IHD) of UNESCO between 1965-1975 (Toebes and Ouryvaey, 1970). Accordingly, under these proposals, watersheds used in research studies can be classified into two types (Ward, 1971), but a third type has been added as a specific variant on the other two (WMO, 1974; Low, In Press):

i. Representative watershed
ii. Experimental Watershed
iii. Benchmark Watershed

As defined by IHD, the main difference between representative and experimental watersheds is that the former will be allowed to remain more or less in their natural or initial condition while the latter will be subjected to deliberate modification in terms of vegetation, land use or landscape. In addition, representative basins are assumed to have hydrological similarities with the hydrological regions. The American Geophysical Union (1965) further elaborated on the two types in terms of their purpose as follows:

> "...An experimental watershed is one that has been chosen and instrumented for study of hydrologic phenomena; a representative watershed is one that been chosen and instrumented to represent a broad area, in lieu of making measurements on all watersheds. Studies using experimental watersheds imply a search for principles, relationships, and factors for prediction schemes; studies using representative watersheds imply that data are transferred quite directly to other watersheds where similar measurements are not available..."

This approach appears to be adopted in many parts of the world since the launching of the IHD including Australia, Germany, Switzerland, the United States and the United Kingdom, the USSR, India, Brazil, Malaysia and Indonesia (IASH, 1980; Law and Ahmad, 1989).

Benchmark watersheds, as defined by WMO (1974), are those intended for reference for the evaluation of long-term change. Generally a benchmark watershed is always selected to be free of cultural and anthropogenic changes, both past and future, so that long-term shifts in the hydrological regime can be observed, without being influenced by the effects of human activities (Low, In Press).

The above watershed types differ mainly in terms of their purposes as well as their practical uses as indicated by many authorities (Australia Water Resources Council, 1969; Toebes and Ouryvaey, 1970; WMO, 1974). Basically, the principal objectives of watershed studies are the prediction and quantitative estimation of the hydrological components and the understanding of the mathematical and physical relationships between the various components of the hydrological cycle. The aim of the studies is to provide knowledge on the interaction between man and environment, embodying soil, water, climate, vegetative cover and fauna within the watershed.

Experimental watersheds are intensively instrumented catchments, usually small and used for very specific studies of some aspect of the hydrological processes. Quite often, experimental watersheds are initiated where the natural conditions are deliberately modified or changed and the effects of such modification on selected hydrological parameters of the watershed can be evaluated. In addition, an experimental watershed is normally homogeneous in soil, vegetation and physical characteristics. The outcome of this type of research would yield cause-effect relationships of various responses and to a certain extent, may lead to defining the factors involved.

The question of size has been intermittently debated as to what is meant by 'small' or 'large'. According to Wisler and Brater (1959), the adjectives small and large were used to indicate basins ranging in size from a few hectares to approximately 26 km^2 and more than 26 km^2, respectively. Hore and Ayer (1965) suggested that experimental watersheds should preferably range in size from 4 ha to about 600 km^2. From the practical point of view, Hewlett (1970) pointed out that a watershed of 50 - 100 ha is a manageable area for rigorous research, but a basin of 1000 ha or larger would be impractical for the application of experimental treatment uniformly. Apparently, there is no universal agreed definition of 'small', although there is almost universal recognition of the need for experimental watersheds to be of such a size that:

> "... data may not only be collected comparatively easily but may also be analysed and extrapolated with reasonable accuracy..."(Ward, 1971)

Despite significant contributions from watershed research to hydrological science, some workers have questioned the value of experimental watersheds. They argue that the results showed problems of transferability, were expensive, possibly indicated leakage, were time-consuming, possibly unrepresentative and proved difficult for detection of changes (Ackermann, 1966; Reynolds and Leyton, 1967). Instead, plot studies and models have been suggested as alternatives. To a certain extent, the criticisms may be true but Hewlett, Hull and Reinhart (1969) defended the importance and appropriateness of this approach which has contributed considerably to our understanding of the hydrologic cycle and the effect of land use upon it.

4.1.2 Types of experimental watershed

With wide acceptance of the experimental watershed as a tool in hydrological research, it has evolved further into three generic types, namely single, paired and nested watershed (Low, In Press; Reigner, 1964; Reinhart, et al., 1963). The differences among these basically arise from the physical make-up of the watersheds, which influences the approach to the research set-up.

a) Single experimental watershed

As the name suggests, a single watershed consists of one watershed used to study the effects of watershed alteration on itself. However, it is not very popular and is seldom used because it does not permit comparison of results; analysis is carried out in terms of comparisons with its own historical data. As such the calibration period is slightly longer and size is normally larger.

b) Paired experimental watershed

Paired watersheds are the most commonly employed throughout the world, principally to elucidate the effects of deliberate change on hydrological parameters. The main principle of the paired watershed experiment is based on the simple assumption that the relation between two catchments experienced in the past will continue into the future unless some change is made on one of the catchments (Hewlett, 1970). The need to account for climatic influences in an experiment requires at least two catchments, and preferably two experimental periods of time. Hence, there must be a treatment catchment and a control catchment located adjacent to or near to each other; the control serves as a climatic standard. Both catchments should be similar in size, shape, geology, exposure, elevation and initially they should be under the same vegetation cover. The experimental periods or phases include calibration, treatment and post-treatment periods. In this context, Hewlett (1970) suggested that an ideal experimental watershed should be in tide-free, upland terrain with distinct surface water divides overlying folded or horizontal geologic formation, to ensure water-tightness of the catchment.

c) Nested experimental watershed

Nested watersheds are in fact a variant on the single watershed. The area is demarcated as a segment of a watershed, based on a common channel system. Subsequently, sub-catchments are deliberately modified to show the effect of change within sub-catchments as well as within the watershed.

Adopting any of the above watershed-design types requires some kind of instrumentation to fulfill research objectives. Whatever the research objective may be, certain basic measurements of hydrological parameters are invariably necessary such as rainfall, discharge and some aspects of climatic variables. In the following sections, discussion will cover the installation of various climatic and hydrological instruments needed by this study located at Berembun Experimental Watershed (BEW).

4.2 Instrumentation and Data Collection

Hydrologic data are indispensable in any hydrological research investigation and are often used for immediate application by relevant water resource agencies. Basically hydrologic data include almost any physical quantity that is pertinent to an understanding of the hydrological processes. For the present study, the following data are of interest namely rainfall and other climatic data, discharge, evaporation and soil moisture changes and thus their monitoring forms a major component of this study. Climatic data of interest comprise air temperature, relative humidity, wind run, sunshine duration and soil temperature.

4.2.1 Installation and collection of climatic data

A climate station has been constructed at the base-camp located outside the watershed, some 0.5 km to the east (Figure 3.2). It is being operated in conformity with the Malaysian Meteorology Departments' regulations. This station is deliberately located near the base-camp to provide a convenient access to the station for frequent data collection and maintenance. The following equipment, (Table 4.1) with its respective uses, has been installed at the climate station for measuring various climatic variables (Plate 1 and Figure 3.2). Data collection and routine maintenance of this equipment has been carried out by the trained staff of the Forest Research Institute of Malaysia (FRIM) under the close supervision of the author. As most of the equipment is of the manual-type, readings are taken twice daily according to specific requirement, normally at

Table 4.1 List of equipment and its uses installed in the climate station

	Equipment	Uses
1.	Maximum thermometer	Maximum air temperature
2.	Minimum thermometer	Minimum air temperature
3.	Wet-bulb thermometer	Wet-bulb temperature
4.	Dry-bulb thermometer	Dry-bulb temperature
5.	Anemometer (Munro IM 119)	Windrun
6.	Sunshine recorder (Campbell Stokes Type II)	Sunshine duration
7.	Right-angled earth thermometer	Soil temperature
8.	Evaporation pan US 'A' class	Evaporation
9.	Thermohydrograph	Air temperature and Relative humidity
10.	Storage and recording rain gauges	Daily and weekly rainfall

0800 and 1400 hrs for air temperature, soil temperature and relative humidity, and at 0800 and 1800 hrs for windrun and evaporation. The sunshine recorder is serviced daily by replacing a sunshine template at 0800 and 2000 hrs. Standard field forms are used to record all daily readings for a particular month. Subsequently, at the end of every month these forms are brought back to FRIM for further computation and processing.

The thermohydrograph is operated by a spring-wound clock and is serviced every seven days by replacing the chart. This chart is sent to FRIM every week together with other recording charts. Calibration of instruments is performed by the Meteorology Department every year or when there is any malfunction.

4.2.2 Rainfall measurement

In a forested area, rainfall is one of the most difficult variables to measure accurately because point measurements are subject to significant error due to the effect of exposure above the ground (Rodda, 1967). In this context, Pereira et al. ,(1962) suggested that rainfall in a forest should be measured by gauges set up at canopy height by means of towers or poles. However, such arrangements are expensive to install and difficult to maintain, especially in the rainforest where trees are mainly more than 60 m tall. Standard gauges located in clearings also give a consistent result if required exposure is closely observed (WMO, 1974).

Optimum station density is invariably required to obtain reasonable areal rainfall measurement and to capture data in cases of extreme localization of storms. The World Meteorological Organization (WMO) has produced a standard guideline for various hydrological regions, but it is meant for long-term hydrological monitoring on a national basis (WMO, 1981/82). For example, in an equatorial region, the station density recommended is 2500 km^2 per station. However for research purposes, a much denser network is needed. In this instance, Low (In Press) suggests that the minimum number of raingauges required to obtain adequate rainfall distribution is as follows:

Size of watershed (ha)	Minimum no. of raingauges
1 - 10	1
11 - 50	2
51 - 100	3
101 - 250	1 per 50 ha
251 -1000	1 per 200 ha
> 1000	1 per 400 ha

In this watershed, rainfall measurement is undertaken using both storage (or manual) type and automatic-recording gauges (Plate 4.2). Rainfall stations are randomly located in the watershed so that areal distribution of rainfall can be captured. However, these stations should preferably be located around the watershed or just outside the catchment boundaries to avoid cutting too many trees in order to achieve adequate exposure. A network of eight rainfall stations has been installed in BEW, three of which are equipped with both storage and recording gauges, namely stations CS, 21B and 32 (Figure 4.1). Adequate clearing at each station provides the needed exposure of 45° from the orifice of raingauge to the nearest forest canopy. The recording rain gauge is of the OTA tipping-bucket mechanism equipped with OTA Keiki recorder, tipping at every 0.5 mm of rain. Recorders are run by dry-cell batteries which normally last for about three months. Orifice measurement of both type of gauges is 8 inches or 203.2 mm and the gauges are installed at the height of 1.5 m above the ground.

All rain gauge stations except the one in the climate station, are serviced every 7 days when used charts are replaced with new ones or weekly totals of rainfall are recorded from the storage gauges. The gauge in the climate station is serviced daily due to close proximity to the base-camp. A standard field form is used to record weekly rainfall and is then sent to FRIM together with other charts every week.

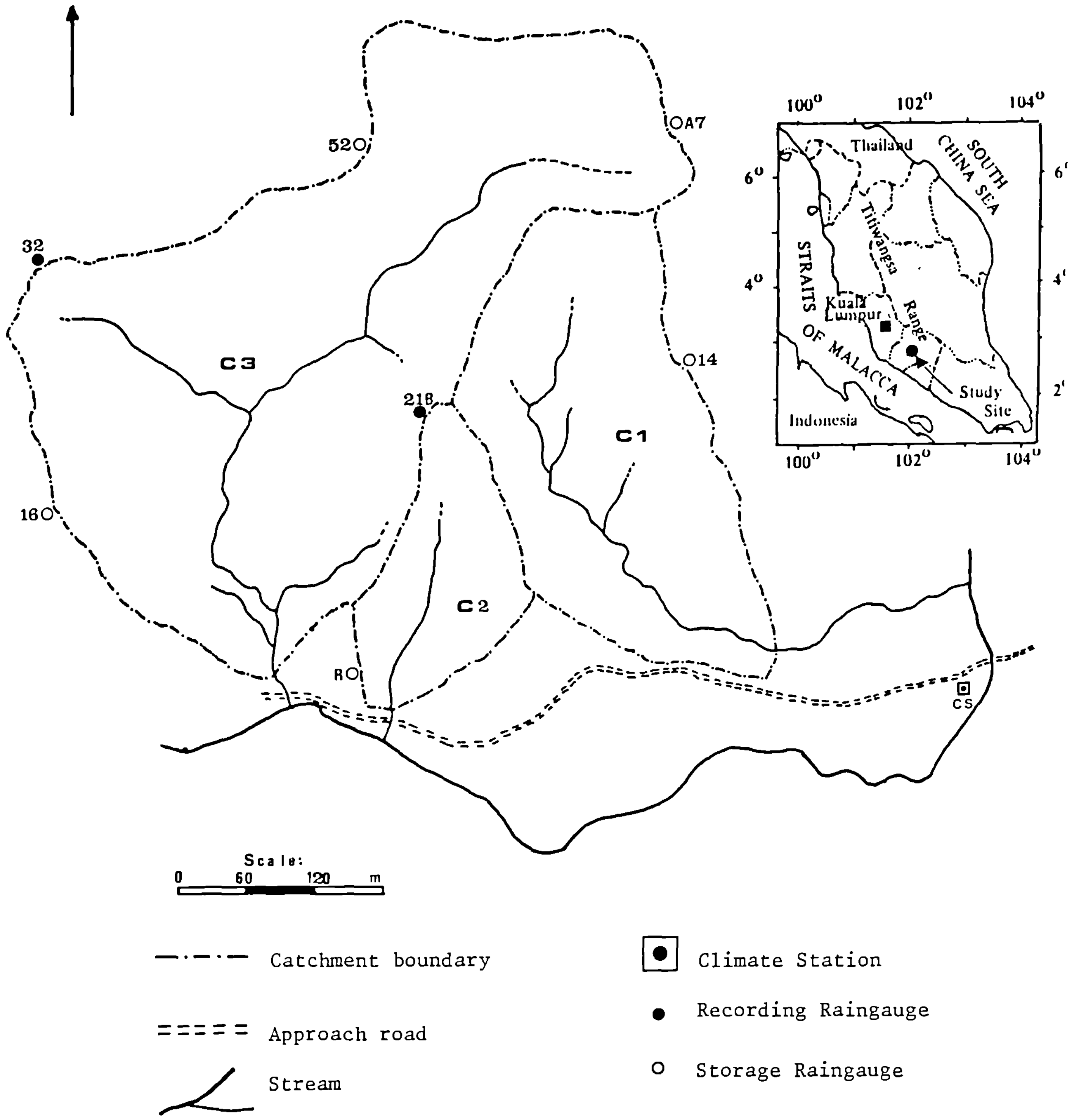


Figure 4.1 Location of Recording and Storage Raingauges in BEW

Plate 4.1 Climate station in Berembun Experimental Watershed

Plate 4.2 Recording and storage raingauges installed in BEW

One pertinent observation with regard to recording raingauges in the humid tropics is that recorders sometimes may not have the required mechanical capabilities to record very intense storms accurately. Realizing this shortcoming, WMO (1983) has warned users of this when purchasing such equipment and also in processing the rainfall charts.

4.2.3 Streamflow measurement

Streamflow discharge reflects an integration of many factors such as soil, geology and geomorphic, hydrologic and climatic factors and land use characteristics acting upon a watershed. It is perhaps the only component in the hydrologic cycle that can be measured with reasonable accuracy (Chang, 1982). Hydrologists and water resource managers are interested in measuring streamflow discharge not only for water supply, flood control or navigation but more importantly to understand the physical laws governing streamflow characteristics. Normally in a well-designed watershed study, an overflow structure is constructed across the channel to measure streamflow. For this study, a 120° sharp-crested V-notched weir has been installed at every catchment in BEW (Plate 4.3). Expected extreme flow variations in this watershed dictate the choice of this type of weir coupled with its acceptably high accuracy for peakflows. The 120° weir records higher maximum flows ranging from 0.45 to 430 l/s as compared with the 90° weir whose range is 0.20 to 240 l/s (Gregory and Walling, 1977). However, the former weir has the limitation of being easily damaged by sediment-laden discharge or floating debris (Ward, 1971).

Sites for weirs at each catchment (Figure 4.2) have been properly selected based on the following criteria:

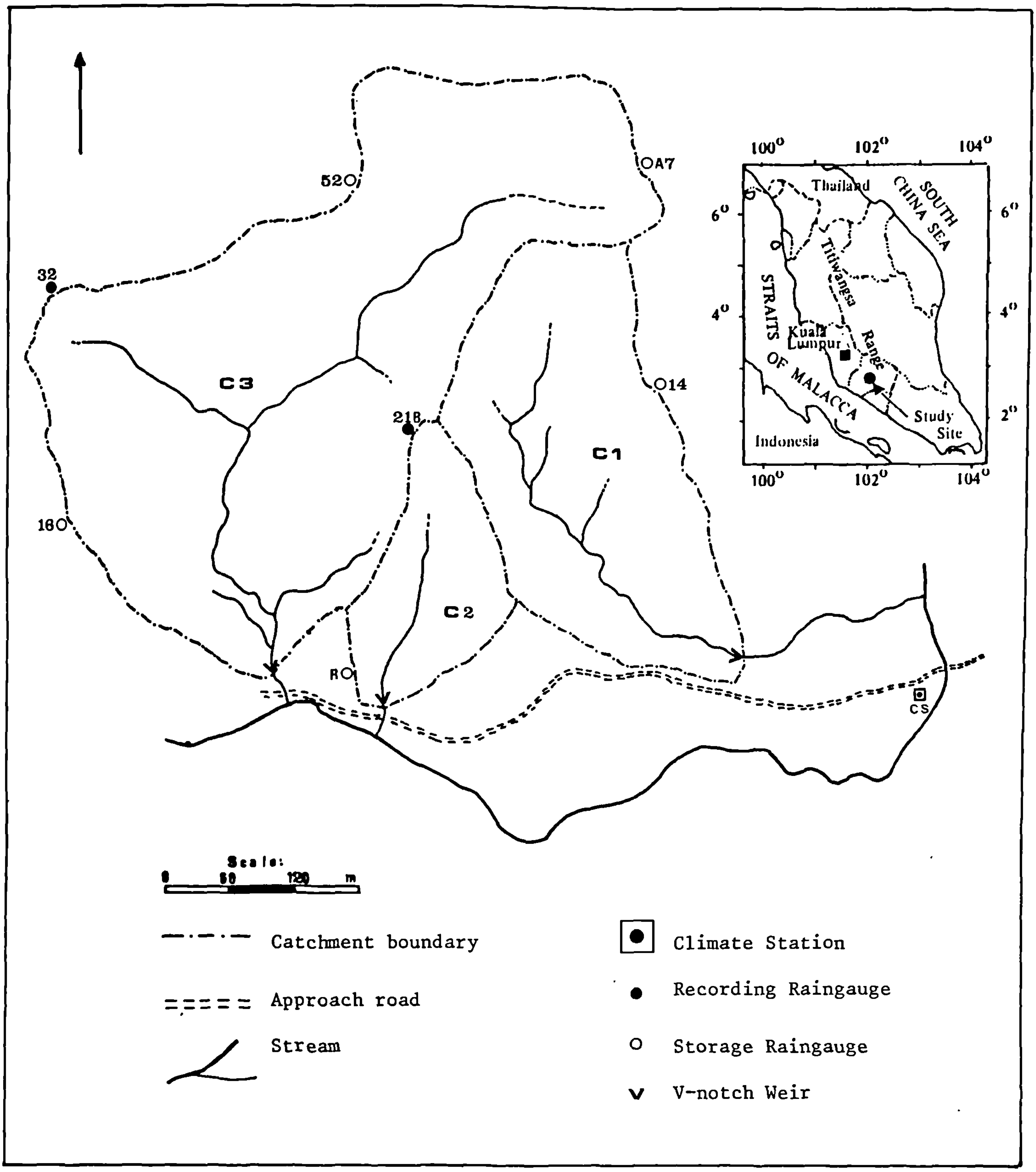


Figure 4.2 Location of three weirs in BEW

1. straight channel approach to the weir
2. well-defined channel that cuts through to the bedrocks
3. constructed on the lowest point of a catchment on an out-cropping bedrock or impermeable materials
4. preferably a channel segment of V-shape.

The cutoff wall, an important structure in the weir construction used to divert surface as well as sub-surface water, is about 1.0 to 1.5 m. Other important features in the construction of the weir are as follows: (Hornbeck, 1965; Ffoliott, 1981).

1. the centre line of the weir should be parallel to the direction of flow
2. the upstream weir blade should be sharp so that the overfalling water touches the crest at only one point.
3. the crest should be high enough for water to fall freely over it leaving an airspace under the overfalling water
4. the face of the weir must be vertical

The sediment trap is usually built behind the weir with the purpose of collecting bed-load sediment over certain time periods. The size of the sediment trap varies according to the catchment size. As such three sediment traps were constructed at the weir sites in this watershed.

Another important structure needed at the weir site is a stilling well that houses a water level recorder for monitoring of water stage (Plate 4.4). This comes with a shelter to protect the recorder from the rain as well as for security reasons. In this watershed, the stilling well is built in the sediment trap itself instead of on the bank channel. This was done to avoid the

Plate 4.3 A 120^0 V-Notch weir constructed in BEW

Plate 4.4 Stilling well and water level recorder at weir basin

possibility of blockage in the inlet pipe due to sediment load if built otherwise. Moreover, this has been a standard practice by the Drainage and Irrigation Department of Malaysia in its hydrological network (DID, 1973).

The water level recorders employed in this study are the Stevens F-Recorders using a float-type mechanism with an accuracy of ± 0.2 mm at the scale of 1:2. Initially it was operated by a spring-wound clock, but it has been replaced by a quartz clock. A 7-day chart is being used, although occasionally a 1-day chart has been used for a selected period.

Manual checks on the water level recorder are necessary and these are being done using a hook gauge mounted on a metal bar attached to an ordinary staff gauge. The staff gauge is fixed to the wall of the sediment trap whose position has been calibrated to the reduced level (RL) of each weir. Although the water level recorder is serviced every 7-day interval, a daily check on its operation is deemed necessary in case of malfunction which does happen occasionally. During the checking, staff gauge reading and time are noted down on the chart corresponding to the hydrograph trace. The above annotations are useful later on as check points whenever malfunctions occur or where there is a mis-match of time or stage between the staff gauge and the recorded time on the chart.

When replacing a new chart, normally at about 0900 hrs, the following information is noted down on the chart:

1. Catchment No. / Name
2. Date
3. Time
4. Staff gauge reading
5. Name of operator

Similar information is recorded at the end of 7 days, before replacing with a new chart. Recorded charts - better known in hydrology as hydrographs - the graphical presentation of stream stage over time, are brought back to FRIM every week for further processing.

The flow of water in a natural channel may be described in terms of its stage (height of the surface above arbitrary level), and velocity (speed with respect to channel direction) or discharge rate. These properties are inter-related, in that, for any particular stream segment, discharge is a product of area and velocity according to the continuity equation (Chow et al., 1988):

$$Q = AV \qquad \text{Equation 4.1}$$

where Q = discharge of streamflow, m^3/sec

A = the cross-sectional area, m^2

V = streamflow velocity, m/sec

With a stable channel bank and bottom, Q may be accurately related to water stage (h) and a plot of measured discharge against h at the time of measurement usually defines a smooth curve known as the stage-discharge relationship or simply a rating curve.

There are a number of methods that can be used to derive a rating curve, but in this study, a volumetric calibration method has been employed using a calibration tank of fixed or known volume. This method affords measurement of discharge even during lowflows where a current meter could not be effectively used. In addition, this method provides a practical yet fast way of measuring stormflow events which normally last for a short duration due to the flashiness of these catchments. However, extreme stormflow events occasionally did evade the calibration as the staff were not around when storms occurred.

In this instance, a volumetric calibration represents baseflow and medium - range flows and also a few peakflows up to the stage of 45 cm. Beyond this stage, a theoretical equation was employed in calculating discharge for selected stages. However, theoretical formulae would not produce reliable results for the lower stages, especially those below 6 cm (Thomas, 1957). The theoretical formula for the V-Notch weir is as follows: (Ffoliott, 1981; Hertzler, 1938; Sharp and Sawden, 1984):

$$Q = C\ (8/15)\ \sqrt{g\ 2}\ \tan a/2\ h^{2.5} \quad \ldots\ldots\ldots \quad \text{Equation 4.2}$$

$$= 2.36189\ C \tan a/2\ h^{2.5}$$

$$= 2.3932\ h^{2.5}$$

where:

Q = discharge over the weir (m^3/sec)
C = app. discharge coefficient (0.585)
g = acceleration of gravity (9.806 m/sec)
h = head (height of water above notch) (m)
a = angle of triangular weir in degrees

Based on the above computations for discharge i.e. volumetric calibration and the theoretical formula, a rating curve can be fitted satisfactorily for each weir. For the purpose of computerization, these rating curves were converted to rating tables as in Appendices 5, 6 and 7. Commenting on the accuracy of streamflow measurement using the 120° weir, Hornbeck (1965) referred to the following factors:

1. the weir blade should be sharp, smooth and clean
2. the napple should be fully aerated and should only touch the upstream edges of the weir blade
3. the velocity of approach should be less than 0.5 fps.

To achieve and satisfy the above conditions, care in construction and periodic maintenance are required.

4.2.4 Processing of rainfall charts and hydrographs

With the development of computer technology today, processing of hydrological data and charts not only becomes easier and efficient but more importantly provides detailed information frequently needed in hydrological analyses. In this study, two types of chart - rainfall charts and discharge hydrographs - require further processing by computer facilities while others such as hygro-thermograph charts are manually processed (Appendix 8 and 9). On receipt in the office, charts are scrutinised for the following errors which are noted by annotation:

i. missing data entries
ii. missing period of records
iii. unusual records

Annotation of the charts refers to the marking and checking of all letters and numbers on the charts to ensure that data records are clearly identified and accurate. In some cases, errors may be minor and can be corrected. Subsequently, rainfall charts are sent to the DID Computer Centre for digitizing and processing using the Time Dependent Data System or TIDEDA. On the other hand, discharge hydrographs are processed at FRIM Computer Centre employing an internally developed software system called DIGITFLOW (Appendix 10). This modest system operates on a minicomputer with CPU of 512 KB and 100 MB of storage capacity. At present, this system is only capable of processing charts in terms of daily, monthly and yearly stage height and discharge values.

4.2.5 <u>Soil moisture monitoring</u>

Measurement of soil moisture and other soil hydraulic properties have been fundamental to hydrological process studies particularly in an environment of high rainfall intensity such as in the humid tropics (Bonell, 1989). Although detailed soil hydraulic properties have not been measured in this study, soil moisture monitoring has been carried out simultaneously with other measurements.

Three sites were selected representing different elevations and slopes angles (Figure 4.3). In fact, the three sites, SM1, SM2, and SM3 are aligned into a straight-line transact crossing the watershed. The specific location of these sites in terms of elevation and slope are as follows:

Site	Elevation (m.a.s.l.)	Slope (%)
SM1	193	10
SM2	247	25
SM3	295	45

Soil samples from each site are taken at two-week intervals from five different depths, namely 5, 10, 20, 40 and 80 cm. A different spot on each site will be sampled during every sampling. Samples are kept in aluminum containers with a proper seal and identification before being sent to FRIM for further analysis at the laboratory.

The gravimetric method has been employed in the analysis of soil samples to compute the soil moisture percentage based on the oven-dry weight (Prichett, 1979). Bulk density measurements have been computed for various depths at each site using the core method.

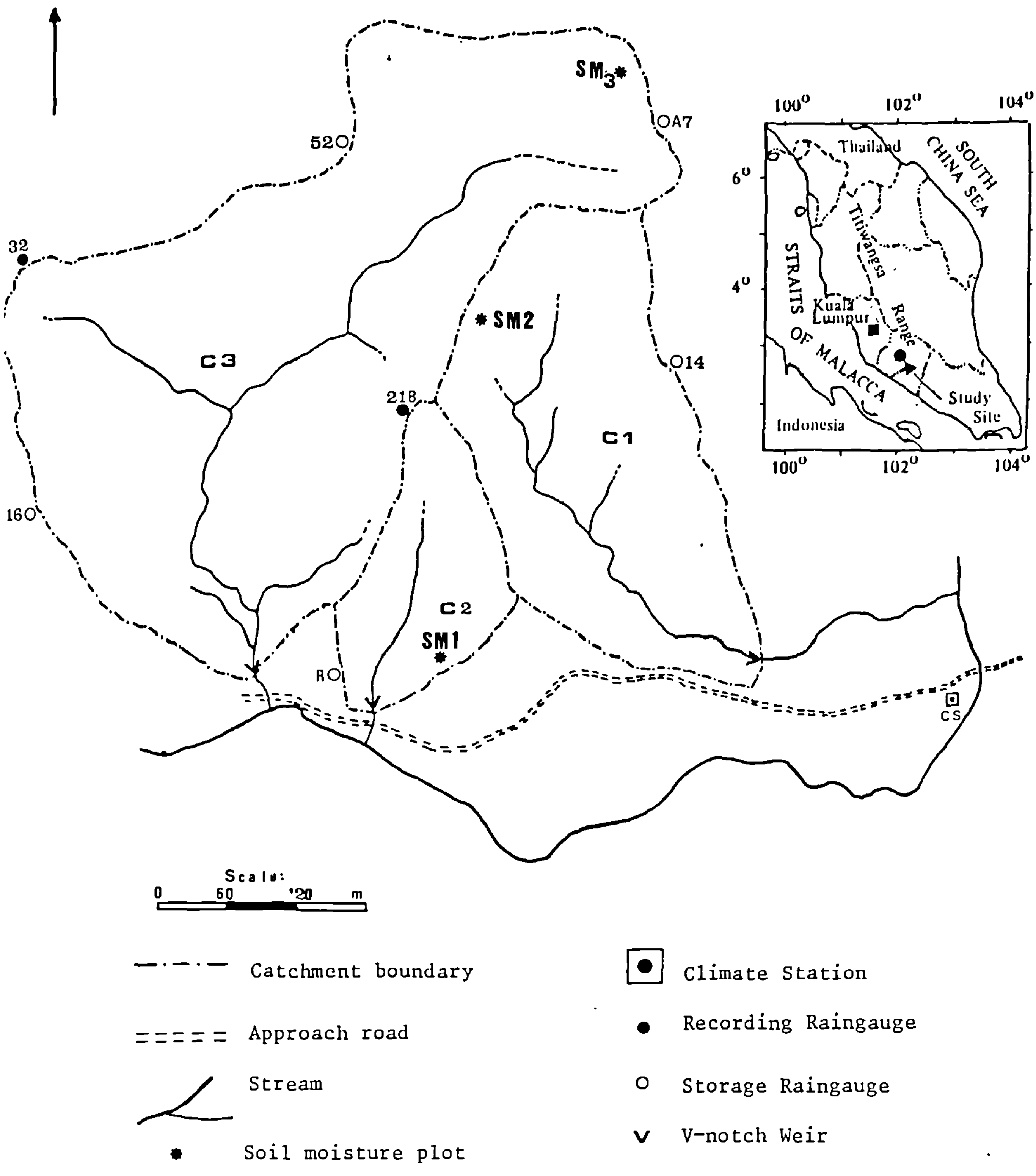


Figure 4.3 Soil moisture sampling sites in BEW

4.3 Calibration Analysis

Experimental watershed research, in particular the paired watershed, invariably involves at least three stages of experimentation, namely the calibration, treatment and post-treatment phases or periods. Each phase may assume a different time period depending upon the nature of study and also catchment land use or vegetation cover. In this study, duration for the three phases was as follows:

Phase	Duration	Activity
I	Jan 1980 - Jun 1983	Calibration Period
II	Jul 1983 - Jul 1983*	Treatment Period
III	Aug 1983 - Jun 1987	Post-Treatment Period

* 1 July - 31 July

The hydrologic year or water year, as a period of record, has been adopted in this study. The hydrologic year as proposed by the Drainage and Irrigation Department (DID) of Malaysia runs from July 1 to June 30 of the following year. Thus all data referred to in the present analysis consistently follow the above period. The beginning of the water year is usually based on months that have the least storage variation and lowest groundwater levels (Reigner, 1964).

4.3.1 Calibration approaches

In watershed research, a calibration period denotes a gathering of climatic and other variables of interest as a basis upon which to predict watershed response after treatment (Reihart et al., 1963). Basically there are three common calibration approaches in which the paired-catchment method is the most common. It may involve one control catchment and one or more treatment catchments or vice versa (Hewlett, 1970). Specifically, the calibration in this approach serves to establish a 'normal' behaviour pattern between the streamflow characteristics and other variables of the control and treated catchments. This is so because of the simple assumption that the relationship between the control and treated catchments experienced in the past will continue into the future unless some change is effected in one of them.

In another variant of the above one-to-one calibration, streamflow from a number of treated catchments may be compared with that from a number of untreated catchments (Golding, 1980). This thus eliminates the need for a pre-treatment period. Swanson and Hillman (1977) as quoted by Golding (1980) employed the above method to determine the effect of clearcutting in Alberta, Canada with only one year of data. While the approach requires a greater input of resources over the short time, results are obtainable in much shorter time, thus avoiding the risk of losing the control basin due to natural calamity such as fire.

Another approach to calibration is to use a single watershed and calibrate upon itself. This is also known as a climatic calibration (Reigner, 1964; Abdul Rahim et al., 1983). During the calibration period, the flow characteristics of interest are related to climatic variables. This method is more informative than the earlier ones because it relates streamflow data to the factors that influence it, and in addition, it costs much less. A third approach to calibration is that of double-mass curves. In this method, accumulated totals of the variable of interest are plotted against accumulated totals of the calibration variable. However, the method is not amenable to statistical analysis and an objective conclusion is difficult to reach (Ziemer, 1981; Golding, 1980; Hewlett, 1982).

In paired watersheds, the purpose of the control catchment is to serve as a climatic standard during the period of study but it is not to be misconstrued as a control on the treatment (Hewlett, 1970). In fact, the control catchment provides a better measure of climatic influence in the watershed experiment than any number of climatic variables measured individually.

4.3.2 Duration of calibration

The duration of the calibration period has been a debatable question in the past. There are, in fact, no fixed rules for determining the optimum length of observation and this largely depends on the research needs, quality of existing data and expected accuracy (Low, In Press). In this context, Wilm (1949) and Kovner and Evans (1954) have proposed analytical techniques for calculating the minimum number of years of calibration in order to obtain sufficient data for statistical analysis. The former method involves fitting regressions and analysis of covariance (AOC) to determine the minimum number of observations that are required to significantly test the differences between, before and after catchment treatment. Subsequently, Kovner and Evans (1954) simplified the method further by using a graphical approach which they claimed was much simpler, for it avoids successive iterations as in the former. Over the years, both techniques have been successfully used to detect changes in streamflow in many major watershed research programmes. However, the minimum possible period as calculated by the above method is three years otherwise the standard error of estimates becomes unacceptably large.

As watershed research requires remarkably high investment in establishment and maintenance of instruments, there is a tendency to resort to a shorter calibration period, without necessarily sacrifying statistical rigour and accuracy. Hence, instead of using yearly data as hydrologic records, monthly data have been suggested (Reinhart, 1967) and have being successfully employed in a number of studies with similar prediction accuracy as those using yearly data (Pearce, et al., 1980; Hewlett and Doss, 1984; Swindel and Douglas, 1984; Hsia, 1987). With this approach, the calibration period can be as short as one year (Hewlett and Doss, 1984) or a few hydrologic years. Thus, this approach would produce results much quicker than the traditional method yet with a lower cost due to the shorter time involved. Inevitably, this procedure invites a serial correlation in the calibration equation (Reinhart, 1967). However, much if not all of the serial correlation could be removed by introducing antecedent variables in the equation. Moreover with the development of integrated statistical software, even on micro-computers, the presence of serially correlated data could be easily detected and at the same time, adjusted to a certain extent, for example using the Durbin-Watson test (Gunst and Mason, 1980; Statgraphics, 1986).

A similar approach has been adopted in this analysis where monthly data are being used as one hydrological record, particularly in the analysis of water yield changes resulting from forest treatment.

4.3.3 Calibration equation

A number of procedures have been used to describe and predict changes in water yield as a result of the treatment of catchments. Basically these methods involve statistical analysis relating the control and treatment characteristics of interest coupled with relevant assumptions. In the early years, regression analysis, followed by analysis of covariance (AOC), were widely used in major catchment studies in the United States (Wilm , 1949; Kovner and Evans, 1954). To get a reliable result, this method requires sufficient post-treatment observation whilst meeting the homogeneity of variance in both periods as another pre-requisite.

Generally the procedure consists of fitting separate regression equations for calibration and post-treatment, always treating data from the control as the independent variable. Once a satisfactory correlation has been achieved within the stipulated calibration period as decided earlier on, regression models are developed and used to predict runoff of treated catchments from runoff and other variables of the control. Prediction models are tested for validity, accuracy and significance before being used to detect changes after treatment. In this regard, the regression technique provides the most precise unbiased estimate of the linear function of observation if the basic assumptions are met (Daniel and Wood, 1971). One of the assumptions is that data are a representative sample from the entire range about which generalizations are made.

Subsequently, an analysis of covariance is followed to find out whether the slopes of two regressions differ or only the intercepts. Based on similar principles, Chow (1960) formulated a procedure by combining them into a series of orderly steps known as the Chow Test. The above test has found increasing use in many econometric and non-econometric analyses (Gujarati, 1970).

Alternatively, Gujarati (1970; 1988) proposed a practical procedure for the same purpose called a dummy variable regression technique. In essence, this method involves comparing the residual error from a full model containing a treatment effect with a reduced model without the treatment effect by treating calibration and treatment periods in the same regression. The dummy variable (T) is assigned and coded '0' and '1' during calibration and treatment, respectively, as indicated below using runoff as a variable of interest:

During the calibration period, T=0, a reduced model results:

$$Q_t = b_0 + b_2 Q_c + E_i \qquad \text{Equation 4.3}$$

During the treatment period, T=1, a full model results:

$$Q_t = b_0 + b_1 T + (b_2 + b_3 T) Q_c + E_i \qquad \text{Equation 4.4}$$

where:

Q = observed runoff
t = treated catchment
c = control catchment
T = dummy variable
$b_0=b_1=b_2=b_3=b_4$= parameter estimates
E_i= error term

The null hypothesis that treatments have no effect on the monthly runoff is tested by the F-statistic computed from the above two analyses:

$$F = \frac{(SS_1 - SS_2)/(df_1 - df_2)}{EMS}$$

where:

SS_1 = sum of squares due to regression of full model
SS_2 = sum of squares due to regression of reduced model
df_1 = degree of freedom associated with full model
df_2 = degree of freedom associated with reduced model
EMS = error mean square of full model

Evidently, the above method offers certain advantages over the Chow Test and AOC as summarized by Gujarati (1970):

1. it clearly points out the sources of difference whether intercept or slope or both.
2. it affords use of additive and multiplicative dummies as alternatives to using AOV and AOC
3. it provides shorter steps of analysis through only one regression equation as compared with multi-stage in the Chow test or AOC.

In recent years, this technique has been increasingly employed in the analysis of paired watershed research data while permitting a shorter calibration period of even one year (Hewlett et al., 1984; Swindel and Douglas, 1984) or slightly more than one year (Hsia, 1987; DID, 1986; Shih and Chen, 1988)

4.4 Watershed Treatment

After completion of a stipulated calibration period, selected catchments will undergo some kind of treatment depending on the objectives of the study and also the type of vegetation cover. Treatment can be in the form of forest clearcutting, forest conversion to other land use, silvicultural practice or selective cutting, either prescribed on the entire or partial area of the watershed. Other related activities normally implemented during the treatment exercise are construction of roads and culverts, extraction of timber and also site preparation in the case of reforestation.

Treatment specified in this study involves a selective forest logging as being the most common method of forest harvesting and management in Malaysia (Yusuf, et al., 1987; Ministry of Primary Industries, 1988). Therefore a brief background of the forest management system practiced in the hill forest of Malaysia is of relevance.

4.4.1 Forest management in Malaysia

In the early 1970s, the Forestry Department of Peninsular Malaysia, whose role is to advise and co-ordinate forestry development activities, introduced the Selective Management System (SMS) to replace the former system, the Malayan Uniform System (MUS). The latter system has been successfully implemented in the lowland rainforest since 1955 (Forestry Department Peninsular Malaysia, 1972). The SMS involves harvesting of marketable trees above a specified diameter at breast height (DBH) and retaining adequate advance regeneration for subsequent harvestings. The cutting limits are determined separately for different areas, and are largely based on the timber stocking and volume as determined in a pre-felling inventory.

Analyzing the supply-demand scenario of forest resources in Peninsular Malaysia, Thang (1984) estimated that two-thirds of the primary forests and one-third of reloggable secondary forests will be managed on a 30-year cutting cycle with a mean annual increment (MAI) of 2.55 m^3/ha/yr and the remainder of the forests on a 55-year cutting cycle with MAI of 1.75 m^3/ha/yr. In prescribing the SMS, the Forest Department of Peninsular Malaysia (1985) calls for a four-step procedure:

1. pre-felling inventory
2. tabulation and analysis of inventory data
3. simulation of various cutting regimes
4. selection of the most appropriate management regime.

Yusuf, et al., (1987) elaborated on the various steps in further detail; however, the fourth step is worth mentioning at this juncture. In effect, the selection is based on two major prerequisites:

1. the harvest volume/ha must be 'economic'- that is profitable for the loggers
2. there must be at least 32 sound stems of equivalent trees per ha of fully and partially marketable trees in the residual stand.

From the forest management point of view, the SMS offers a more flexible system than the earlier ones for managing the hill forests on a sustained yield basis.

In harvesting practice, a permitee or logger is guided by two standard guidelines in an effort to minimize the detrimental effects on the environment, namely Forest Harvesting Guidelines and Standard Forest Road Specifications. The two guidelines provide among others, specifications pertaining to tree marking, directional felling, road construction, alignment, gradient and location of landings. At the same time, the Forest Department's role is to provide close supervision and advise on some conservation measures to be undertaken during the harvesting operations. However, the major short-coming of the above guidelines is that specifications formulated are not based on rigorous research but are intuitively imposed, conceivably deduced from experience at other places. Therefore, despite its benign intention of safeguarding the environment, the guidelines still lack a scientific basis in their formulation which could ultimately invite criticism and could even encourage inappropriate practice.

4.4.2 Recommended Guidelines during treatment

In this study, two methods of selective logging, namely supervised and unsupervised methods, have been prescribed in the two catchments, C1 and C3. Adequate conservation measures were imposed and instituted in C3, whilst C1 was logged with a commercial selective logging as normally prescribed and practiced in the hill rain forest of Peninsular Malaysia.

In devising recommendations for logging in C3, pertinent conservation measures are implicitly introduced while incorporating some of the present guidelines, categorised into four major areas:

1. Road planning and construction
2. Logging operations
3. Landings, and
4. Maintenance of roads

Detailed specifications on the above four categories are given in Appendix 11, while the prominent features prescribed are summarized in Table 4.2. Figure 4.4 shows the road system constructed in both

Table 4.2 Logging prescriptions in catchment 1 and catchment 3 of BEW

Prescriptions	C1 (Unsupervised)	C3 (Supervised)
1. Cutting regimes (cm, at dbh)		
-Dipterocarp	60	90
-Non dipterocarp	45	60
2. Stocking removed (%)	40	33
3. Road planning	not specified except what is in the permit	-road area <6 % -road grade 20% -culvert if road crosses stream -cross-drains installed along logging road
4. Road system (km/ha)		
-Logging road	0.06	0.07
-Skid trail	0.08	0.03
5. Buffer strip	not specified	20 m from each side of the stream
6. Area disturbed (%)	11.0	9.0

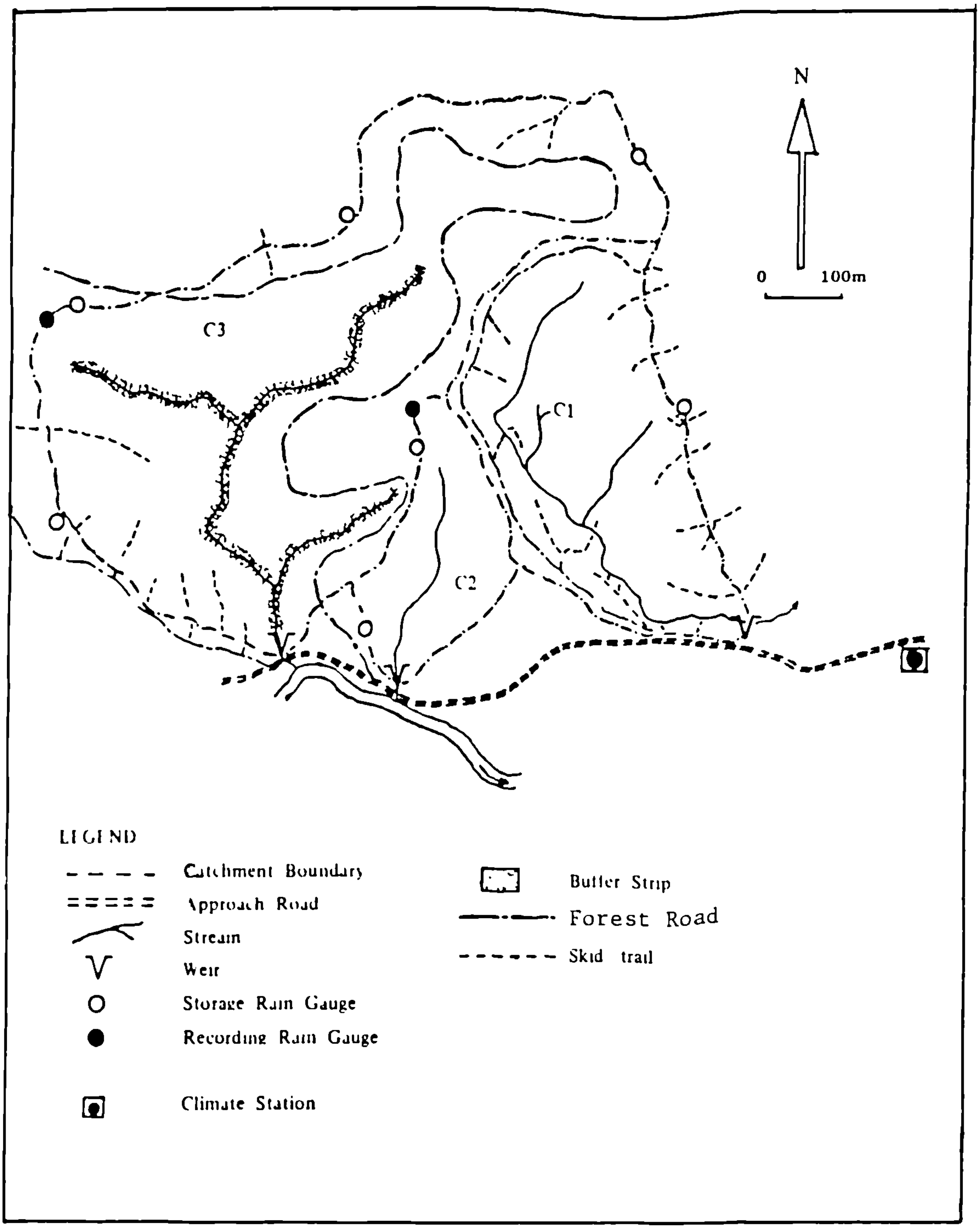


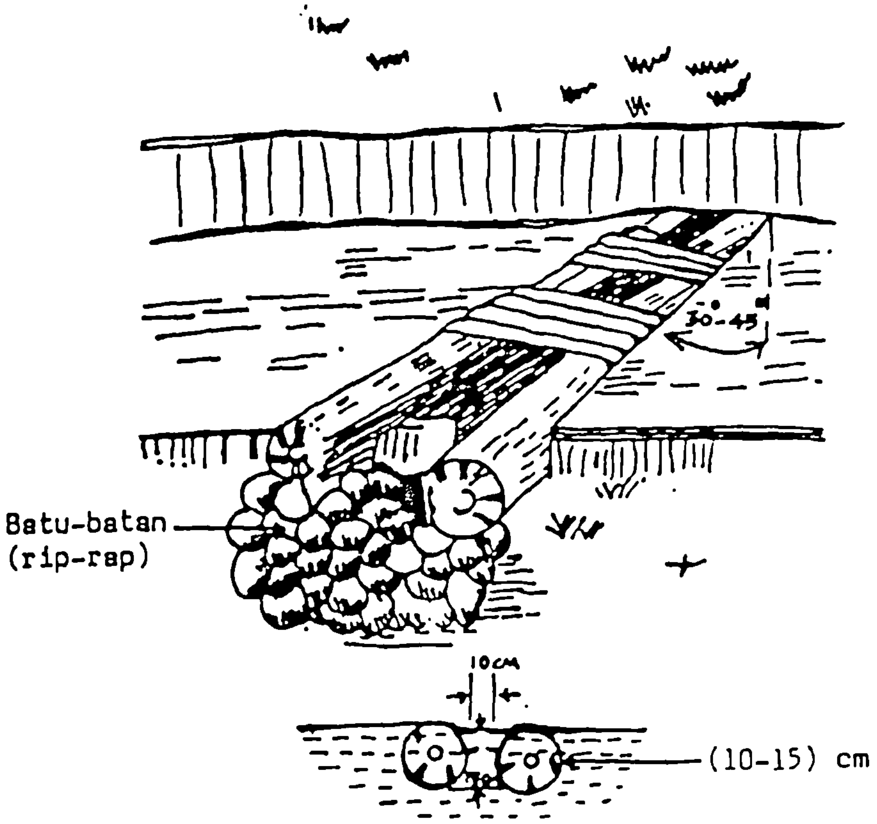
Figure 4.4 Forest road network in catchments 1 and 3 at BEW

catchments while Figure 4.5 shows the designs of cross drains installed on the road.

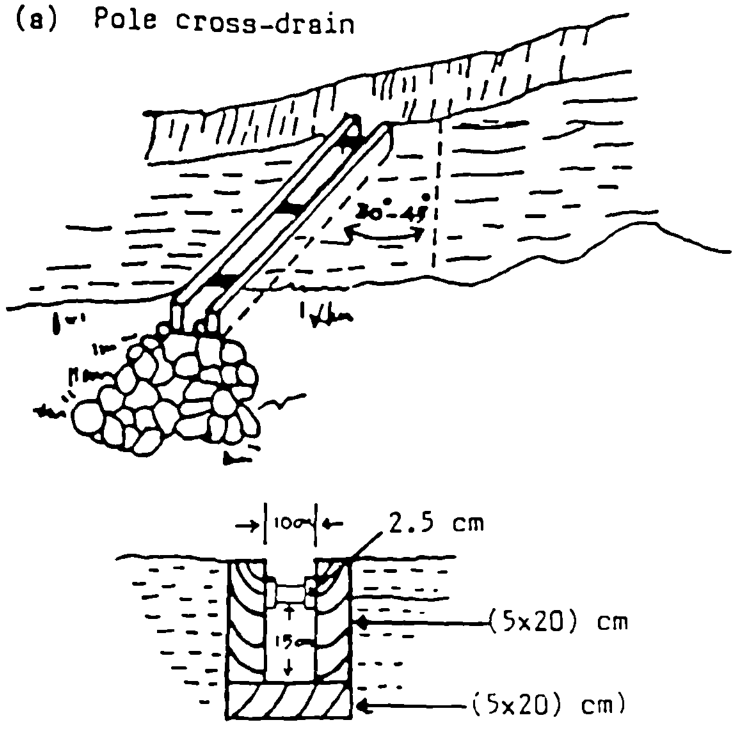
4.5 Conclusion

Watershed research has been widely adopted in many places as the most logical and scientific approach to elucidate the effects of land use change on hydrological parameters. In fact, it has significantly contributed to the detailed understanding of cause and effect relationships of land use modifications within the hydrological cycle. This is especially true in temperate areas where it has also, to a certain extent, assisted in the understanding of hydrological processes operating within catchments. Despite some weaknesses and disadvantages inherent in this method, its role in hydrological research remains important and amenable to further improvements, taking into account the vast experience gathered in the past based on this method. One of the practical improvements includes the adoption of a shorter calibration period, thus reducing cost of establishment in addition to getting relatively quicker results.

Adequate instrumentation in watershed research forms a major pre-requisite to obtain high quality and valid results. Nevertheless, inherent climatic conditions and physical features prevailing in the humid tropics dictate the level of sophistication in the instruments used. In particular, with high rainfall intensity and extreme humidity, robust and reliable yet inexpensive equipment is invariably needed. In such environments, therefore, intensive and operational data monitoring and collection systems are required. Otherwise, data collected can be unrepresentative and inadequate for rigorous analysis.



(a) Pole cross-drain



(b) Box cross-drain

Figure 4.5 Line drawings of two types of cross drain installed in Catchment 3, BEW

Fortunately, with all necessary equipment required for a well-designed catchment study installed at BEW, an excellent opportunity existed to conduct detailed hydrologic research representative of Malaysian conditions, and indeed of the humid tropics of the ASEAN region.

As forest land area in the humid tropics is rapidly reduced due to unscrupulous exploitation of the past decades, the need for a sustainable system of forest management that entails minimal damage to watershed resources is greater than ever. A selective logging method with implicit consideration of hydrologic responses should be promulgated as an alternative to the present commercial logging that is devoid of any significant conservation measures. The supervised logging method as prescribed in this study undoubtedly affords a unique opportunity to work towards the multiple use of forested watersheds especially in the humid tropics.

Pertinent results derived from this study spanning three years of calibration and four years of post-treatment period will be presented and discussed in the following chapter. In particular, the chapter presents the results and relevant analyses of rainfall, discharge, evapotranspiration and soil-moisture characteristics whilst depicting the significant effects of the treatment operations on selected variables.

CHAPTER 5

HYDROLOGICAL ANALYSES AND CHARACTERISTICS

Measurement of hydrological parameters is essential in the understanding of catchment processes and characteristics. However, measurement itself is normally just the prelude to detailed processing, analysis and evaluation of the data collected. In this instance, the analysis of hydrological data normally involves computation of pertinent indices including areal values of relevant variables, frequency distributions, variation of catchment responses both in space and time and relationships among variables. In addition, pertinent statistical analyses of the processed data are invariably required in order to provide certain inferences about the data as well as their significance levels.

5.1 Rainfall Characteristics

Rainfall parameters vary in space and time and largely depend on the general climatic pattern and on local factors. Rainfall constitutes the most important input component in the hydrological cycle. Hence, rainfall analysis becomes essential not only for describing its areal distribution and frequency, but also for subsequent applications in many disciplines. According to WMO (1974) two purposes of interpreting rainfall are, firstly, to evaluate the observations which sample rainfall events and secondly, to analyze observed measurements for subsequent uses and applications. Assessment of error in catch or deficient gauge exposure, normally considered in the first category, are beyond the scope of the present analysis. Basically the analysis of rainfall records involves three major elements, namely parameters of depth, intensity and spatial and temporal variations (Gregory and Walling, 1977).

5.1.1 Areal rainfall depth

Areal rainfall or average rainfall depth in mm over the watershed area for BEW is computed using the arithmetic mean method based on the three recording rain gauges, namely the Climate Station (CS), Station 21B (S21) and Station 32 (S32) (Figure 4.1) (Appendix 12). Resorting to recording gauges allows the use of computer facilities in the analysis of rainfall charts, and is thus consistent with the subsequent analyses of hydrographs which invariably involve a great deal of computer processing. The data from storage rain gauges are only used as check gauge data in the processing of rainfall charts.

Computation of areal rainfall for each catchment employs the following recording stations based on their relative location in respective catchments:

C1 - CS and S21

C2 - S21

C3 - S21 and S32

a. Annual totals

In this study, the normal annual rainfall based on the nearby station, Kuala Pilah, 15 km away, is 1902 mm using 50 years of record. This station has been maintained by DID since the 1920s.

Monthly and annual rainfall totals of the three catchments based on seven hydrologic or water years, 1980/81 to 1986/87, are given in Table 5.1. Although actual measurement of rainfall began in

Table 5.1 Monthly and Annual Rainfall (mm) of Three Catchments at Berembun Experimental Watershed (BEW)

WT.YR.[1]	CATCH.	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	TOTAL
	BC1	150.0	185.8	243.5	205.3	299.0	175.5	51.8	240.8	167.3	352.5	352.5	41.5	2465.3
1980/81	BC2	119.5	215.5	250.0	203.5	323.0	184.5	60.0	251.0	172.5	379.0	391.5	39.5	2589.5
	BC3	143.0	204.5	264.0	210.3	324.5	191.3	60.0	263.8	164.5	374.5	370.0	40.8	2611.0
	BC1	27.3	42.8	322.5	97.6	231.8	163.0	21.0	44.5	271.8	379.0	96.0	125.0	1822.1
1981/82	BC2	23.0	45.5	327.0	102.1	229.0	157.5	19.5	35.5	279.0	352.5	86.5	129.0	1786.1
	BC3	19.8	40.0	355.0	91.8	230.5	149.5	21.8	44.5	290.5	352.3	89.0	137.8	1822.3
	BC1	105.3	75.3	96.8	273.5	355.3	89.0	88.5	21.5	6.0	115.0	93.8	122.8	1442.5
1982/83	BC2	102.0	70.0	89.5	266.0	377.5	106.0	101.5	22.5	5.0	131.0	71.0	120.0	1462.0
	BC3	93.5	74.0	79.3	282.5	356.8	120.5	94.5	19.8	5.8	120.0	82.0	124.8	1453.3
	BC1	185.0	169.0	191.3	234.3	246.0	163.3	164.8	404.0	201.8	122.5	221.3	106.8	2409.8
1983/84	BC2	195.5	171.5	212.5	249.5	252.0	171.5	173.5	417.5	216.5	127.5	227.5	102.5	2517.5
	BC3	180.0	167.3	197.5	227.8	245.0	170.0	177.8	396.8	202.8	116.5	215.8	106.3	2403.3
	BC1	119.0	103.5	150.8	219.8	452.5	237.5	59.8	177.0	132.8	115.8	240.3	10.5	2019.0
1984/85	BC2	110.5	107.5	145.5	234.5	493.0	261.5	59.5	167.5	131.0	119.5	265.5	12.5	2108.0
	BC3	112.5	115.5	154.5	225.5	506.3	243.0	50.8	169.5	116.0	116.8	237.0	13.3	2060.5
	BC1	156.3	23.5	127.5	231.5	309.3	333.0	213.8	129.8	277.0	281.8	274.0	38.0	2395.3
1985/86	BC2	168.0	28.0	132.0	229.5	312.5	347.0	245.0	141.0	291.5	283.0	289.0	38.0	2504.5
	BC3	165.5	24.0	128.3	212.5	308.8	324.8	235.5	118.8	268.2	291.0	278.5	38.5	2394.2
	BC1	135.0	46.3	247.5	285.3	278.0	255.8	71.8	7.8	132.8	234.3	275.3	128.0	2097.5
1986/87	BC2	146.5	46.5	268.5	298.0	279.5	267.0	68.5	9.0	141.0	272.5	272.5	142.5	2212.0
	BC3	130.8	42.0	246.0	281.8	277.5	236.5	61.3	8.0	132.0	254.5	261.3	128.5	2060.0

[1] Water Year

February, 1980, the hydrologic year for this study only commences in July. The annual totals for the above period range from 1442 to 2611 mm, with a mean of 2126 mm (Figure 5.1). Water years 1980/81, 83/84 and 85/86 can be considered as wet years with annual totals fluctuating about 35, 28 and 27% higher than the normal rainfall or annual rainfall data averaged over many years, respectively. On the other hand, the water year 82/83 was a dry year with rainfall 24% below the normal. However, the occurrence of wet and dry years in this region is largely related to natural variations, which are highly unpredictable. Variations in the total among catchments are acceptably low and seldom exceed 5% of the catchment's mean. This apparently reflects the adequacy of the arithmetic mean method in computing areal rainfall for this particular watershed.

The rainfall regime over a greater part of Peninsular Malaysia closely follows the general wind pattern (Wycherley, 1967), especially the tropical easterlies where a low pressure prevails due to the generally strong heating in the equatorial zone. This normally gives rise to the so-called Inter-Tropical Convergence Zone (ITCZ) resulting from the flow convergence of air masses from both the northern and southern hemisphere at the equator (Lauer, 1989). In addition, distance from coastline and topographical features also profoundly influence the distribution of rainfall on an areal basis. The rainfall within the tropics usually shows a characteristic vertical distribution as a function of height above sea level. However, as a result of the primarily convective and orographic type of rainfall, the zone of highest rainfall is located at altitudes between 800 and 1500 m.a.s.l. The highest rainfall recorded in Peninsular Malaysia is 4154 mm in the Maxwell Hill area of Taiping, Perak (1036 m.a.s.l) (Oldeman and Frere, 1982).

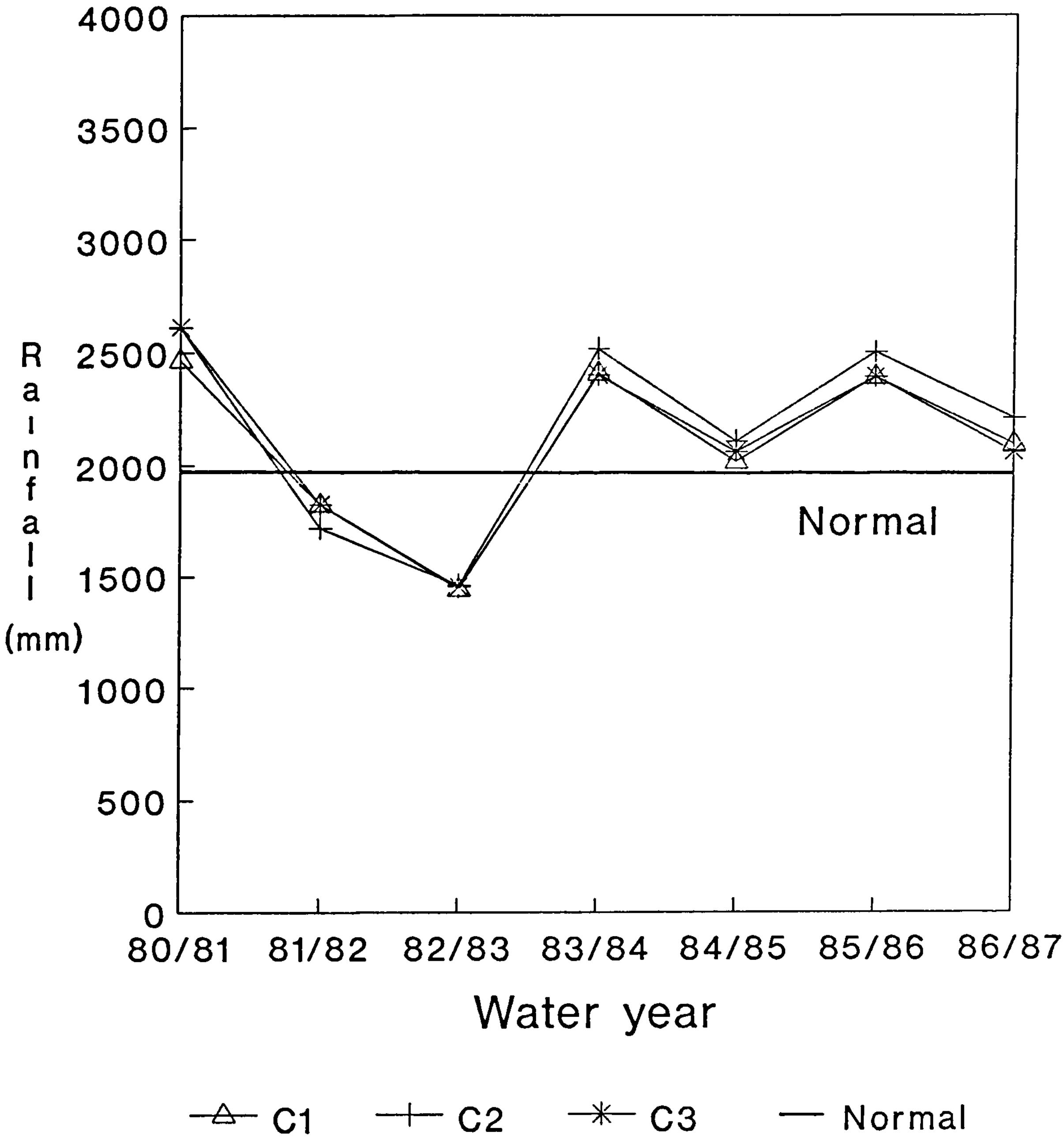


Figure 5.1 Annual rainfall (mm) at BEW and the normal at Kuala Pilah, Negeri Sembilan

b. Monthly totals

The monthly rainfall pattern of BEW generally shows a double-maxima or two-peak distribution which normally coincides with the north-east monsoon and the transitional period (Figure 5.2) (Abdul Rahim, 1983). The two maxima occur in the months of November and April. However, the peak in November is higher than the latter. As expected the normal monthly rainfall also exhibits a similar pattern but with slightly lower maximum values. The highest monthly rainfall total is 506 mm in 1984/85 whilst the lowest is 5.0 mm in 1982/83 which is considered a dry year. The monthly mean of the entire watershed is 177 mm with the coefficient of variation (CV) of 4.0%.

The rainfall regime portrayed above is in agreement with the description of Beckinsale (1969) regarding equatorial areas which to a certain extent follow Koppens's scheme of classification. The author described the above pattern as the 'equatorial double-maxima', characterized as having the heaviest rains in Spring and Autumn following the equinoxes and there is no apparent distinct dry season. Other regions exhibiting these characteristics besides South East Asia are the Upper Amazon and the main valley of the Congo lying athwart the equator.

It is the annual course of the sun between the Tropic of Cancer and Capricorn which results in the above phenomena. In principle, two maxima occur in the annual rainfall at the equator shortly after the sun has passed the equinoxes (Lauer, 1989). However, the above regular cycle often deviates to a certain extent, largely depending on the land to water distribution ratio, the types of relief and altitude, the exposure and the circulation regime.

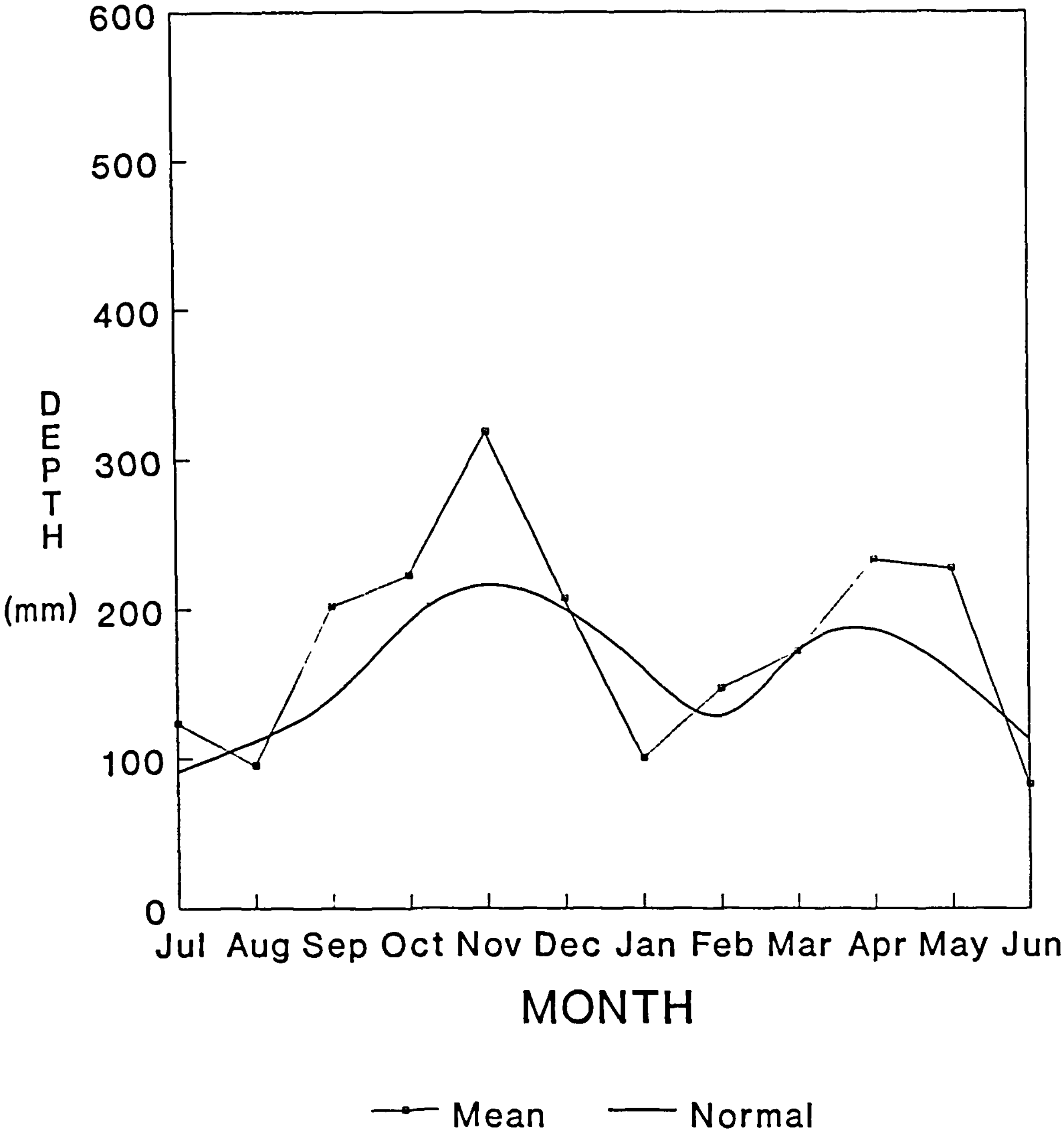


Figure 5.2 Mean monthly rainfall (mm) at BEW and the normal at Kuala Pilah, Negeri Sembilan

c. Raindays

The average number of raindays per year is 163 and the highest number per month is 20, this normally occurring during the north-east monsoon (October to December). November usually records the highest raindays whilst January has the lowest (Figure 5.3). A slightly higher number of raindays, 168, is recorded at the Jengka Experimental Watershed, Pahang (Abdul Rahim, 1983). Interestingly, the mean number of raindays closely follows the monthly pattern of rainfall observed in the area.

The rainfall pattern of BEW is typical of the 'west region' type as described by Dale (1959). November is the peak period of the north-east monsoon while April corresponds with the transitional period during which winds are light and variable.

5.1.2 Rainfall Frequency

Rainfall frequency of various magnitudes is important in assessing the susceptibility of sites to hydrological impacts and also in determining the required capacity of engineering structures. However, the analysis of rainfall occurrence largely depends on the length of rainfall record for which the information is required (Shaw, 1983). For example, in engineering applications, a frequency analysis should be avoided when working with data sets shorter than 10 years (Viessman et al., 1977). But as the present study only deals with impacts of catchment treatment, a frequency analysis will be based on either storm or daily and monthly totals. A similar approach has been adopted in analyzing rainstorm characteristics affecting water availability for agriculture in Nigeria (Oguntoyinbo and Akintola, 1983).

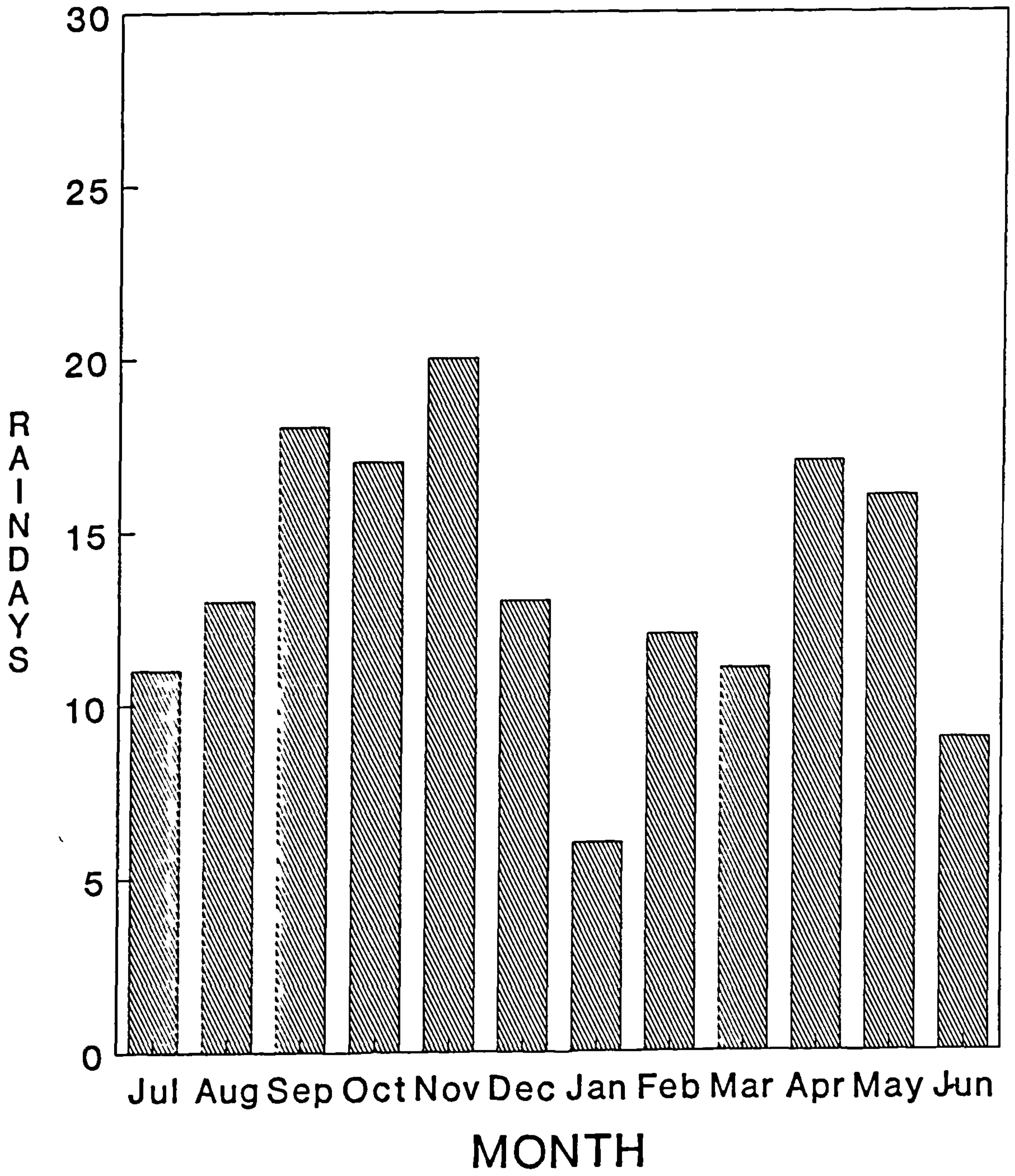


Figure 5.3 Mean monthly raindays at BEW

Data from storage gauges will not be used directly in the analysis as their totals do not provide information on the time of occurrence. Instead, the analysis entirely uses data taken from automatic rain gauges that identify the incidence of rain coupled with rainfall quantities as related to time.

A rain or storm event can be defined differently, mainly depending on the purpose of the analysis and the availability of data, and other factors. Hewlett and Helvey (1970) working at Coweeta, USA defined a storm as the rain depth that was capable of producing an effective hydrograph record and that this was 20 mm. Conversely, Oguntoyinbo and Akintola (1983) in Nigeria considered a storm to be an amount of 12.5 mm or greater, simply because of the practicality of extracting data from charts. In the present analysis, a storm event of 5 mm and greater will be used and analysed. On this basis, a preliminary analysis of three-year data indicated that more than 75% of rainfall amounts fall in this category (Abdul Rahim, 1983). For this purpose, only data from the Climate Station (CS) are used for a detailed analysis as this data set is more complete than those for the other two stations.

a. Yearly frequency

Based on a seven-year period, the total number of storms equal to or greater than 5.0 mm at CS amounts to 710. The yearly frequency of storms shows a quite variable pattern (Figure 5.4). To a certain extent, it seems to follow the pattern of the annual rainfall, in that the water year 1982/83 records the lowest percentage of storms over the 7-year period. On the other hand, the water year 1980/81 records the highest number of storms amounting to 152. The storm characteristics displayed by this station obviously resemble those of

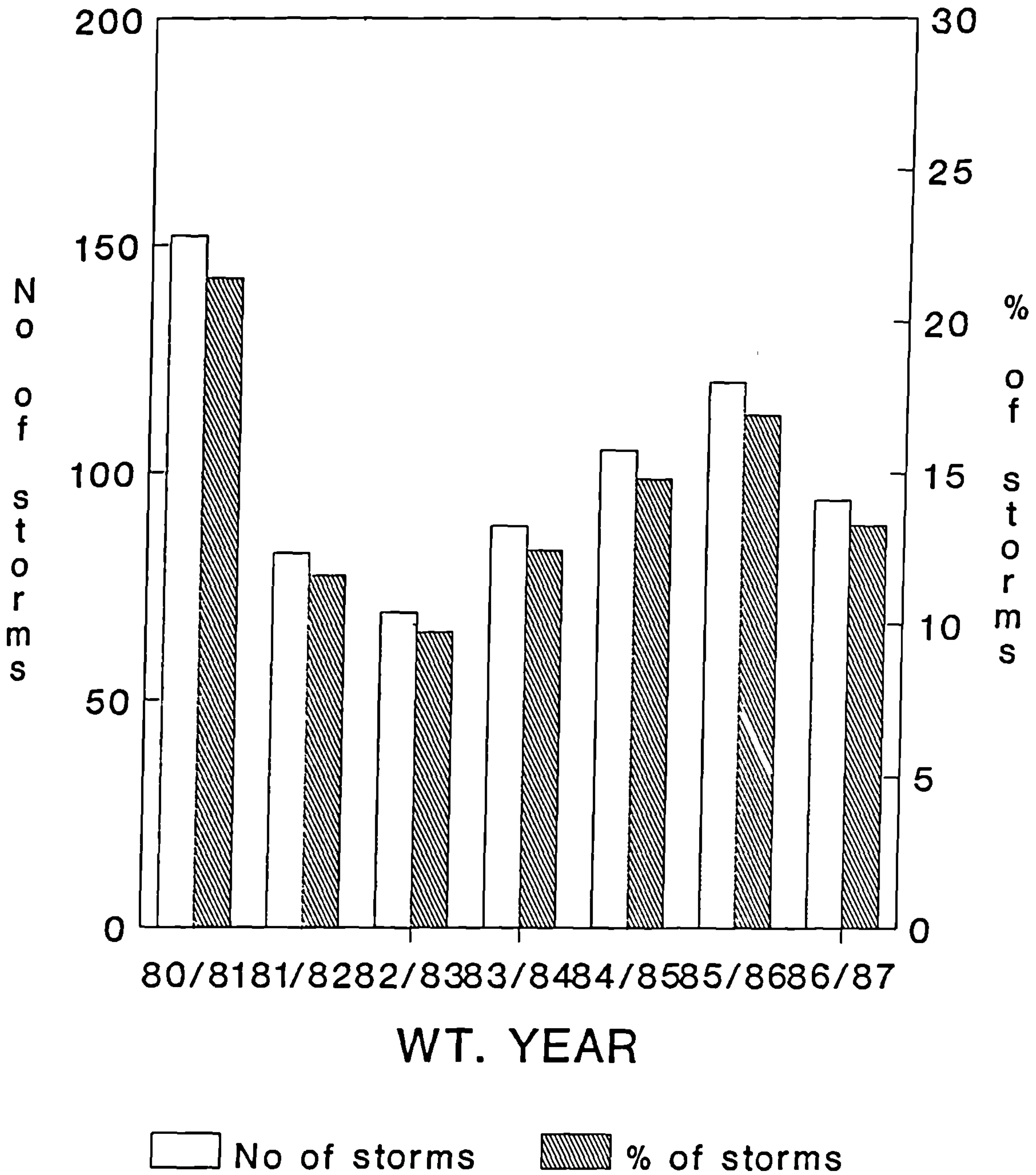


Figure 5.4 Yearly storm frequency (≥5.0 mm) at BEW

the other stations, S21 and S32. Similar patterns are observed at the Jengka Experimental Watershed which falls in the same rainfall region as classified by Dale (1959).

b. Monthly frequency

Monthly frequency of storms ≥ 5.0 mm, computed using 7 years of data, indicates a double -maxima pattern, resembling that of the monthly areal rainfall (Figure 5.5). November receives the highest number of storms, 120 or 15%, and the lowest is in June, which records less than 4% of the annual total. The mean monthly value is 59 storms. It can be seen that the figure also depicts another interesting pattern of the rainfall regime with regard to the so-called 'dry-months. Two prominent periods can be identified, the first beginning from June to August and the second from January to February, with an average number of storms of less than 5% per month. The above storm pattern coincides with the beginning of the water year adopted, from July to June, but not, interestingly, with the calendar year January to December.

c. Diurnal storm frequency

Frequency analysis of diurnal rainfall indicates that most storms occur during the late afternoon and early evening; this is highly characteristic of convectional rainfall (Figure 5.6) (Lauer, 1989). Specifically, about 50% of rainstorms occur between 1500-2100 hrs, and more than half of these occur during 1500 - 1800 hrs. (Figure 5.6). A similar diurnal storm pattern , using eight time class intervals, is exhibited in Ibadan, Nigeria which also experiences a convectional rainfall pattern (Oguntoyinbo and Akintola, 1983). The above periodicity of diurnal rainfall can be

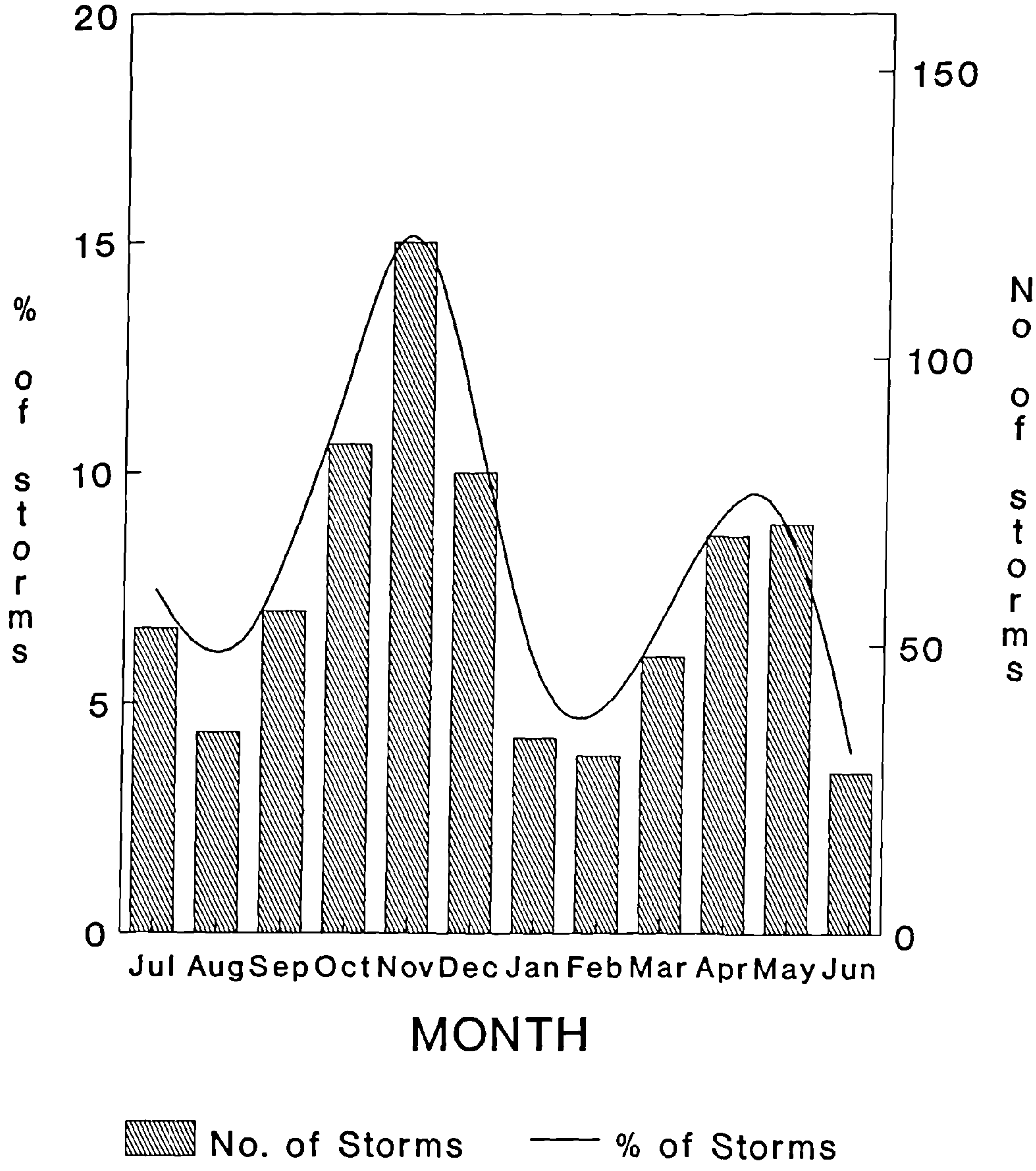


Figure 5.5 Monthly storm frequency (≥5.0 mm) at BEW

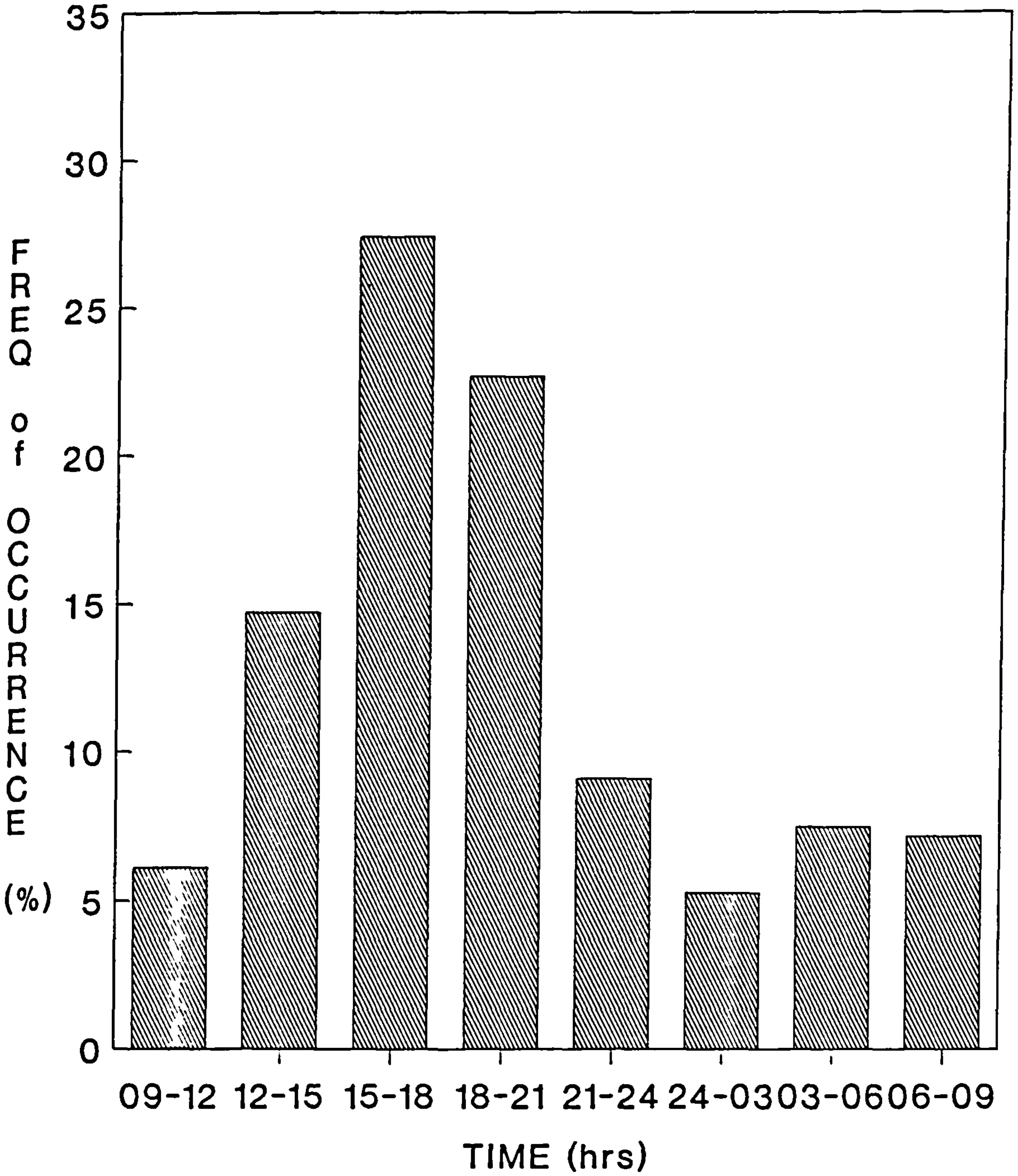


Figure 5.6 Diurnal rainfall frequency (≥5.0 mm) at BEW

attributed to the fact that the rains will set in only after the time of daily maximum convection following the sun's zenithal position. In most cases, the mountain slopes and inland regions attain their maximum rainfall earlier in the afternoon whilst towards the coasts, the daily maximum of convectional rainfall is normally shifted into the evenings.

5.1.3 Frequency based on daily and monthly totals

Occurrence of a particular rainfall pattern, based on daily and monthly totals, is computed for this watershed using seven years of record. In this case, a daily total of 2 mm or more is arbitrarily considered. A J-distribution curve of daily rainfall frequency is observed, indicating that a lower rain depth category has much higher frequency of occurrence (Figure 5.7). A similar distribution emerges when using data for individual years, for instance 1984/85 and 1986/87 (Figure 5.8). On the other hand, when considering frequency of monthly values, a weak skewed positive curve is observed (Figure 5.9). Conceivably, it is an inadequate number of months used in this particular analysis that prevents this from showing a smooth positive curve. A normal curve would appear should annual frequencies be computed when using an adequate number of records. However, the rather short period data available from this study does not afford such computation.

Essentially, the above analysis indicates that the frequency distribution of rainfall and its statistical properties can be used as a reliable tool in assessing the probability occurrence for water resource evaluation purposes (Shaw, 1983). However, some kind of transformation of the original non-normal rainfall is required to convert it to a normal distribution. Although such an analysis is

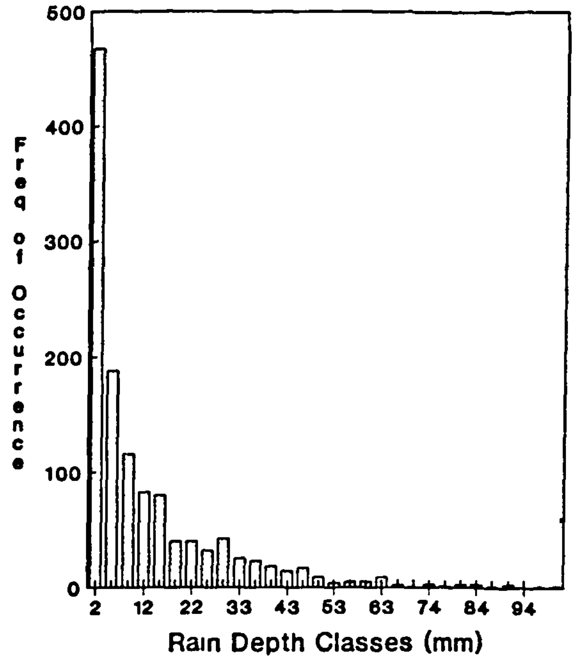


Figure 5.7 Rainfall frequency based on daily totals at BEW

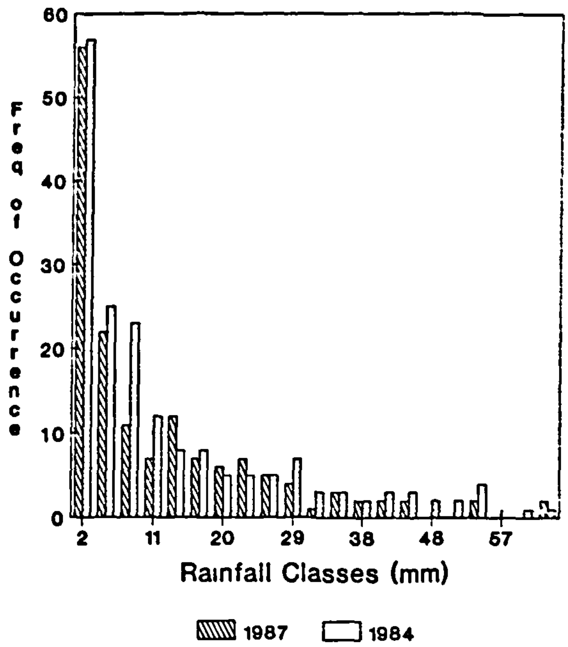


Figure 5.8 Rainfall frequency based on daily totals for water years 1984/85 and 1986/87

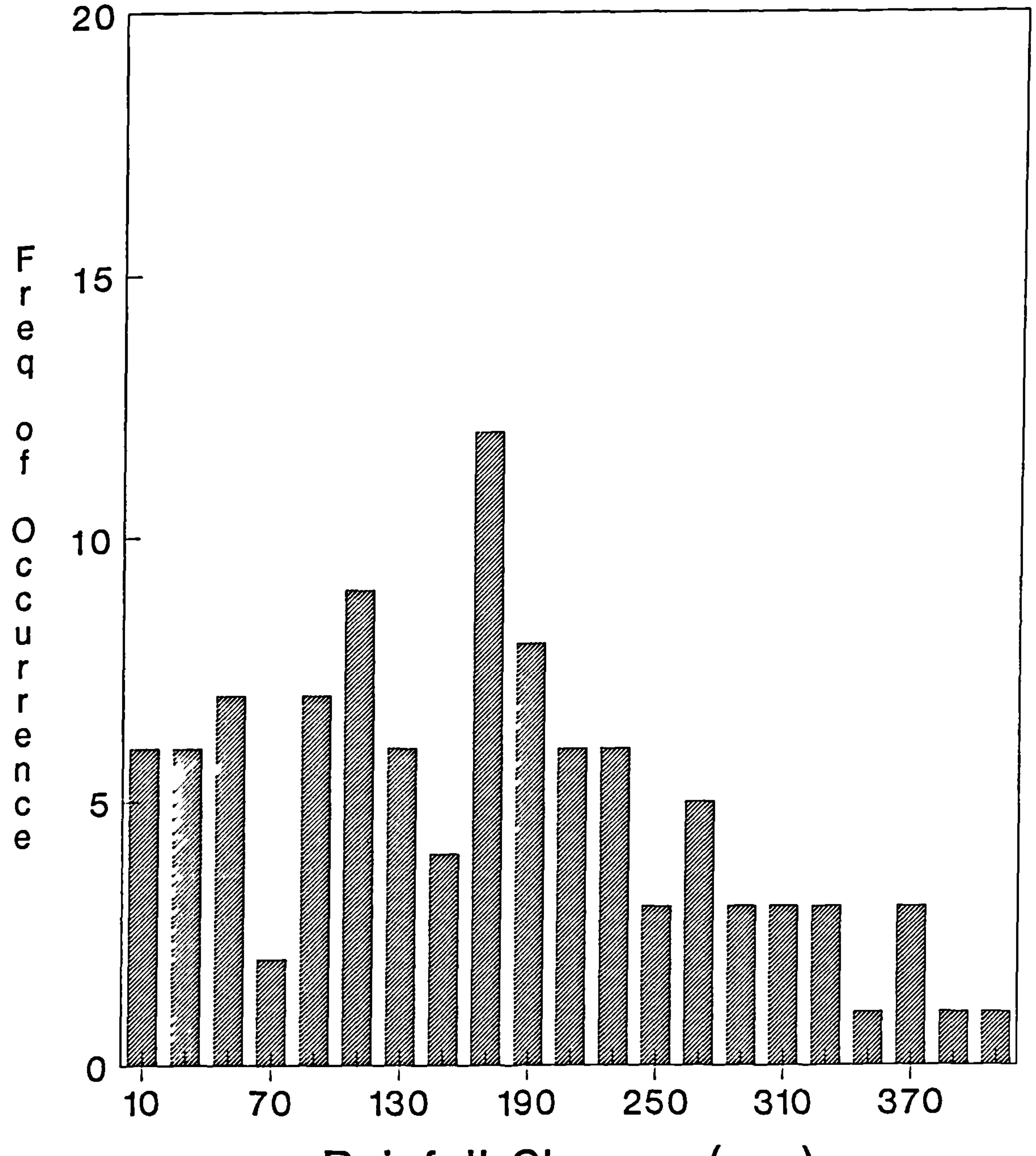


Figure 5.9 Rainfall frequency based on monthly totals at BEW

primarily concerned with prediction for engineering design purposes, it can be employed to provide indices which reflect the long-term character of the rainfall regime (Gregory and Walling, 1973).

5.1.4. Rainfall intensity

Rainfall intensity, normally expressed as depth over time or mm/hr, is an important variable in hydrology which has a direct application in characterizing certain hydrologic responses or events. In particular, it has been used to characterise individual storms in relation to runoff hydrographs, to compute return periods, to derive infiltration curves and also in the empirical equation for predicting soil erosion, for example, in the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1958).

In this analysis, the intensity of all storms considered namely those equal to and above 5.0 mm, amounting to 710 -is calculated for frequency tabulations. The frequency occurrence of storm intensity portrays a J-curve distribution (Figure 5.10). In other words, the smallest intensity interval (0 - 20 mm/hr) shows the highest frequency and vice versa (Appendix 13). In fact, more than 75% of storms fall within 5 - 40 mm/hr intensity and slightly more than 50% within 5 - 10 mm/hr. The highest storm intensity attained at this station (CS) is 460 mm/hr with an overall mean of 30.3 mm/hr (s.d. of 43) and the median is 18.0 mm/hr.

The mean intensity for most of the months seldom exceeds 30 mm/hr, except for September and December which attained intensities of greater than 40 mm/hr (Figure 5.11). January has the lowest monthly intensity, the value being 21 mm/hr (Table 5.2). In this context, a mean intensity has been employed to indicate the erosive

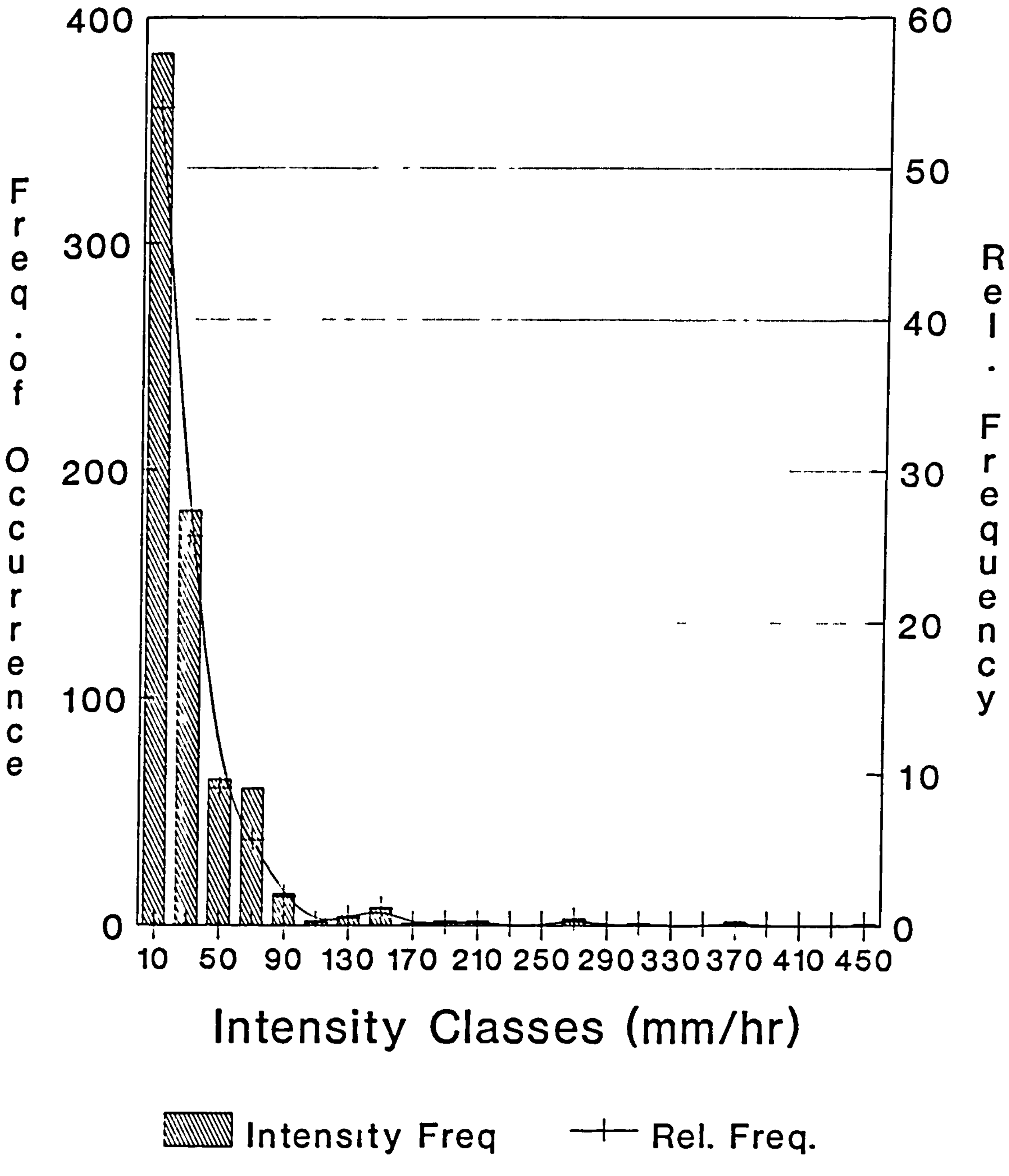


Figure 5.10 Frequency of storm intensity for all classes (≥5.0)

Table 5.2 Mean Storm Intensity (mm/hr) of Climate Station

Month	Intensity	Std. Dev.
Jul	24.9	25.6
Aug	22.4	20.0
Sep	41.0	66.9
Oct	29.4	33.4
Nov	28.7	32.7
Dec	42.6	82.3
Jan	21.9	27.9
Feb	28.6	30.4
Mar	32.5	37.5
Apr	27.9	21.8
May	28.2	28.2
Jun	23.0	17.4

capacity of rainfall in which a value of 25 mm/hr has been suggested as a threshold level (Hudson, 1971). Based on this arbitrary value, eight months of the year exceed the threshold level, particularly September and December which exceed the level by nearly two-fold. However, a mean monthly value for this watershed could be slightly lower if all storms were considered rather than limiting the analysis to those above 5.0 mm. Storm duration shows a highly positive skewed distribution, resembling that of the intensity distribution (Figure 5.12). More than 60% of storms last for less than 60 min and 34 % of those last less than 15 minutes (Appendix 14). In Nigeria, about 50% of the storms last for the same duration. The mean duration of the 710 storms is 60 minutes (s.d. of 59.7 min) whilst the longest storm lasted for 8.62 hrs with a total rainfall of 46 mm.

Storm intensity values can be applied as important indices in many hydrological-related processes such as erosion potential, infiltration capacity, hydrograph response and flood events, and an appropriate threshold value for various applications can often be established and calibrated under local conditions. Coupled with other pertinent indices, such information will form an immense contribution to the application of hydrological knowledge.

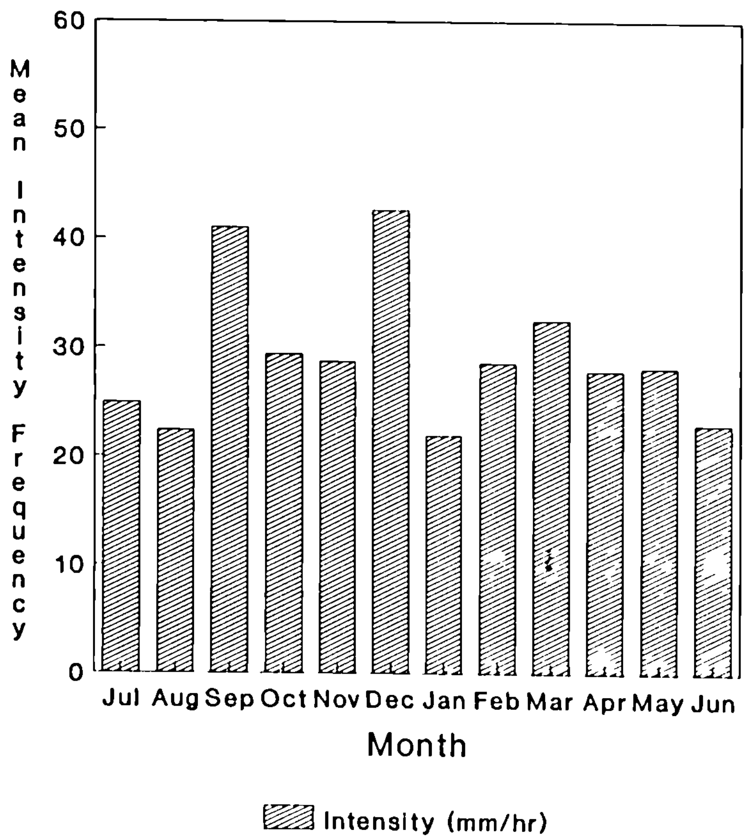


Figure 5.11 Mean monthly storm intensity at BEW

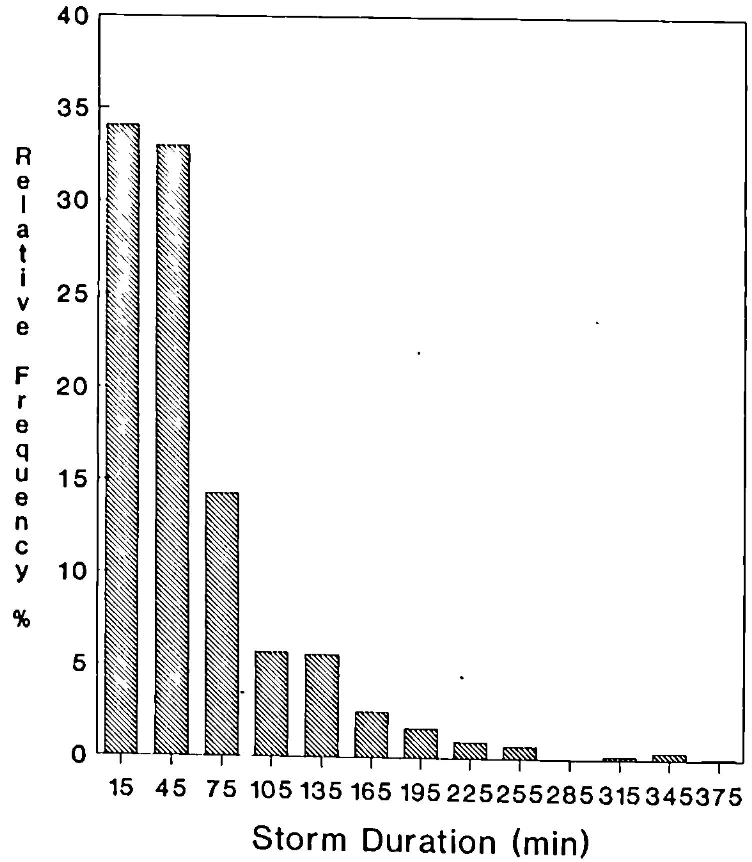


Figure 5.12 Relative frequency of storm duration at BEW

5 1 5 Rainfall interception

Rainfall interception in the forest constitutes another important variable in most hydrological studies, particularly in a forested catchment such as in BEW Furthermore, the role of the interception component in total evapotranspiration has been recently emphasized and often included in the water balance analysis (Holmes and Wronski, 1982, Bruijnzeel, 1989b, Pearce and Rowe, 1979, Pilgrim et al , 1982)

Although this component has been monitored and evaluated since the inception of this study, its detailed analysis will not be presented here as it has been reported by Baharuddin (1989) as a part of FRIM's forest hydrology research programme The above study shows that the interception component in this forest type amounts to 26 6% of the gross rainfall while 0 4 and 73% of incoming rainfall reach the forest floor as stemflow and throughfall, respectively As expected, the interception loss varies inversely with the storm amount and intensity The rather high percentage of interception loss observed at this site may reflect the density of the forest cover

Similar studies conducted at different locations in mixed dipterocarp forests documented diverse values of the interception loss, ranging from 18 - 35% (Brunig, 1970, Kenworthy, 1971, Manokaran, 1979, Nik Muhammad et al , 1979) In reviewing the values for the natural and plantation forests in South-East Asia, Bruijnzeel (1989) also observed a great variation in results ranging from 9 to 35% However, the data seem to suggest that the average value lies close to 20% of the gross rainfall

Variations in values, more often than not, relate to the differences in the methodology of sampling of throughfall and stemflow under the forest canopy in addition to other determinant factors including the climatic regimes , the time gap between storms, the canopy wetness and structure of the forest canopy. For these reasons, many workers recommended that a roving-gauge type of measurement be employed to reduce the standard error of the mean throughfall estimates (Bruijnzeel, 1989b; Lloyd and Marques Filho, 1988). In an effort to explain anomalous results of interception studies, the relationship between the interception catch and above-canopy climatic conditions should be rigorously studied (Calder, et al., 1986; Shuttleworth, 1988).

5.2 Runoff Characteristics and Responses

As mentioned earlier, streamflow or discharge is an integration of all hydrologic factors- climatic, catchment characteristics and the land use pattern, acting upon a watershed. Thus detailed analysis of discharge records can provide meaningful characteristics and the pattern of responses prevailing in the catchment. Accordingly, this affords further comparison among catchments in terms of their specific responses to any modification of the land cover or land use. In particular, simple graphical presentations and quantitative indices will be employed to describe the inherent characteristics and their subsequent variation due to treatment operations.

5.2.1 Annual Runoff

In evaluating the streamflow variation and regimes, the significant effect of the treatment exercise (Chapter 4) will be highlighted, in addition to describing the general pattern of runoff during the calibration and post-treatment phases. Both periods require a separate discussion in the present analysis in order to highlight the treatment effect.

Annual runoff for the three catchments during the calibration period (July 1980 to June 1983) shows a decreasing pattern from the first year to the third year, ranging from 395 to 135 mm (Figure 5.13). It is clear that the runoff pattern closely follows that of the rainfall in that, as has been indicated earlier, the water year 1982/83 was a dry year with consequent low flows (Figure 5.1). The annual runoff of C2 during the first two years is consistently higher than the other two catchments, although differences in rainfall total for the respective catchments are minimal. However, in the third year of calibration, the annual runoff of C2 levels off with respect to the other catchments. The runoff coefficient or runoff as a percentage of total rainfall, ranges from 9.5 to 16.0%, averaging 12.2 %. The mean specific discharge ranges from 0.071 to 0.093 $l/s/km^2$, with a mean of 0.080 $l/s/km^2$.

After the treatment or harvesting of C1 and C3 in July 1983, both catchments showed some increases in the annual runoff or water yield as compared to C2, the control (Figure 5.13). The increases seem to persist in the following years until the fourth year after the treatment, beyond which data are not yet ready for the present analysis. The observed increases in the annual runoff are also reflected in the corresponding runoff coefficients which ranged from 13.4 to 19.8 % in C1 and 13.4 to 17.2 % in C3. As expected, the runoff coefficient of C2, the control, remains relatively unchanged between the calibration phase and after treatment (Table 5.3a and b). The annual increase of water yield in C1 seems to be larger than C3. However, it is still difficult to quantify solely based on the runoff

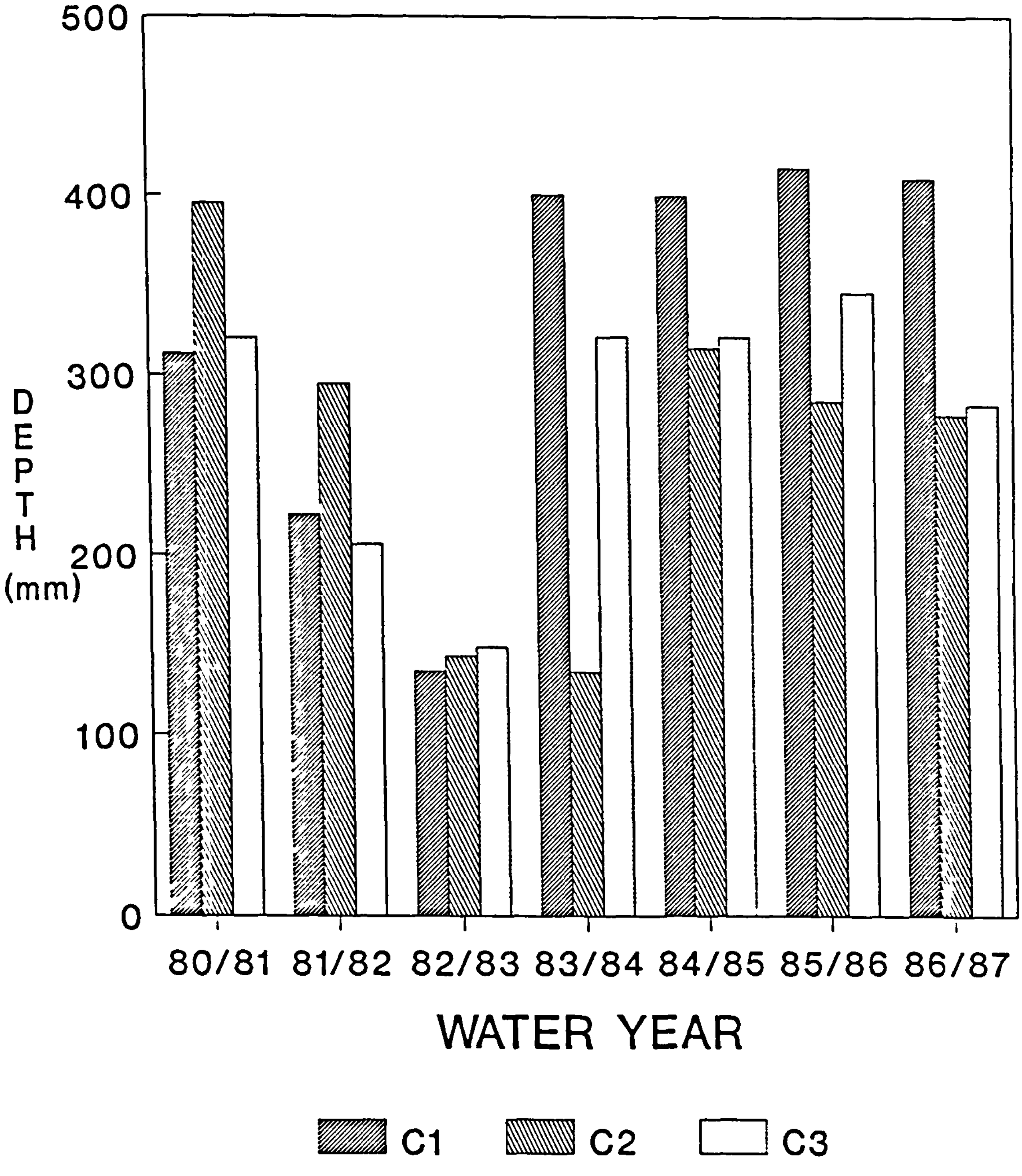


Figure 5.13 Annual runoff of three catchments in BEW

Table 5.3a MONTHLY AND ANNUAL RUNOFF (mm) OF THREE CATCHMENTS IN BEREMBUN EXPERIMENTAL WATERSHED

WT.YR	CATCH.	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
1980/81	BC1	7.3	5.2	17.3	19.1	43.5	34.5	15.0	19.4	13.1	46.1	66.2	25.0	311.7
		(4.9)	(2.8)	(7.1)	(9.3)	(14.5)	(19.7)	(29.0)	(8.1)	(7.8)	(13.1)	(18.8)	(60.2)	
	BC2	3.9	10.8	24.1	30.6	42.0	43.4	26.8	25.3	23.0	58.0	73.3	33.9	395.1
		(3.3)	(5.0)	(9.6)	(15.0)	(13.0)	(23.5)	(44.7)	(10.1)	(13.3)	(15.3)	(17.9)	(85.8)	
	BC3	6.5	9.8	17.8	22.2	41.2	27.7	13.7	20.2	13.5	48.8	67.7	25.8	320.3
		(4.5)	(4.8)	(6.7)	(10.6)	(12.7)	(14.5)	(22.8)	(7.7)	(8.2)	(13.0)	(19.8)	(63.3)	
1981/82	BC1	12.5	5.7	34.4	16.4	22.4	33.5	7.3	3.8	4.6	50.3	16.0	15.7	222.6
		(45.9)	(13.3)	(10.7)	(16.8)	(9.7)	(20.6)	(34.8)	(8.5)	(1.7)	(13.3)	(16.7)	(12.6)	
	BC2	19.5	12.8	50.6	21.0	38.3	36.4	13.4	4.0	8.3	47.9	16.7	14.8	283.7
		(84.5)	(28.1)	(15.5)	(20.6)	(24.4)	(23.1)	(68.7)	(11.3)	(3.0)	(13.6)	(19.3)	(11.5)	
	BC3	11.0	4.7	33.7	14.0	25.9	31.6	6.5	4.1	9.2	37.1	15.2	12.8	205.8
		(55.7)	(11.8)	(9.5)	(15.3)	(11.2)	(21.1)	(29.9)	(9.2)	(3.2)	(10.5)	(17.1)	(9.3)	
1982/83	BC1	14.2	10.8	5.4	16.0	51.0	21.0	14.4	2.3	0.0	0.0	0.0	0.0	135.1
		(13.5)	(14.4)	(5.6)	(5.9)	(14.4)	(23.6)	(16.3)	(10.7)	(0.0)	(0.0)	(0.0)	(0.0)	
	BC2	15.9	12.3	6.8	17.2	49.1	24.2	16.6	1.3	0.0	0.0	0.0	0.0	143.4
		(15.6)	(17.6)	(7.6)	(6.5)	(13.0)	(22.8)	(16.4)	(5.8)	(0.0)	(0.0)	(0.0)	(0.0)	
	BC3	12.4	9.1	5.5	19.5	44.6	22.7	10.3	6.6	0.1	0.8	1.5	1.6	148.3
		(13.3)	(12.3)	(6.9)	(6.9)	(12.5)	(18.8)	(25.3)	(33.4)	(2.1)	(0.7)	(1.8)	(1.3)	
1983/84	BC1	5.1	22.1	21.3	31.2	43.9	21.7	24.4	89.9	65.5	24.2	30.4	20.7	400.4
		(2.8)	(13.1)	(11.1)	(13.3)	(17.8)	(13.3)	(14.8)	(22.3)	(32.5)	(19.8)	(13.7)	(19.4)	
	BC2	3.3	12.1	14.2	13.6	30.9	17.9	17.2	61.9	42.7	21.6	24.2	18.5	278.1
		(1.7)	(7.1)	(6.7)	(5.5)	(12.3)	(10.4)	(9.9)	(14.8)	(19.7)	(16.9)	(10.6)	(18.0)	
	BC3	6.4	12.6	14.7	16.8	33.5	19.9	13.6	64.7	50.8	27.6	30.1	30.6	321.3
		(3.6)	(7.5)	(7.4)	(7.4)	(13.7)	(11.7)	(7.7)	(16.3)	(25.1)	(23.7)	(14.0)	(28.8)	
1984/85	BC1	20.6	19.6	18.3	24.8	97.9	76.2	28.5	25.8	29.3	17.7	28.9	12.1	399.7
		(17.3)	(18.9)	(12.1)	(11.3)	(21.6)	(32.1)	(47.7)	(14.5)	(22.1)	(15.3)	(12.0)	(115.2)	
	BC2	19.1	12.8	17.9	28.1	75.0	43.4	22.3	23.6	23.6	16.2	23.6	9.6	315.2
		(17.3)	(11.9)	(12.3)	(12.0)	(15.2)	(16.6)	(37.5)	(14.1)	(18.0)	(13.6)	(8.9)	(76.8)	
	BC3	16.4	13.6	13.8	22.7	72.4	64.7	28.0	19.1	18.7	13.1	26.5	12.2	321.2
		(14.6)	(11.8)	(8.9)	(10.1)	(14.3)	(26.6)	(55.2)	(11.3)	(16.1)	(11.2)	(11.2)	(92.1)	

* Value in bracket indicates the Coefficient of Runoff

TABLE 5.3b MONTHLY AND ANNUAL RUNOFF (mm) OF THREE CATCHMENTS IN BEREMBUN EXPERIMENTAL WATERSHED

WT.YR	CATCH.	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
	BC1	16.2	8.1	9.1	16.4	29.8	97.4	41.8	24.6	41.6	54.4	49.6	27.1	416.1
		(10.4)	(34.5)	(7.1)	(7.1)	(9.6)	(29.2)	(19.6)	(19.0)	(15.0)	(19.3)	(18.1)	(71.2	
1985/86	BC2	14.3	1.5	0.0	8.6	23.5	60.6	33.8	17.9	30.6	33.9	37.6	23.5	285.8
		(8.5)	(5.4)	(0.0)	(3.7)	(7.5)	(17.5)	(13.8)	(12.7)	(10.5)	(12.0)	(13.0)	(61.7)	
	BC3	15.7	6.3	4.4	15.2	28.0	83.3	24.3	17.7	31.0	36.5	55.6	27.7	345.7
		(9.5)	(26.3)	(3.4)	(7.2)	(9.1)	(25.7)	(10.3)	(14.9)	(11.5)	(12.5)	(20.0)	(71.9)	
	BC1	22.7	15.0	25.8	39.1	92.7	76.7	23.9	10.3	13.3	19.7	43.1	27.4	385.8
		(16.8)	(32.4)	(10.4)	(13.7)	(33.3)	(30.0)	(33.3)	(133.4)	(10.0)	(8.4)	(15.7)	(21.4)	
1986/87	BC2	18.9	7.7	19.8	29.3	41.4	71.4	19.8	7.5	8.3	15.4	30.6	18.5	268.7
		(12.9)	(16.6)	(7.4)	(9.8)	(14.8)	(26.7)	(28.9)	(83.2)	(5.9)	(5.7)	(11.2)	(13.0)	
	BC3	18.7	11.2	16.8	34.8	75.7	54.8	23.3	9.6	14.3	24.4	25.4	12.5	283.8
		(14.3)	(26.6)	(6.8)	(12.4)	(27.3)	(23.2)	(38.0)	(120.3)	(10.8)	(9.6)	(9.7)	(9.7)	
	BC1	14.2	17.7	19.5	36.6	55.8	72.6							
		(40.1)	(10.3)	(9.8)	(12.1)	(19.7)	(44.0)							
1987/88	BC2	7.0	10.8	14.2	28.1	36.4	33.2							
		(18.5)	(5.5)	(6.9)	(9.1)	(12.6)	(19.1)							
	BC3	11.2	10.7	10.7	21.7	30.7	45.5							
		(30.7)	(5.8)	(5.4)	(7.2)	(11.3)	(26.0)							

* Value in bracket indicates the Coefficient of runoff

coefficient. As regards the rainfall regime after the treatment, the annual variation among catchments is acceptably small.

The rather low runoff coefficients observed in this watershed are quite acceptable due to its location in upper reaches which are totally covered by the rain forest. Similar values for the runoff coefficient were observed in the Sg. Tekam Experimental Basin, in Pahang, Malaysia, where they ranged from 9 - 14 % (DID, 1986).

5.2.2 Monthly runoff and regime

In addition to the basic parameter of annual flow, the chronology of discharge from a watershed can be examined by the runoff regime based on monthly runoff. The runoff pattern for the three catchments fluctuates to a certain extent over the seven-year period, strongly reflecting the rainfall regime as described earlier (Figure 5.14). In the dry year of 1982/83, a zero flow intermittently occurs in all catchments, although the duration varies between them. However, after the treatment operation, the zero flow ceases to occur in C1 and C3, but persists in C2.

The mean monthly runoff of the three catchments, based on the calibration records, indicates a similar pattern to that of the monthly rainfall (Figure 5.15). Higher flows normally attain in the months of November and April whilst minimum flows are usually observed in the beginning and the end of the water year. Interestingly, there is apparently no lagging effect of the runoff evident in the regime except during minimum flows where a one month-lag from that of monthly rainfall has been observed. This could be

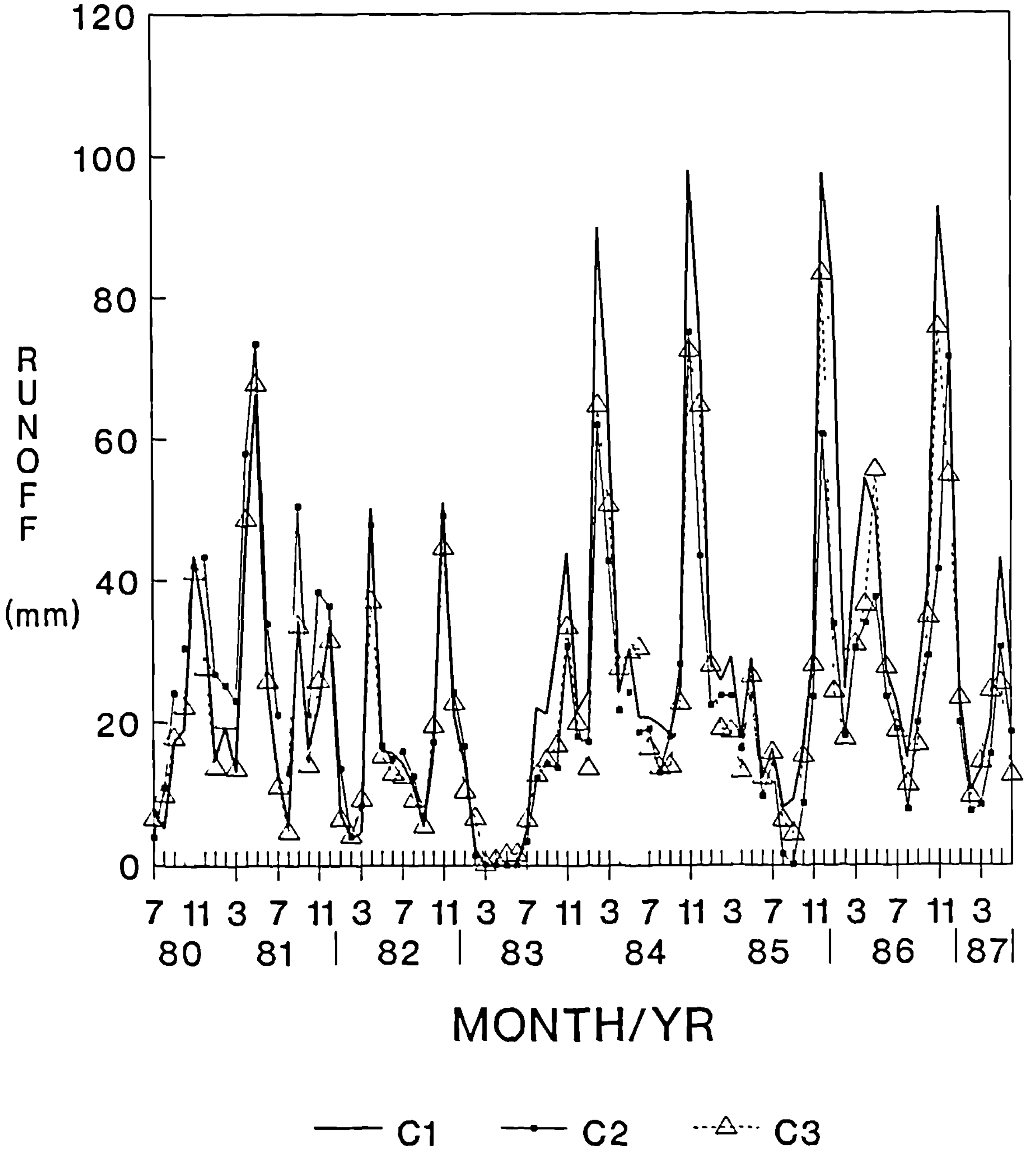


Figure 5.14 Monthly runoff of three catchments in BEW

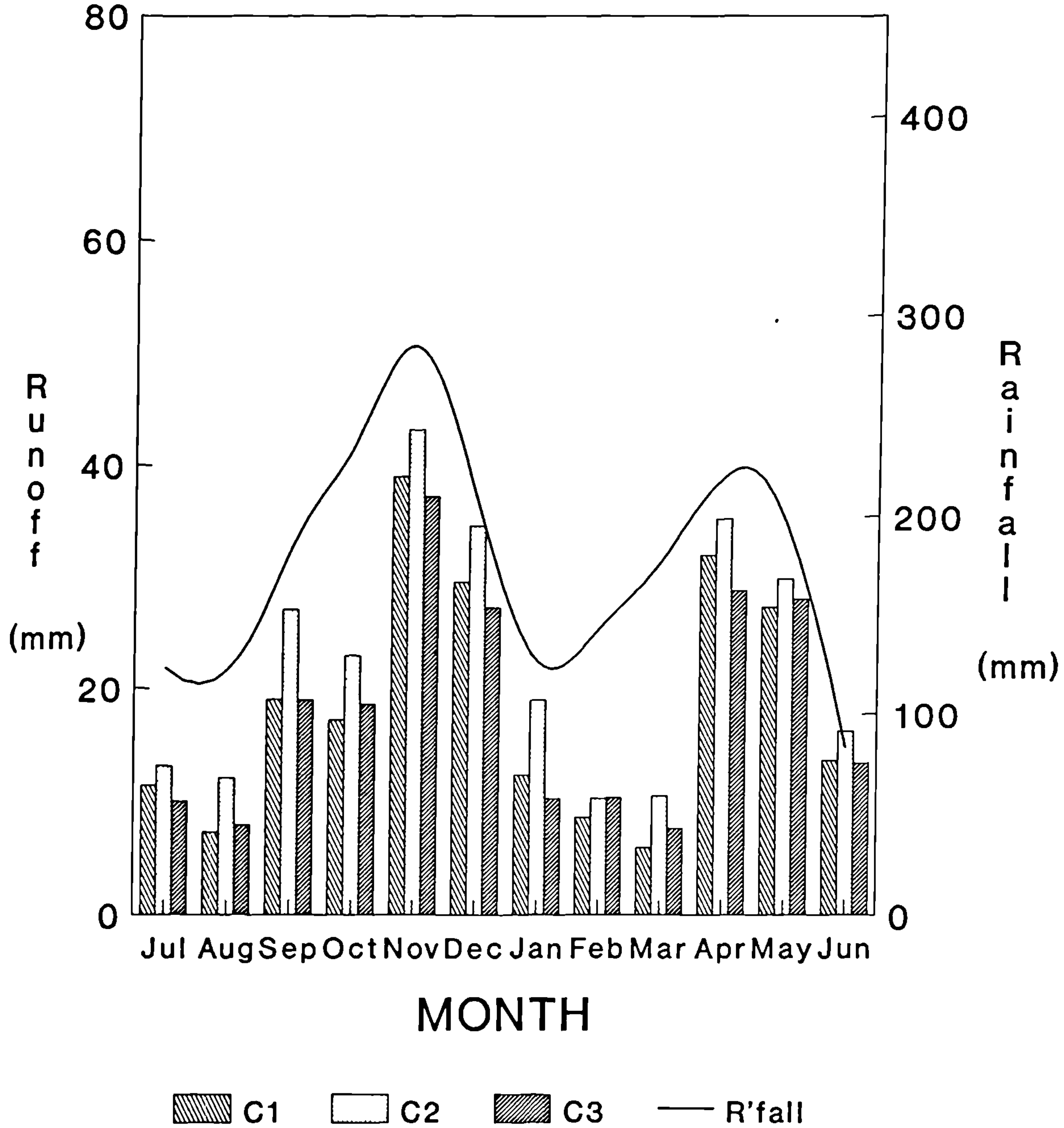


Figure 5.15 Mean monthly runoff of three catchments and mean monthly rainfall at BEW

due to the typical runoff mechanism of this watershed and could in part be a characteristic of the small catchment size.

The monthly runoff coefficients of C1 and C3 during the calibration period range from 1.7 to 60.0 % and 0.67 to 63.0 %, respectively excluding zero flow records (Table 5.3a and b). Increase in the runoff coefficients after the treatment were observed and ranged from 2.7 to 115.0 % and 3.6 to 92% in C1 and C3, respectively. However, the pattern of the monthly regime essentially remains the same as that during the calibration period. The control catchment produces similar runoff coefficients throughout and they range from 2.9 to 85.8% during calibration and 1.7 to 83.2% after treatment, respectively. Based on the above, the treatment operation has shown some changes in the flow regimes as indicated by the annual and monthly runoff coefficients in addition to observed patterns in the graphical presentations. However, the above parameters do not provide a quantitative measure regarding the magnitude of the increase nor its significance. Moreover, the increase in yield could be attributed to an annual fluctuation of rainfall and thereby streamflow. Thus subsequent analysis is requiredto provide further detail to investigate this further.

5.2.3 Double-mass curves

The double-mass curve method can be employed to detect changes in runoff, although originally it was meant to check inconsistency in data sets (Searcy and Hadison, 1970). Theoretically, it is based on the fact that the cumulative values of one variable versus the cumulative values of a related variable during the same period will plot as a straight line as long as the data are proportional. The slope of this line represent the constant of proportionality. Thus, a break in the slope of the double-mass curve means that a change in the constant of proportionality between the two variables has occurred.

This method has been frequently applied in hydrological analysis to document in part the effects of treatment changes on discharge as well as other parameters of interest (DID, 1986; Hsia, 1983; Leitch and Flinn, 1986; Pearce et al., 1980; Swindel et al., 1982 and Ziemer, 1981). However, with this method, it may be difficult to reach an objective conclusion although it can provide the general trend of response, if such a trend is present (Hewlett, 1982; Reinhart, 1967; Ziemer, 1981).

The double-mass curves for this watershed are computed using monthly flows of the treated catchments, C1 and C3, against the control, C2 (Figure 5.16 and 5.17). These mass-curves comprise six years of runoff including three years of post-treatment. The double-mass curves of C1 and C3 clearly show a break in the slopes commencing with the start of forest logging operations and continuing thereafter. The above characteristics obviously provide further evidence on the effects of treatment on discharge immediately after forest harvesting. However, based on the curves, it is difficult to evaluate the magnitude of changes; thus comparison between the two treated catchments in terms of magnitude of increase is not instructive.

Although some workers have devised several approaches to reducing the subjectivity of the double-mass curve, for example by using a statistical method and also a computerized method of stepwise slope comparison (Chang and Lee, 1974; Searcy and Hadison, 1960), the conclusions drawn from the double-mass curve method are fraught with

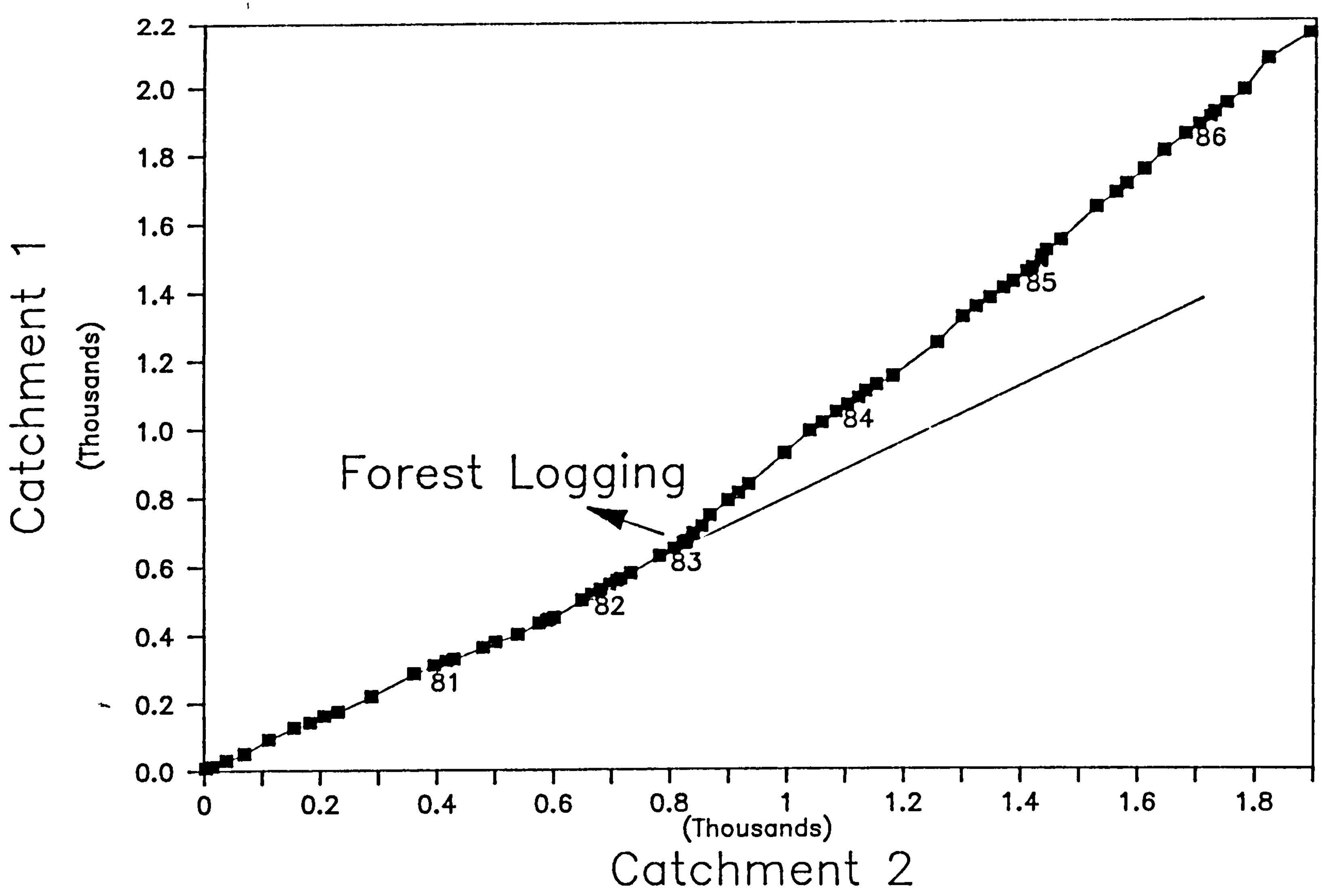


Figure 5.16 Double-mass curves of catchment 1 (commercial logging) against catchment 2 (control) at BEW

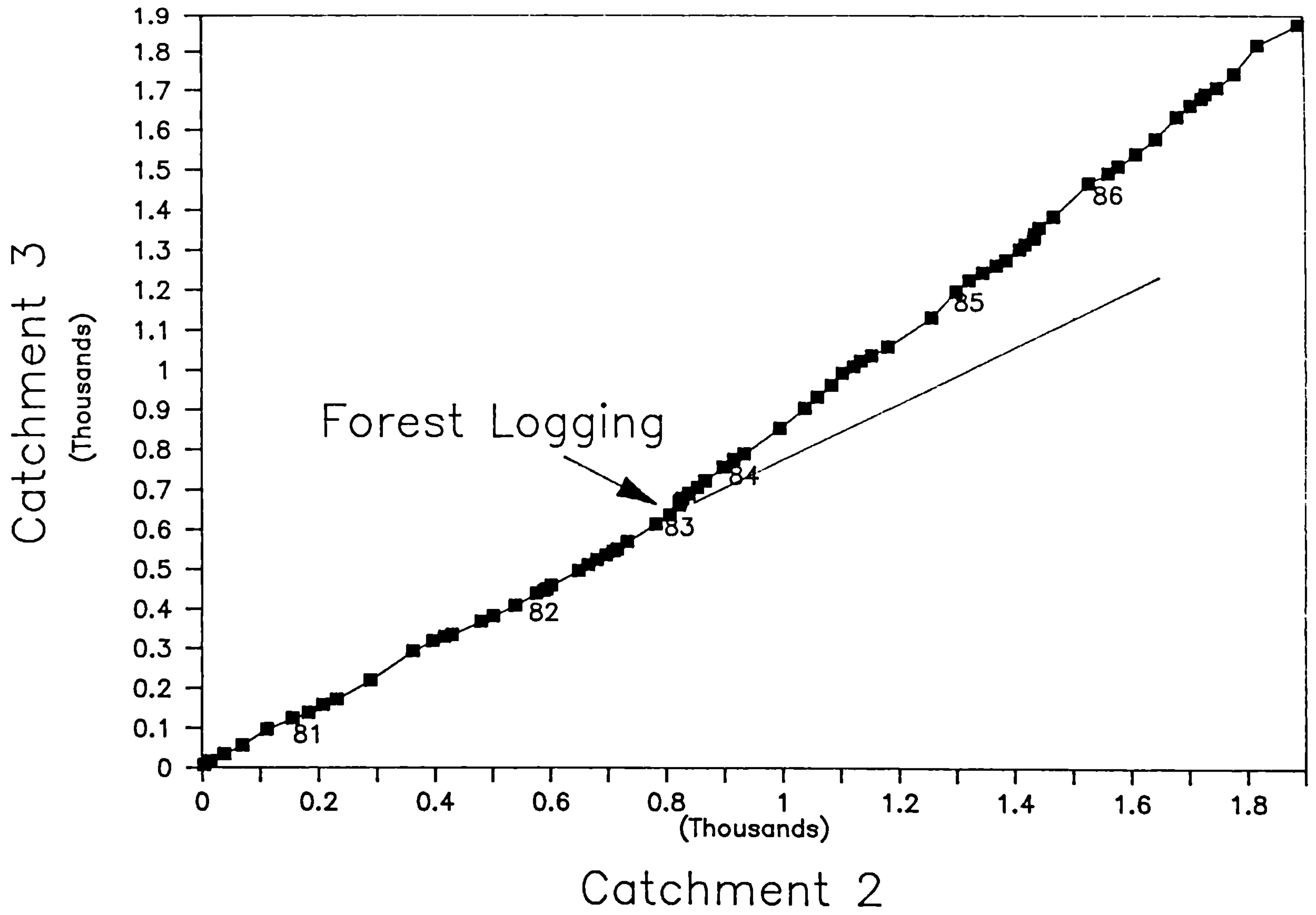


Figure 5.17 Double-mass curves of catchment 3 (supervised logging) against catchment 2 (control) at BEW

hazards of accidental or hidden correlations between variables (Hewlett, 1982). Furthermore, the combined effects of site and treatment on streamflow cannot be separated from one another. As such, other evidence is needed to amplify the magnitude of increment and its significance. In addition, the question of whether the water yield increase is largely associated with baseflow augmentation or an increase in stormflow variables, is still inconclusive.

5.2.4 Flow duration curves

Annual and monthly flow regimes described earlier provide little impression on the variability of flow in the record. In this context, flow variation can be conveniently demonstrated by the use of flow duration curves which are essentially cumulative frequency curves that show the percentage of time specified discharges are equalled or exceeded during a given period (Searcy, 1959). The flow duration curve combines in one curve the flow characteristics of a stream encompassing the entire range of discharge, but without regard to the sequence of occurrence. The flow duration curve method has been used since about 1915 (Searcy, 1959) and is still widely applied in many hydrological analyses (DID, 1986; Gilmour, 1977; Hornbeck, et al., 1977; Mumeka, 1986; Newson and Robinson, 1983; Pearce et al., 1976).

For the present analysis, daily discharges (litres/sec) of the three catchments are used in the computation of the duration flow curves by separating them into two periods, the calibration and post-treatment phases. Specifically, three years of flow record are employed for both periods by arranging them according to magnitude and years. Subsequently, the percentage of time during which flow equalled or exceeded the specific values are computed. For comparison purposes, discharge values are converted to the specific discharge unit in litre/sec/km^2. A curve is drawn through the plotted points of specified discharges versus the percentage of time during which they are equalled or exceeded. Hence, the curve represents an average distribution of discharge for the period under study rather than for a single year.

The flow duration curves of C1, C2 and C3 provide a convenient means not only for evaluating the flow characteristics of each catchment but also for comparing them, particularly in terms of treatment effects (Figures 5.18, 5.19, 5.20). It is clear from the figures that the flow duration curves of C1 and C3 reveal some changes whilst C2 indicates insignificant change when comparing the calibration period with that of the post-treatment period. In particular, the specific discharge of C1 at 50% of the time during the calibration is 9.0 l/s/km^2 as compared with 12.0 l/s/km^2 during post-treatment. Corresponding values for C3 also indicate some increase, ranging from 7.0 to 10.0 l/s/km^2. Increases in flow must be attributed to the treatment operation, for the control catchment which experienced similar rainfall regimes, did not show comparable changes in the flow duration curves. Two notable characteristics elicited from the above curves are worth pointing out with regard to C1 and C3. Firstly, a greater change apparently occurred in C1 as compared with C3 as is shown quite clearly by the curves; this result is further emphasiszed by the specific discharge values. Secondly, the increase in C1 covered a wider range of discharge whilst in C3, the increment was limited to the lower discharge values, particularly those less than 30 l/s/km^2.

The above response actually implies an important ramification with

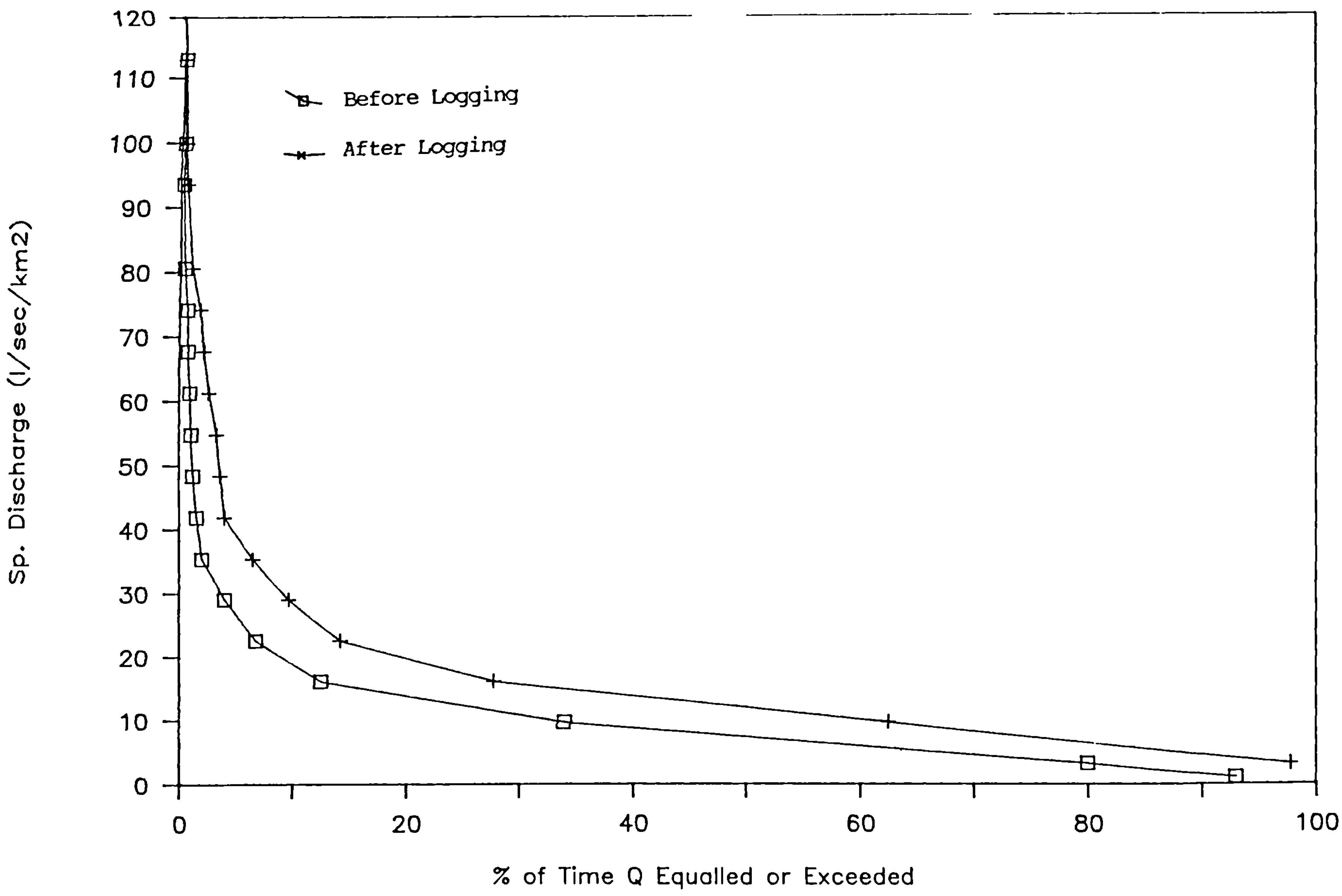


Figure 5.18 Flow duration curves of catchment 1 at BEW

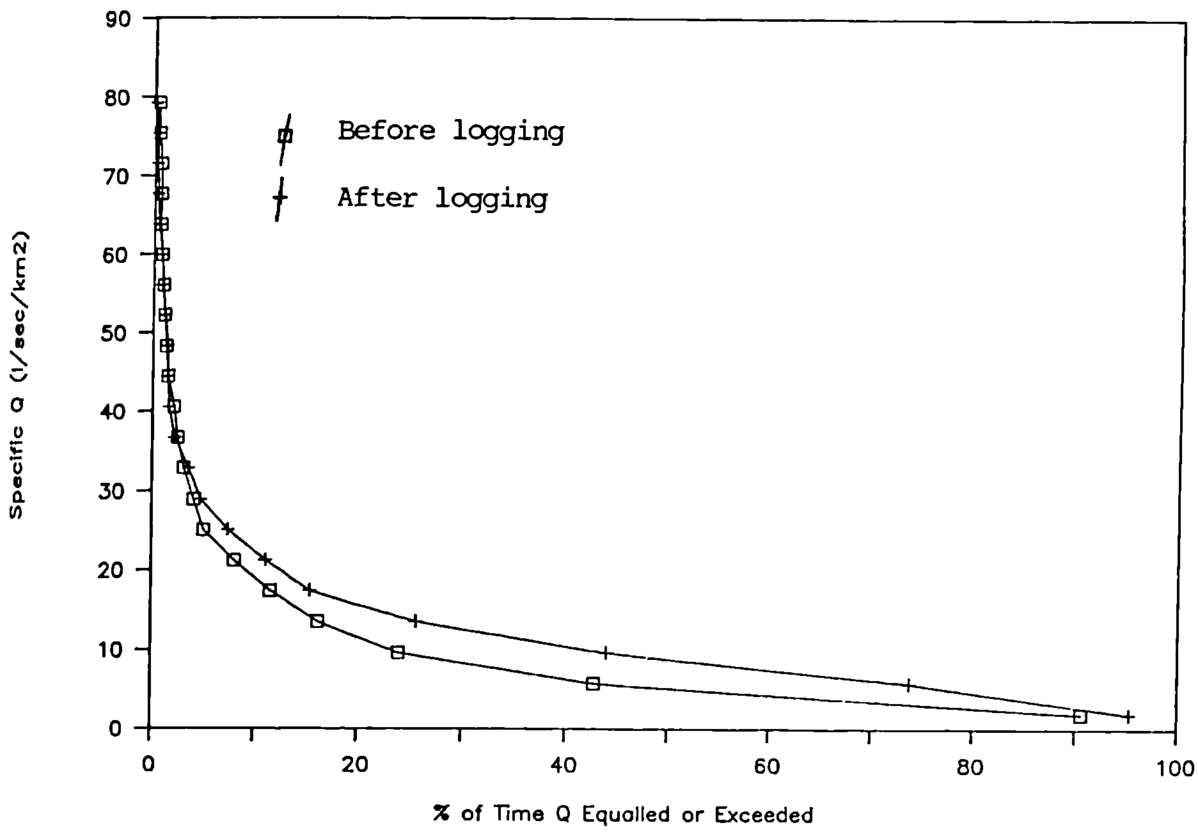


Figure 5.19 Flow duration curves of catchment 3 at BEW

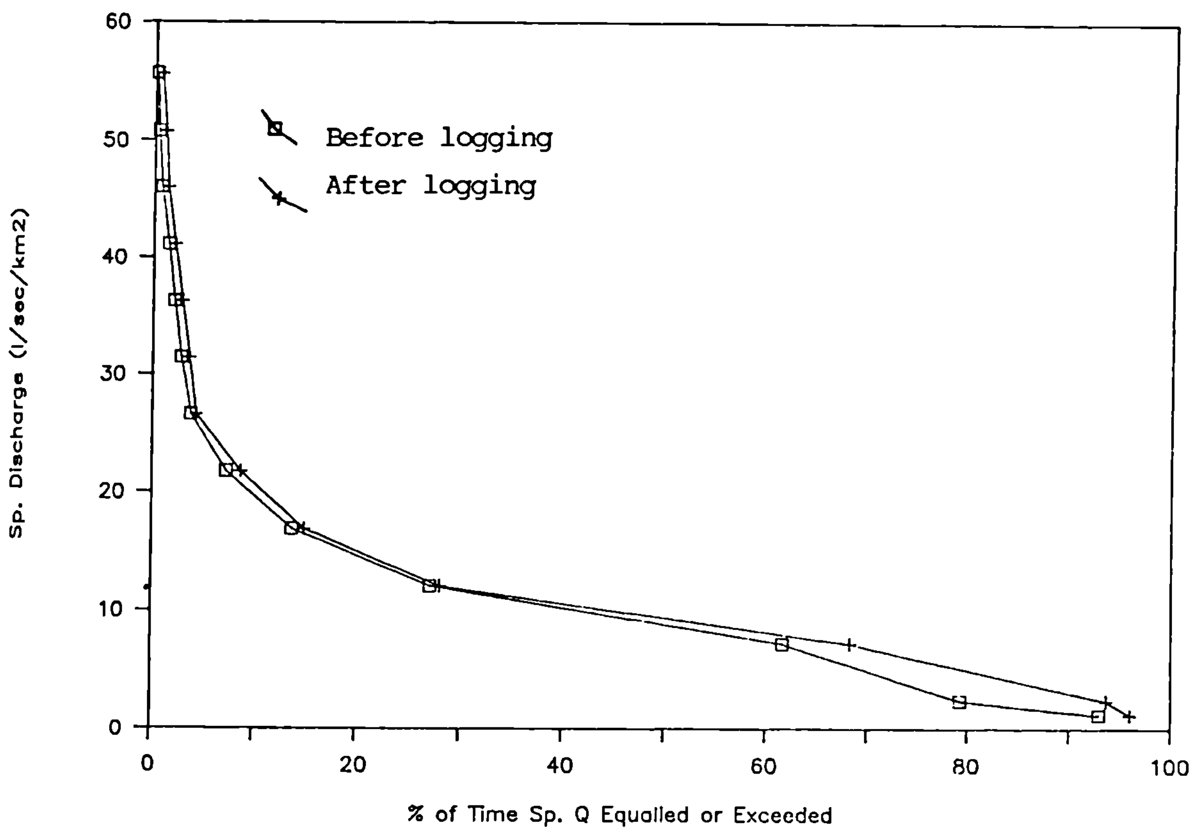


Figure 5.20 Flow duration curves of catchment 2 at BEW

regard to the effect of the forest logging on water yield. The question is whether the increase in water yield resulting from the catchment treatment is largely associated with lowflow augmentation or increases in the stormflow volume and peakflows, or a combination of both. The above results seem to suggest that increases in flow are more associated with baseflow rather than peakflows. However, further evidence is required to confirm this. In this context, another study of the effect of forest conversion to agricultural land use in Malaysia, using flow duration curves, has revealed that increases in water yield have largely occurred during the baseflow regime (DID, 1986; DID, 1989). However, the same study also documented increases in peak discharge using the unit hydrograph analysis, although the increment has not been statistically quantified.

5.2.4 Baseflow recession curve

Assessment of a recession curve as one of the three major components of the storm hydrograph may provide pertinent information regarding the magnitude of groundwater storage during a certain period (Chow et al., 1988; Raudkivi, 1979). In fact, recession curve analysis has proved useful in many hydrological studies such those for low flows, storage yields, flood hydrographs and reservoir drawdown for flood storage (James and Thompson, 1970) and also in climatological modelling (Federer, 1973). In the present study, the baseflow recession curve analysis is applied to examine the treatment effect on baseflow characteristics and groundwater storage. Ultimately, this analysis will help determine whether treatment leads to augmentation of baseflows resulting from treatment or otherwise.

According to Raudkivi (1979), the falling limb of a hydrograph can be sub-divided into a number of recession curves, namely the hydrograph recession curve, interflow recession curve and baseflow recession curve. If the logarithms of discharges are plotted against time, recession curves should plot as straight lines and possess distinctive recession characteristics of their own. In this relation, Barnes (1959) maintained that any type of flow recession curve takes the form of an exponential equation:

$$q_t = q_0 e^{-at} \qquad \text{......................Equation 5.1}$$
$$= q_0 k^t$$

where:

q_0 = initial discharge at the start of recession
q_t = discharge at time t
e = base of the natural logarithm
a = constant
t = time interval
k = constant representing (e^{-a})

In addition to the above simple exponential curve equation, Toebes et al., (1969) reviewed other equations including the double-exponential, hyperbola and ice-melt hyperbola. If the streamflow recession curve can be fitted to one of the above equations, then its form can be simply described by the values of the recession constant (Gregory and Walling, 1973). The exponential function is normally used for this purpose because it can be portrayed by the k value which in turn represents the slope of a semi-logarithmic plot. Generally, the normal recession curve or master depletion recession curve is derived to represent the flow recession compiled by superimposing many of the recession curves observed on a given stream (Chow et al., 1988).

A number of methods are available for the construction of the above curve as discussed by Toebes et al.(1969):

a. the strip method (Wisler and Brater, 1959)
b. the correlation method (Langbein, 1940)
c. the tabulation method (Johnson and Dils, 1956)
d. the flow measurement method

The fourth method only gives a single recession curve which is valuable for prediction purposes when correlated with rainfall records. Different master curves may be required for the summer and winter seasons due to the differences in evapotranspiration loss (Gregory and Walling, 1973), but they may not be applicable in the tropics.

In this analysis, the tabulation method has been applied using daily mean discharges. Basically, it involves the tabulation of flows in vertical columns with one column for each recession representing a segment of a selected hydrograph. The columns are adjusted vertically until the discharges agree horizontally. Accordingly, discharge values are averaged horizontally and these mean discharges contribute to a master recession curve. Although this method gives a reasonably good control of the data, its disadvantage is that irrelevant parts of the recession cannot be omitted without detailed inspection (Toebes et al., 1969). In this study, the construction of the curve becomes easier with the help of spreadsheet software particularly in the tabulation and adjustment of columns and in finally computing the average values.

Two different curves are constructed for each catchment representing the calibration and treatment periods. Hydrograph segments selected for this purpose comprise a series of discharges that are not interrupted by rainfall events (Appendix 15).

The master recession curves for respective catchments are plotted on semi-log paper together with k values using equation 5.1. It is clear that recession curves of C1 and C3 for the post-logging period shifted upwards as compared with those of the calibration period (Figures 5.21 and 5.22). Similarly, changes can be detected by the corresponding recession constants (k) for both catchments which increase from 0.928 to 0.940 in C1 and 0.930 to 0.950 in C3. The k value for C2 practically remains unchanged, ranging from 0.910 to 0.912, respectively. Consequently, the above indices directly imply that the baseflow characteristics of C1 and C3 have changed after the treatment operation with C3 apparently showing the greater changes. The upward shift in the curves reflects an increase in groundwater storage resulting from the removal of forest cover. In this instance, for any particular discharge on the recession limb of a hydrograph, it would be reached much later than before the treatment had been imposed. A plausible reason for the above response could be the fact that the surface infiltration capacity becomes less affected by the logging operations which left a substantial area undisturbed. Thus a greater recharge of the groundwater storage is possible as a result of a remarkable reduction in evapotranspiration. In fact, the ground disturbance only occurs where there are roads , skidding tracks and log landings which constitute somewhat less than 20% of each catchment. Conceivably the different magnitude of change observed between C1 and C3 may be due to the different intensity of logging prescribed on them.

Comparable changes were observed in the Sg. Tekam Experimental Basin, Malaysia resulting from forest logging and clearance with k values varying from 0.795 to 0.848 (DID, 1986). Working in the tropical

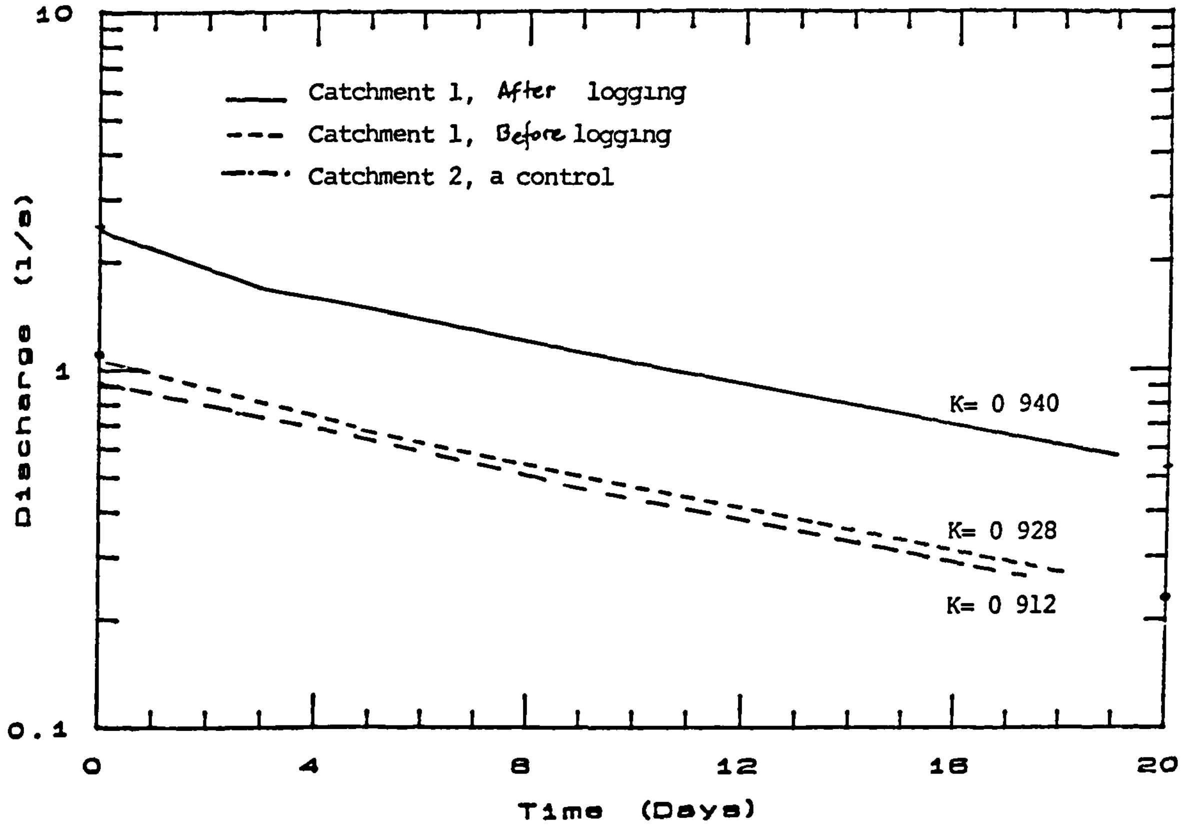


Figure 5.21 Baseflow recession curves for catchments 1 and 2 at BEW

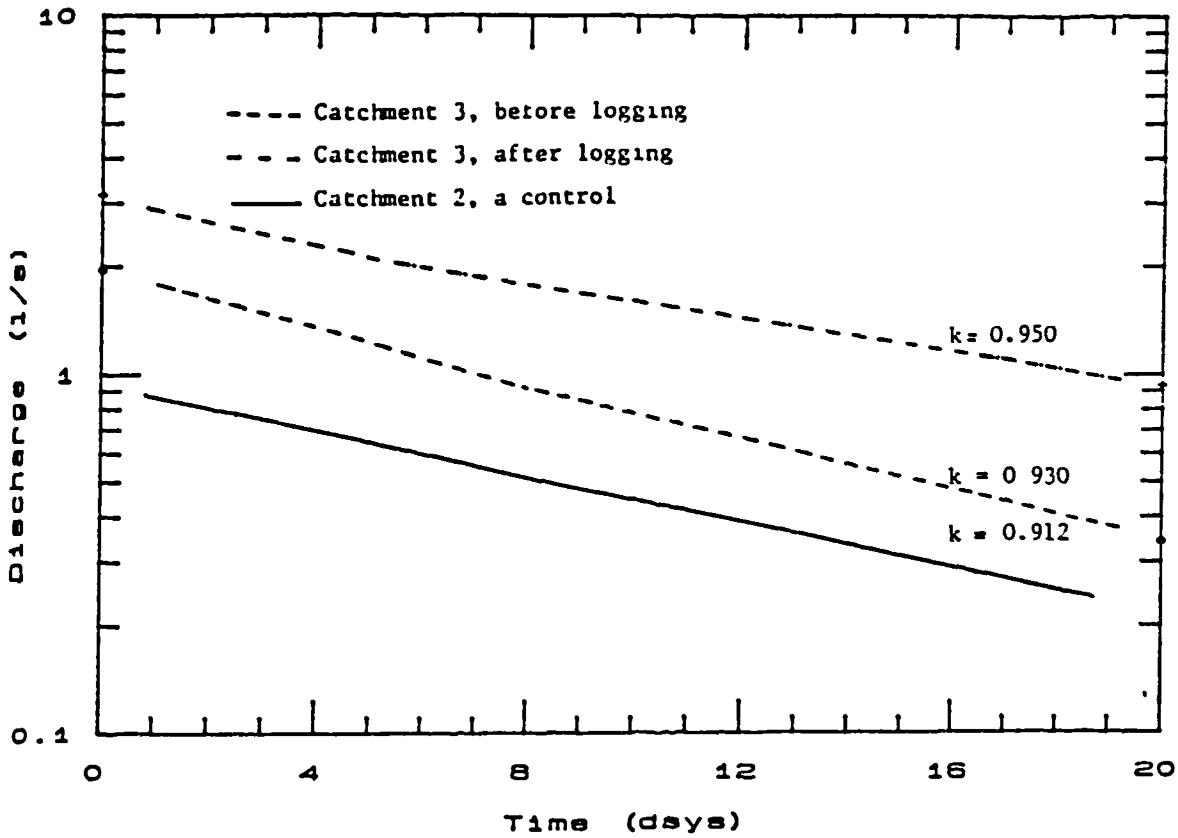


Figure 5.22 Baseflow recession curves for catchments 3 and 2 at BEW

north-east of Australia, Gilmour (1977) documented an increase in the recession constant after forest clearing in a catchment, translating into a 135% increase in discharge.

Based on the above analysis, it is suggested that the increases in water yield disclosed by the previous results are largely associated with baseflow augmentation owing to minimal changes in the surface infiltration opportunity. This in turn leads to a greater recharge of the groundwater storage and ultimately sustains a larger baseflow. This argument seems in agreement with the monthly discharge regime of C1 and C3 which do not experience any zero flows as they did in the calibration period. Conversely, the control catchment still experiences zero flow conditions, albeit for a short duration in the water year 1985/86. Nevertheless, the above evidence is still inconclusive without a detailed analysis of the effects of the treatment operation on stormflow variables. This pertinent analysis will be presented in Chapter 7.

5.3 Soil Water Regimes

Information on soil moisture or water content measured at different times and sites is useful in hydrological investigations for describing seasonal fluctuations and available water for the plant community. In the ensuing analysis, results of soil water monitoring at three sites representing different edaphic factors and topographical variations are presented.

5.3.1 Soil water storage

Soil water calculated by the Gravimetric Method expresses moisture in percent, on a weight basis (V_w). To make comparisons compatible with other parameters, the above value is converted as percent by volume (V_v) and equivalent depth or storage (S) using the following formula:

$$V_v = BD\, V_w \quad \text{.................................} \quad \text{Equation 5.2}$$

$$S = V_v\, d \quad \text{.................................} \quad \text{Equation 5.3}$$

where:

S = soil water depth (storage) , cm
BD= bulk density (gm/cm^3)
V_w= soil water content (% by weight)
V_v= soil water content by volume
d = depth of soil column (cm)

In the present analysis, soil samples from the 80 to 100 cm layer are employed, so that the calculated total soil water content represents the volumetric water content down to the 100 cm layer. The above layer coincides with the upper root zone of the tropical rainforest which has been estimated to be within 1.0 to 2.5 m (Ashton, 1982). In fact, a much deeper sampling layer is highly desirable in this kind of analysis because of the deep nature of the Ultisols soil, which is typical of this watershed. However, deeper monitoring was limited by the instrument available to this study at the time. Alternatively, a neutron probe method should be used which not only allows sampling to a much greater depth but also supports a much larger network of sampling sites.

5.3.2 Seasonal course of soil water

In the seasonal soil water regime analysis, the last measurement on a weekly basis for a respective month is considered and thus represents a monthly sample. As such, a monthly fluctuation of the soil water content can be portrayed along with the monthly rainfall regime. Reigner (1964) and Reinhart et al., (1963) adopted a similar approach in reporting the soil storage of forest catchments. Owing to the location of sampling sites and the nature of selective logging carried out in this watershed, the soil water regimes reported here do not indicate the treatment effect which was evident with earlier parameters. The three sampling plots were not located within the logging operation area. This is rather unfortunate and should have been envisaged in locating the respective plots. Nevertheless, a reasonably long record obtained from this watershed may provide the spatial and temporal variations of soil water regimes in response to the climatic and edaphic factors over the study period.

The seasonal course of soil water regimes of the three sites based on 57 monthly records are plotted against monthly rainfall of the nearest stations to the respective site (Figures 5.23, 5.24, 5.25). Although each site indicates a slight variation from the other, generally the overall values for the entire period are comparable, with a mean value of 30 cm and ranges from 22 to 36 cm (Table 5.4). As expected, the point sampling of soil water content normally shows high variation as indicated by a relatively large coefficient of variation, about 9.0 %. Kamarudzaman and Nik Muhammad (1986) observed similar magnitudes of variations when reporting the total soil water content of a forest plantation in Kemasul Pahang, Malaysia. The soil water regime generally follows the monthly rainfall pattern prevailing at the site. The soil water at SM2 attained the lowest level amounting to 22 cm in March of 1983 after three consecutive months of rainfall less than 80 mm with the third month receiving as little as 5 mm (Appendix 16).

Conversely, the soil water content steadily increased immediately after the above so-called drought months where monthly

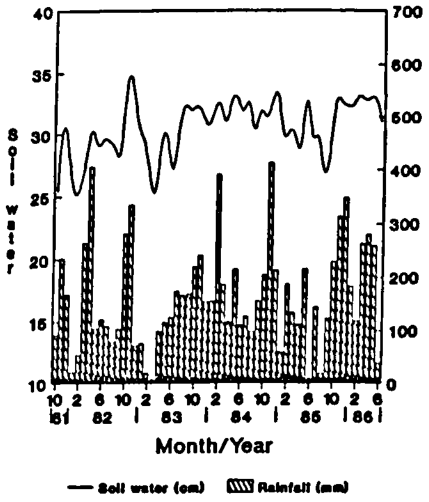


Figure 5 23 Soil water regime of SM1 at BEW

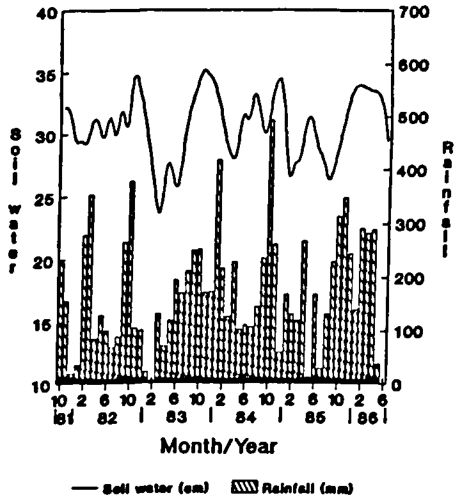


Figure 5 24 Soil water regime of SM2 at BEW

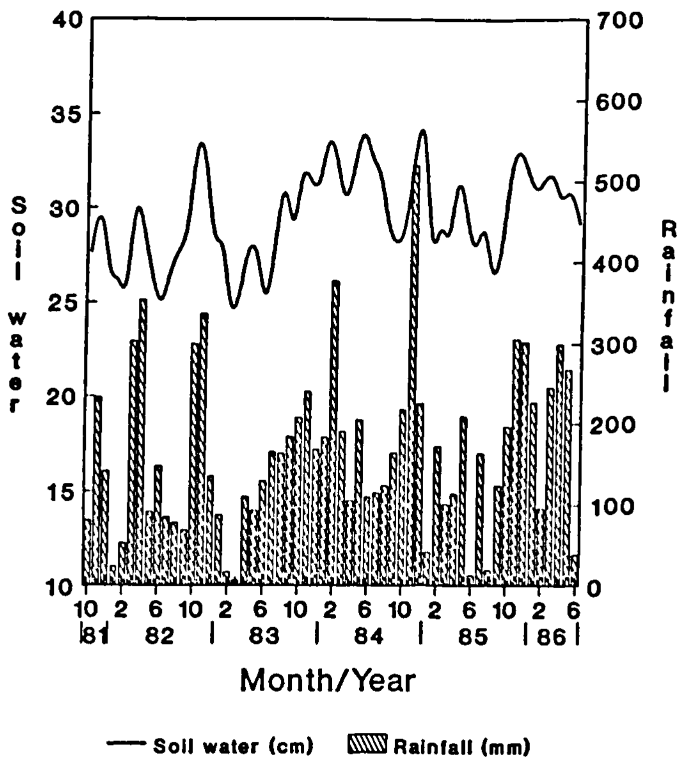


Figure 5 25 Soil water regime of SM3 at BEW

Table 5.4 Soil water content of the three sites in BEW

Site	SM1	SM2	SM3
Mean (cm)	30.58	30.70	29.60
Std. Dev	2.77	3.10	2.88
Maximum	35.41	35.62	35.53
Minimum	23.93	22.24	23.93
Bulk density (gm/cm^3)	1.39	1.39	1.28

rainfall totals generally exceed 100 mm per month. Despite an apparent strong correlation between soil water regime and monthly rainfall, statistical correlations are rather weak with r^2 ranges between 0.60 to 0.65, mainly due to high variations in the soil water measurements. Ideally, the throughfall record should be used and correlated with the total soil water content as suggested by Eschner (1967) and Boyles and Tajchman (1983/84). In this context, the mean percentage of throughfall in this watershed constitutes about 73 (Baharuddin, 1989).

The seasonal variation of soil water content of the three sites tells very little of the specific influence of each site apart from the influence of the rainfall pattern. In this instance, a cumulative frequency distribution of soil water may signify the effect of site particularly in terms of slope and elevation (Boyles and Tajchman, 1983/84).

5.3.3 Soil water frequency distributon

The empirical frequency distributions for the above sites are represented by smooth curves in Figure 5.26 using weekly observations of the soil water content of each site. Frequency values in the figures provide the probability that the soil water content will be less or equal to the indicated water content. Obviously the figure shows that SM3 holds less water than the other two sites for most of the time, possibly due to its position on the highest and steepest slope of the three. Specifically, at 50% level, SM3 held about 28 cm of water whilst SM1 and SM2 held a similar volume of water-approximately 29 cm. In fact, SM1 and SM2 shared almost similar soil water characteristics for most of the range despite some differences in elevation and slope. Although the figure seems to suggest that the site of higher slope and elevation holds less soil water probably due to a greater drainage or percolation or faster soil drying rate, more evidence and replication of a similar set-up are needed in order to confirm the above responses conclusively. Conversely, the observations at SM1 and SM2 did not seem consistent with the above phenomena.

The apparent differences in the soil water content at the above locations could not be ascribed to the effect of aspect as is normally the case in higher latitudes because declination of the sun in the tropics fluctuates at very small angles (Lee, 1980, Lauer,1989). Conceivably the differences among the sites may be related to the soil characteristics of respective sites. Although the entire watershed shares a common soil series, there could be some variation in the soil texture particularly in terms of sand and stone content. In this context, Werling and Tajchman (1983/84) have shown that less soil water is retained on the site with a higher stone content. Another likely factor worth examining is the relative amount of throughfall vis-a-vis the density of the tree species at each site. It has, of course, been shown that higher tree density tends to reduce the amount of the throughfall (Eschner, 1967). However, the throughfall dimension has not been pursued further in

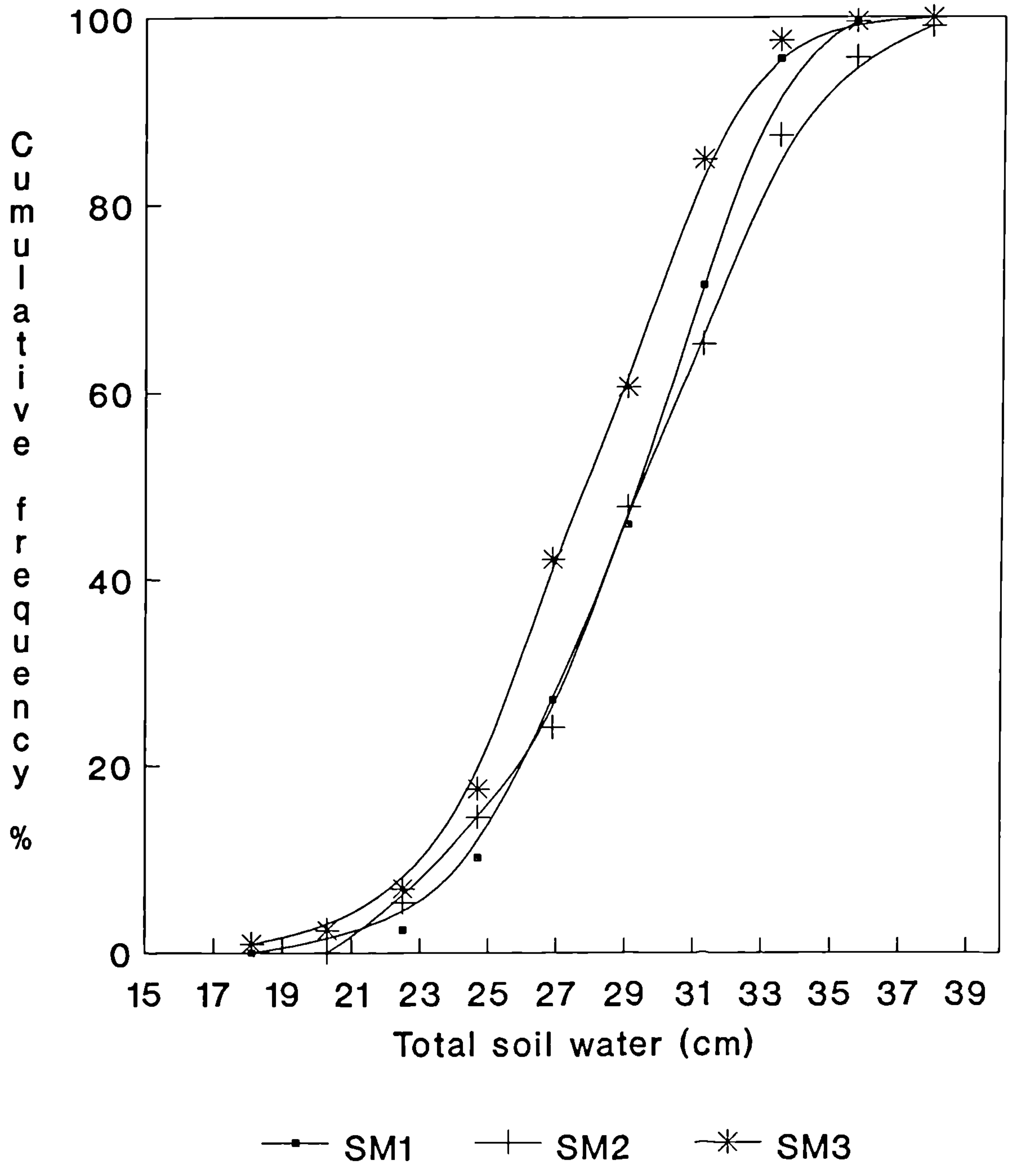


Figure 5.26 Frequency distribution of soil water content of SM1, SM2 and SM3 at BEW

the present analysis for another independent study is being carried out by FRIM associated with the canopy interception study (Baharuddin, 1989).

Despite some shortcomings in the set-up of the soil water plots as described earlier, data gathered from these sites are useful in examining the seasonal variation of soil water as well as disclosing the effect of the topographical features of the sites. However, in order to quantify the above differences between sites, a further detailed study covering a much larger sampling network is needed, which involves monitoring of other meteorological and environmental variables such as solar radiation, soil temperature, soil evaporation, vapour pressure and humidity, wind speed and rooting zone (Stearns and Carlson, 1960; Nisbet, Mullins and Macleod, 1989; Jorgensen and Gardner, 1987). In this context, the use of a neutron probe is highly recommended.

5.4 Forest Evapotranspiration

Estimation of the forest evapotranspiration (ET) is fundamental to most hydrological studies and is also important in the understanding of natural cover growth and responses. However, estimation of ET from the forest environment has proved to be elusive as it is not only controlled by climatic factors but also by physiological factors (Monteith, 1965; Stewart, 1977; Halldin et al., 1984/85; Sharma, 1984).

The term evapotranspiration used in this analysis, as adopted by the Australian Water Resources Council (1969), refers to evaporation from natural surfaces regardless of whether the water source is in the soil or vegetation, or, as is generally the case, is a combination of both. Hence, the word evaporation, as occasionally used in this study is in the above context. The term potential evapotranspiration (PET) is understood to refer to the maximum rate of ET, under the given weather conditions, from a large area covered completely and uniformly by actively growing vegetation with adequate moisture supply at all times (Brutsaert, 1982 as quoted by Be Bruin, 1983). Shuttleworth (1979) adopted a similar definition in his exhaustive review on evaporation and its methods of estimation.

5.4.1 Estimation of forest evaporation

In the ensuing analysis, the estimation of ET is undertaken using both the Penman Method (1948) and the Priestley-Taylor or P-T method (1959). In fact, the construction of the climate station at BEW has been geared to using the above equations for estimating ET. Evaporation estimated by the Pan Methods from this watershed will also be referred to but data from this instrument will not be subjected to detailed analysis. This is because estimation by this method is believed to be doubtful and inaccurate for the following reasons:

a. occurrence of overflows during extreme storm events
b. presence of forest insects, amphibians and other small aquatic animals in the pan
c. difficulty in maintenance and logistics during the rainy season

Despite the above shortcomings, the Drainage and Irrigation Department (DID) and Meteorology Department of Malaysia have been using the above method in their climatic monitoring, mainly covering non-forested areas in addition to using the Penman Method (Scarf, 1976).

a. The Penman method

The choice of the Penman Method is not only dictated by its extensive use in many hydrological studies (Shuttleworth, 1979; Shaw, 1983) but also because of the satisfactory results obtained by several authors working in the tropics in Africa, Indonesia and Malaysia (Edwards et al., 1981; Bruijnzeel, 1989; DID, 1986; De Bruin, 1983). As for the Priestley-Taylor method, essentially a modification of the Penman Method, De Bruin (1983) found that it is applicable in the tropics with prediction almost equal to the water equivalent of net radiation. Furthermore, DID of Malaysia has recommended both methods for estimation of ET and has produced several empirical constants for the respective formulae (DID, 1977).

Due to the different form of the Penman equations and diversity of computation methods (tables and monographs), the present analysis employs the methodology as adopted by DID (1977) which essentially conforms to the original form of the Penman (1948) equation (Appendix 17). McCulloch (1965) has applied a similar approach in estimating ET for forested watersheds in Kenya, Africa. Derivation of empirical constants including R_A, 'a' and 'b' and their statistical significance has been discussed by Scarf (1976) based on local data in Malaysia (Appendix 17). However, a slight modification is introduced in this analysis with regard to the albedo value. Instead of a value of 0.18 as originally recommended, this study adopts a value of 0.12 based on recent work in the tropical forests of Thailand, Nigeria and Brazil, respectively (Pinker et al., 1980; Oguntoyinbo and Oguntala, 1976; Shuttleworth, 1984).

b. The Priestley-Taylor method

As for the P-T formula, De Bruin (1983) suggested the following form taking into account some of the empirical constants recommended by Doorenbos and Pruitt (1977):

$$(PET)_0 = (0.36\ R_a - 41)(n/N) + 0.18\ R_a - 5 \quad \text{.....Equation 5.4}$$

where:

$(PET)_0$ in W/m^2

R_a = extraterrestrial incoming shortwave radiation

n/N = relative duration of bright sunshine

Necessary data for the two methods - air temperature, relative humidity, wind speed and net radiation - are continuously monitored at the Climate Station in BEW. Estimation of net radiation is obtained by the empirical equation relating to the sunshine duration (Scaft, 1976).

The crop-factor approach as recommended by Doorenbus and Pruitt (1977) has been employed in computing the forest evapotranspiration as follows:

$$ET_{crop} = k_c \times (PET)_0 \quad \text{....................Equation 5.5}$$

$$(PET)_0 = f \times E_0 \quad \text{........................Equation 5.6}$$

where:

k_c = crop factor

$(PET)_0$ = pot. evapotranspiration of open water
f = pan coefficient
E_0 = pot. evaporation of open water

Basically Equation 5.6 follows the approach of Penman (1948) in its original form but the value of 'f' has been modified in this case following the DID recommendation which is 0.85. The crop-factor (k_c) of 1.15 is adopted for the tropical forest as suggested by Edwards et al. (1981) based on their work carried out in Kenya and Tanzania, Africa.

5.4.2 Monthly and annual evapotranspiration

Estimation of monthly and annual ET for this watershed using the two methods are in strong agreement (Table 5.5) although the P-T method consistently exhibits a slightly higher value than that of the Penman method by approximately 1 to 2 %. The forest ET in the humid tropics normally assumes a conservative value and varies over a small range. The annual ET ranges from 1362 to 1481 mm with an average of 1438 and a coefficient of variation of 2.5% as opposed to 17% for the annual rainfall. The Pan method systematically gives a much lower value than the other two methods by about 15%, thus rendering these measurements doubtful as indicated earlier.

The annual ET of Sg. Tekam under forested conditions ranged from to 1482 to 1567 mm, employing an albedo value of 0.18 thus giving slightly higher values (DID, 1986). However, Bruijnzeel (1983, 1989) obtained a similar value amounting to 1527 mm, using the same framework while working in a forest plantation in Indonesia while Edwards (1979) reported a value of ET of 1510 for forested areas in Africa. Adopting a sophisticated micro-meteorological research set-up in the Amazon forest in Brazil, Shuttleworth et al., (1984) reported daily mean ET values ranging from 3.80 to 5.24 mm by using several formulae with an albedo value of 12%. In reviewing forest ET research work representing the three rainforest zones, Bruijnzeel (1989a) suggested a mean value of 1460 ± 27 mm per year.

Monthly ET of this watershed is less variable and ranges from 90.0 to 153.0 mm with a mean of 120.0 mm and C.V. of 9.2 % based on

Table 5.5 Monthly and Annual Evapotranspiration of Berembun Experimental Watershed, 1980/81 - 1986/87

WT. YR	METHOD	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
	PENMAN	122.0	116.3	129.8	118.8	104.8	104.4	106.5	119.0	153.1	126.9	123.0	131.3	1455.8
1980/81	P-T	124.6	119.2	128.9	125.0	109.1	108.2	113.8	126.3	159.9	123.9	124.6	126.3	1489.9
	PAN	93.2	95.3	100.3	104.6	82.1	86.9	94.9	122.5	141.2	106.5	104.6	100.2	1232.3
	PENMAN	129.0	142.1	122.8	124.9	109.3	104.8	120.9	126.5	129.5	128.2	126.4	116.4	1480.9
1981/82	P-T	131.6	144.8	120.0	127.1	110.0	110.1	132.3	135.7	129.0	123.6	123.1	112.5	1500.0
	PAN	103.9	108.8	83.9	96.0	85.0	103.2	107.4	118.3	124.2	98.2	88.9	105.2	1223.1
	PENMAN	119.1	114.5	113.3	120.7	120.2	107.0	120.0	133.7	151.6	129.7	127.9	109.5	1467.2
1982/83	P-T	121.0	116.3	110.4	126.4	123.4	113.0	128.4	142.0	147.3	117.0	122.7	103.4	1471.3
	PAN	99.7	84.8	117.3	119.9	91.9	105.9	108.8	146.7	140.4	120.8	119.4	113.2	1368.8
	PENMAN	116.5	117.5	124.6	128.4	102.1	90.0	103.4	95.9	128.7	128.8	114.9	110.6	1361.5
1983/84	P-T	115.1	118.2	123.9	134.2	102.2	92.7	106.0	99.1	136.1	126.4	113.2	106.2	1373.2
	PAN	103.6	102.4	95.2	114.6	89.9	85.5	103.6	106.6	131.9	112.0	117.6	93.3	1256.3
	PENMAN	119.3	125.6	127.8	121.0	114.9	95.9	126.9	111.5	128.0	122.8	119.5	123.0	1435.9
1984/85	P-T	118.3	131.1	126.6	125.5	116.2	100.7	138.7	116.1	130.4	119.5	117.9	115.7	1456.7
	PAN	99.1	112.0	114.1	109.5	109.0	99.1	110.1	106.4	96.4	103.8	106.2	97.1	1262.7
	PENMAN	122.4	121.9	129.2	113.3	109.6	106.4	94.6	118.1	122.0	129.5	125.2	130.0	1422.3
1985/86	P-T	122.3	124.5	127.9	118.1	110.0	113.6	97.9	128.0	123.7	127.9	124.6	126.1	1444.6
	PAN	102.5	90.2	107.2	98.1	97.8	87.5	88.6	112.4	113.4	92.7	98.3	74.3	1163.2
	PENMAN	130.1	125.2	116.9	122.6	101.2	117.3	126.9	111.5	127.9	122.8	119.4	123.0	1444.7
1986/87	P-T	130.7	124.8	113.6	125.0	103.4	125.0	116.7	141.1	146.2	139.5	129.3	120.5	1515.9
	PAN	75.6	85.0	86.6	99.7	0.0	0.0	88.6	112.4	113.4	92.7	98.3	74.3	926.7

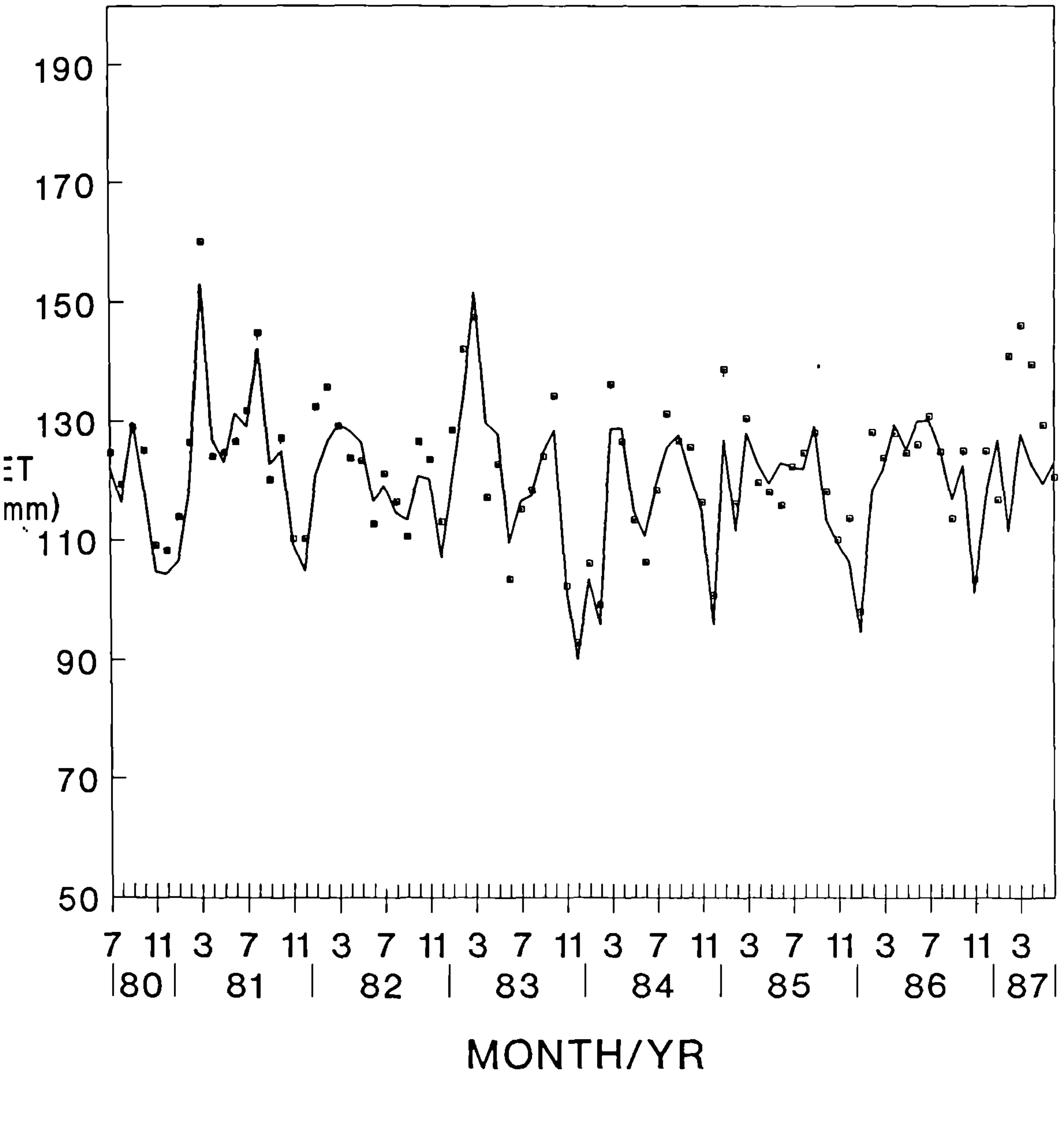


Figure 5.27 Monthly forest evapotranspiration at BEW based on a 7-year period

the Penman Method (Figure 5.27). Corresponding estimates by the P-T methods are 93.0 and 160.0 mm with an average of 120.0 mm and C.V. of 9.8%, respectively. The monthly ET seldom drops below 100 mm except for a few occasions as also observed in Sg. Tekam Experimental Basin (DID, 1986). Despite a moderate variation in ET, a monthly fluctuation still exists which possibly reflects in part fluctuation of other determinant factors including soil moisture storage, micro-climatic variables and physiological factors. In this respect, the ET is normally assumed to consist of three main components such as in the following equation (Bruijnzeel, 1989b):

$$ET = E_i + E_t + E_s \quad \text{.............................Equation 5.6}$$

where:

E_i = rainfall interception (evaporation from a wet canopy)

E_t = transpiration (evaporation from a dry canopy)

E_s = evaporation from a forest floor

The mean monthly ET, based on seven years of data reveals a recognizable pattern but one which is slightly different from that of monthly rainfall (Figure 5.28). A minimum ET occurs immediately after the peak rainfall, in the months of November, December and January. Accordingly, the monthly ET remarkably increases and attains a maximum value in March, one month before the second rainfall peak. Minimum ET in the above three months, essentially the wet months of the North-east monsoon, can be associated with cloudy days and overcast conditions, which invariably reduce the amount of solar radiation input. In fact, this phenomenon is reinforced by the sunshine duration for the three consecutive months which recorded lower values (Figure 3.8). As soon as the sunshine duration increases in the following months, February and March, the monthly ET steadily increases.

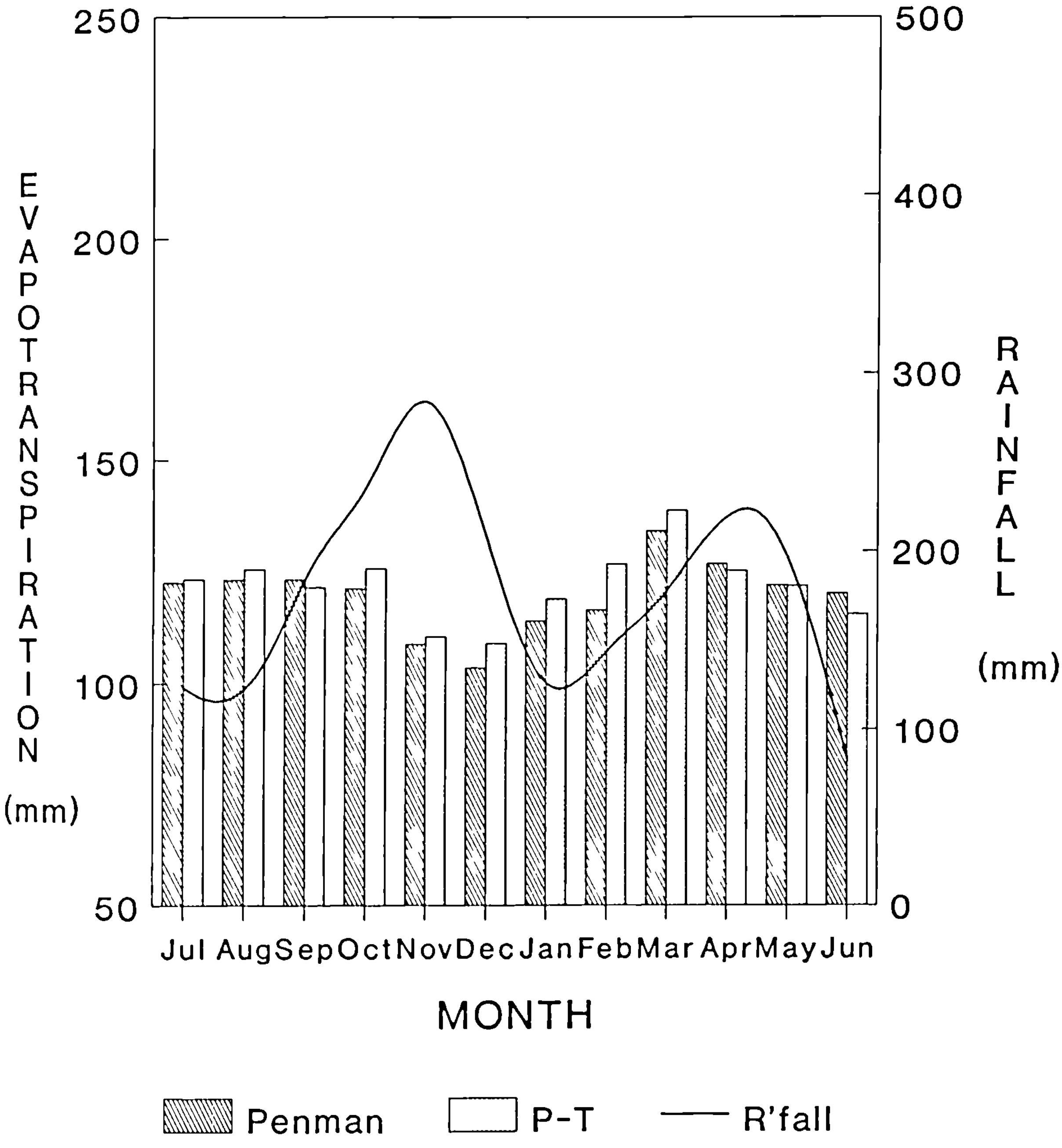


Figure 5.28 Mean monthly forest evapotranspiration and mean rainfall at BEW

Despite a reasonably high soil water content during the wet months of the North-east monsoon, November to January, monthly ET depicted relatively low values. This could suggest that in the tropical forests, the solar radiation is relatively more important than other determinants, including soil water storage and wind speed, in controlling the rate of ET. Moreover, the wind speed in the tropics is normally low compared with other regions of higher latitude (Lauer,1989). Hence, the contribution from the soil water and forest floor evaporation to the total ET in the tropical forest can be practically relegated to minimal at best, or even neglected as suggested by several authors (Bruijnzeel, 1989b; Jordon and Heuveldop, 1981; Roche, 1981 as quoted by Bruijnzeel, 1989b).

5.5 Conclusion

The preceding results reveal some pertinent hydrological characteristics emanating from the humid tropics. As often emphasized by many authors, adequate and high-quality databases on hydrological parameters are essential and fundamental in order to describe fully the hydrological role of tropical watersheds. In this instance, the presence of a dense forest cover in such a watershed indeed provides a unique opportunity to attempt to quantify the influence of tree cover on hydrological processes considering the inherent physical and climatic features in the tropics. Hence, the frequently asked question, as to whether or not tropical watersheds are any different from those of temperate areas in terms of their hydrological responses, could be objectively examined.

As presented earlier, amongst characteristics typical of the rainfall in tropical watersheds are a double-maxima rainfall pattern with no appreciable distinct dry season and a convectional type of rainfall which leads to a remarkable diurnal rainfall pattern. An exceptionally large number of storm events is evident and normally typified by an extreme intensity and short duration. As a result, the mean monthly intensity often exceeds the threshold level of the rainfall erosive capacity. The forest evapotranspiration in the tropics normally assumes a conservative value and shows minimal variation over the years and constitutes more than 50% of the gross rainfall. Apparently, high input of solar radiation in the humid tropics seems to be the primary factor causing high annual ET, the rate of which is probably comparable to the potential rate. In this context, direct evaporation from the soil water conceivably contributes little to the total ET under the forest environment whilst a great variability in the soil water content largely depends on topographical factors and also antecedent conditions as influenced by the rainfall regime.

This chapter also specifically dealt with the question of what happens upon harvesting or partial removal of forest cover under humid tropical conditions with respect to the water yield. The preceding discussion indicates that forest operations such as the selective logging method as prescribed by the Forest Department of Peninsular Malaysia, result in a substantial increase in the water yield and the increase persists for some years following the harvesting operation. The climatic regimes during and immediately following treatment largely influence the magnitude of increment in addition to other factors such as the extent of forest cover removal and the soil composition of the site.

Up to the present level of analysis, the increase in water yield is primarily associated with the augmentation of baseflow, principally due to the nature of selective logging, which leaves a large area undisturbed, and thus permits greater recharge to groundwater storage, coupled with reduced forest evapotranspiration. However, the above inference is still not wholly conclusive without a detailed analysis of the stormflow parameters which will be discussed in the later chapter.

In spite of remarkable findings from the above analysis, some shortcomings in the experimental set-up emerge especially in the location of the soil water network. For a similar study in the future, greater replication is necessary together with rigorous monitoring of other environmental variables, and, in addition, a neutron probe should be used for comprehensive sampling.

While the above analysis suggests an increase in water yield resulting from forest logging, the following chapter will quantify the magnitude of increase in reasonable detail. In addition, the chapter will assess the increase with appropriate statistical tests and also indicate its significance. Finally, the apparent increase in yield will be discussed in relation to results of other paired-catchment studies, and in particular, those from other tropical regions.

CHAPTER 6

WATER YIELD CHANGES FOLLOWING CATCHMENT TREATMENT

Forest cover generally utilizes much more water than other types of vegetation such as agricultural crops and grass, mainly due to its canopy structure and species composition. This is particularly true of the tropical rainforest. Consequently, the conversion of forest to other types of land use is usually accompanied by increases in streamflow discharge as a result of a reduction in evapotranspiration (Bosch and Hewlett, 1982; Hamilton and King, 1983). As tropical forest continues to be exploited at an alarming rate, its disappearance may constitute major environmental and hydrological problems for mankind. Sustained yield management of tropical forests has therefore been suggested in an effort to conserve natural forests for continuous production of timber and commodity services including the protective role of forests. The above approach essentially entails a partial removal or selective type of forest logging according to certain prescribed cutting regimes and criteria, for example, as currently practised in Malaysia (Thang, 1986). While adequate information on the effect of forest conversion on some hydrological parameters has been gathered (DID, 1986; DID, 1989), there has been little information on the effects of selective logging methods on the hydrological regime. Therefore, a quantitative evaluation of water yield changes resulting from the current practice of forest harvesting is essential to satisfactory forest management as well as in watershed management generally. In this instance, a paired-catchment research project provides an objective approach to detecting the magnitude of water yield increase as a result of forest logging.

6.1 Calibration Analysis

As mentioned earlier, the calibration phase in this study lasted for a three-year period, from July 1980/81 to June 1982/83. Subsequently, C1 and C3 were harvested or treated according to specified regulations and guidelines as discussed in Chapter 4. Basically, a selective logging method has been prescribed in the framework of the current management practice adopted by the Forestry Department of Peninsular Malaysia called the Selective Management System or SMS (Ministry of Primary Industries, 1988). Accordingly, C1 underwent a commercially selective logging or the unsupervised method which is locally known as the 'San-tai-wong' method, whilst C3 follows a supervised selective logging. Detailed prescriptions of the above methods are given in Table 4.2 and are elaborated on in Appendix 11.

A three-year calibration period is deemed sufficient to account for climatic variations prevailing at this location. In fact, the calibration period embraced extreme rainfall regimes in that both wet and dry years were experienced (Figure 5.1). More importantly, the statistical analysis of the calibration period indicates satisfactory results. In addition, the area was due for logging according to the local schedules as administered by the District Forest Office of Kuala Pilah, Negri Sembilan.

In fitting a calibration equation using the regression techniques, an approach proposed by Gujarati (1970; 1988) has been adopted in this analysis as it has been widely applied in detecting water yield changes following treatment in paired-watershed studies (Hewlett et al., 1984; Swindel et et., 1982; Hsia, 1987; DID, 1986). The monthly runoff of treated catchments (C1 and C3) serves as the dependent or response variables against selected variables of the control catchment as independent or predictor variables. In this case, the choice of predictor variables is essentially based on the common statistical parameters that reveal the best fit including the coefficient of determination (r^2), standard error of estimate (s.e.) and Durbin-Watson (D.W.) value (Table 6.1). Two calibration equations are required for this purpose, involving C1 and C3 against C2, which serves as the control. The step-wise regression suggests that the likely predictor variables for the above models are monthly runoff (Q_2), monthly rainfall (P_2) and one-month antecedent runoff (Q_{2a}). In model specification for prediction purpose, the simpler the model, the better it is (Gunst and Mason, 1980). Thus, the three best combinations of regression models incorporating the above mentioned variables with number of samples (n) = 36, have been short-listed for further consideration (Table 6.1). Evidently, the best fit for calibration equations based on statistical indices comprise Model 2 and 5; essentially both models use runoff and rainfall as predictor variables. Although the addition of monthly rainfall in both cases increased r^2 only by about 1%, it correspondingly reduces the s.e. whilst the variable itself is highly significant, except for Model 2 which is only significant at $p < 0.01$. On the other hand, the introduction of one-month antecedent runoff apparently did not improve the fit remarkably and furthermore the variable itself was insignificant based on its t-value for both cases (Model 3 and 6). The test for presence of any serial correlation in the equation was provided by the Durbin-Watson values, results of which are discussed in the following section.

Table 6.1 Parameter estimates of the regression models

#	Y	Predictor variables Q_2	P_2	Q_{2a}	r^2	s.e.	D.W.
1	Q_1	0.8672 (20.210)**			0.9231	4.641	1.755
2	Q_1	0.7900 (12.797)**	0.0165 (1.696)*		0.9293	4.517	1.872
3	Q_1	0.8969 (18.126)**		-0.0442 (-0.886)ns	0.9268	4.633	1.752
4	Q_3	0.8091 (20.913)**			0.9278	4.185	1.642
5	Q_3	0.6985 (13.478)**	0.0236 (2.900)**		0.9425	3.792	1.731
6	Q_3	0.8323 (18.464)**		-0.0358 (-0.788)ns	0.9297	4.221	1.767

Numbers in brackets indicate t-values

**significant at $p<0.001$

* significant at $p<0.01$

ns not significant

Hence, the above model specification indicates the adequacy of the equation for prediction purposes. Incidentally, similar model specifications have been employed by DID (1986; 1989) and Hewlett et al. (1984) in detecting water yield changes in Malaysia and the USA.

The adequacy of fit of a particular model can be further validated using a residual analysis. In fact, statistically, the above analysis constitutes one of the most important tasks in any regression analysis (Gunst and Mason, 1980). It involves a careful inspection of the difference between the observed and predicted data or residual values after the equation has been fitted to the data set. Familiar techniques for examining residuals involve plotting of the residuals against corresponding fitted values and also computation of several numerical approaches. A graphical approach will indicate any trend or extreme measurements in the data (e.g. outliers). The residual plot will also identify potential problems, to verify model assumptions, such as the shape of error distribution, and to determine the relative importance of predictor variables. As for the numerical approaches, there are many types of residual measure such as raw residuals, deleted residuals, standardized residuals and studentized residuals. However, in this analysis, the raw residual and standardized residual are employed in the residual plot. Examination of the fitted regression around the observed data shows that all data are within the 95% confidence interval for both equations (Figure 6.1 and 6.2). The minus intercept indicates that, on average, the monthly runoff of C2 is systematically higher than C1 and C3 during the calibration period as pointed out previously.

Residual plots between observed and predicted values reveal no discernible pattern and points are randomly scattered around the zero line (Figure 6.3 and 6.4). In this case, standardized residuals are used which are essentially residuals which are divided by estimated standard deviation of residual to mimic standard normal deviates (Gunst and Mason, 1980). In addition, the absence of any recognizable pattern demonstrates that the models have correct specifications and proper functional forms of each predictor variable. In the above cases, the absolute standardized residuals are less than 10 mm. The above plots simultaneously help in detecting outliers or observations that have extremely large residual values. No obvious outliers are present in the data set.

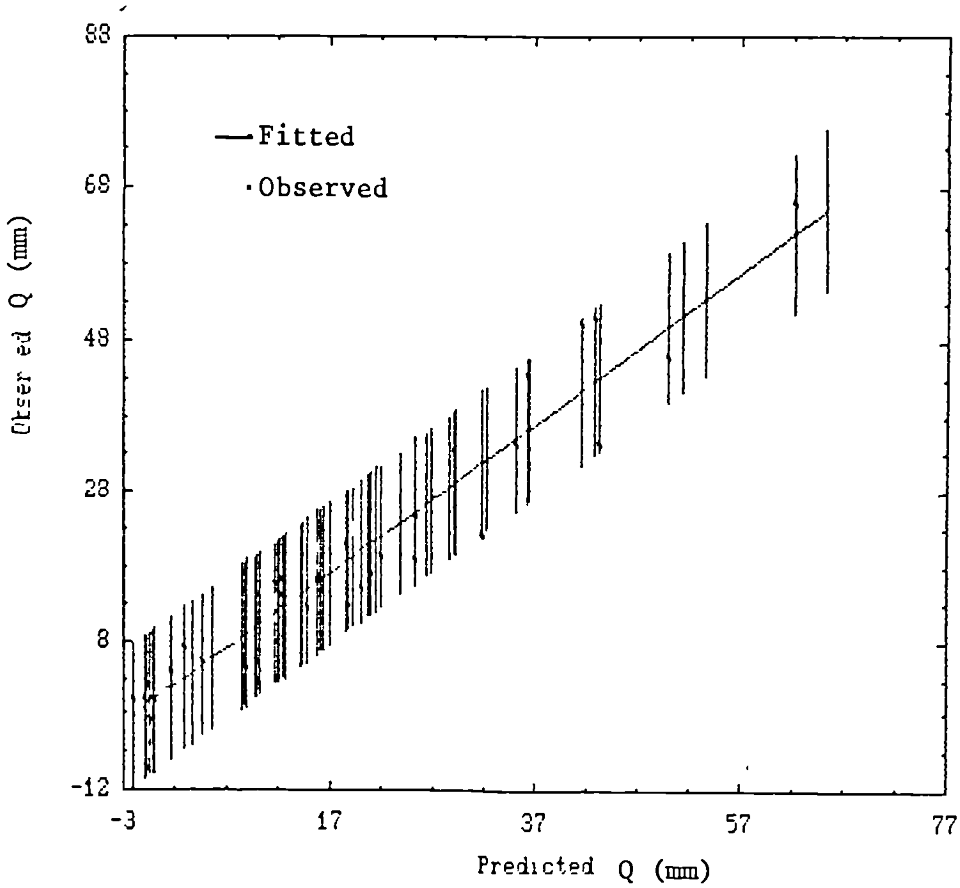


Figure 6.1 Regression line of Model 2 with 95% C.I. and observed runoffs (mm) of C1

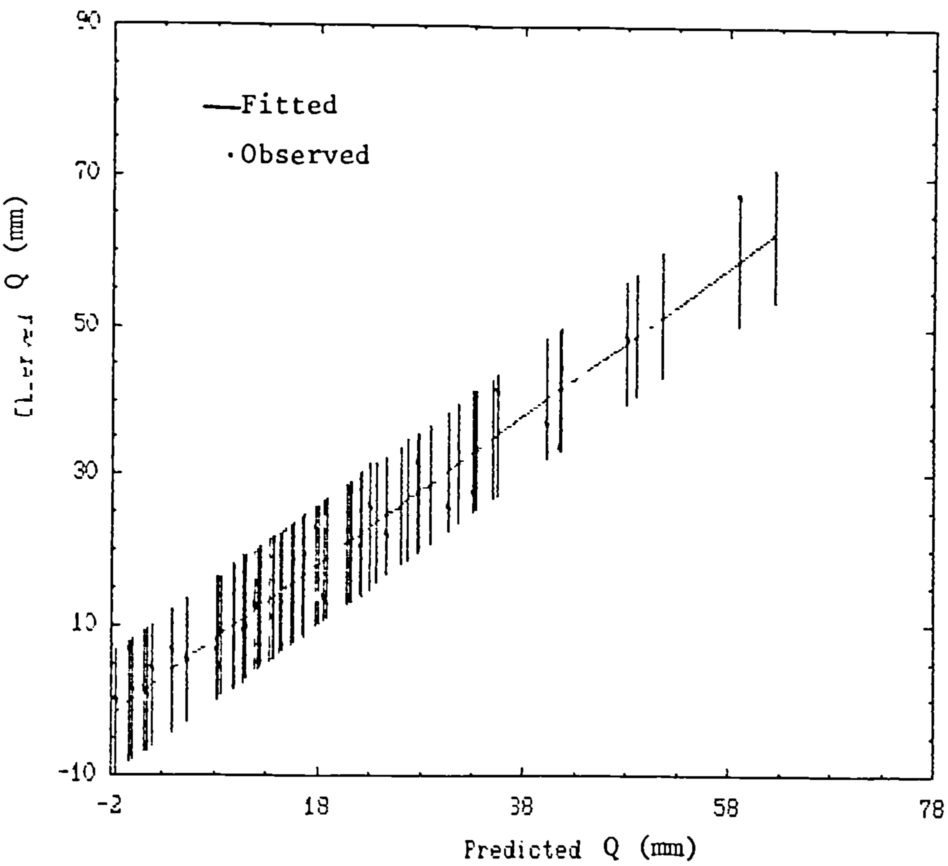


Figure 6.2 Regression line of Model 5 with 95% C. I. and observed runoffs (mm) of C3

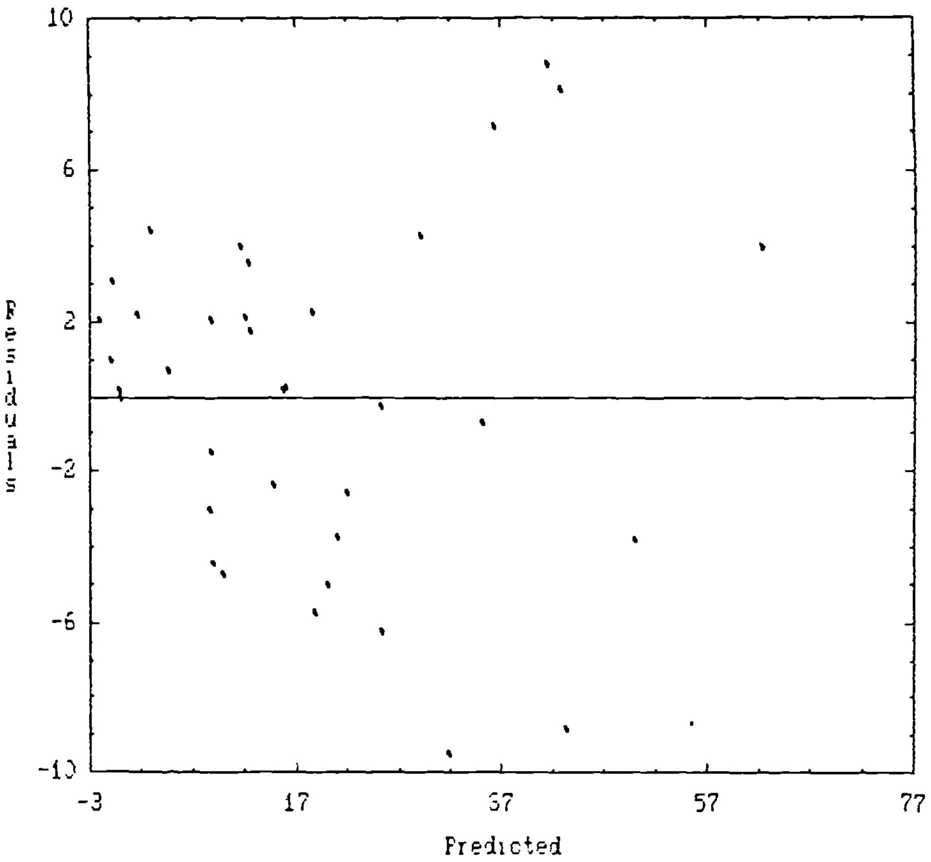


Figure 6.3 Residual plot of Model 2

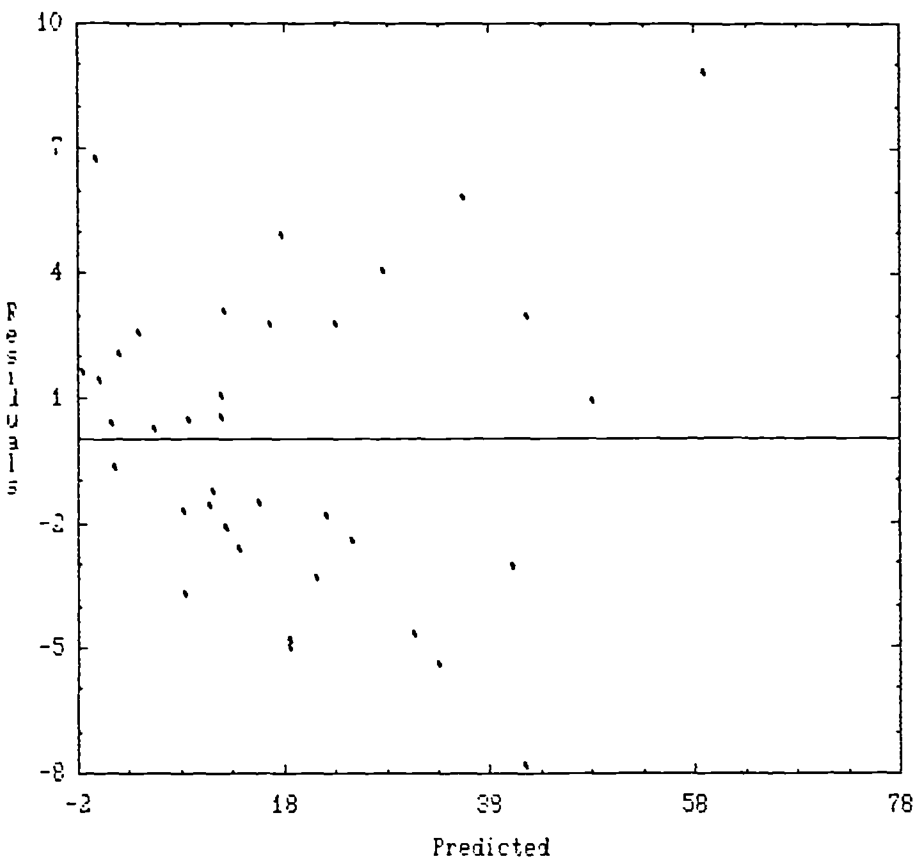


Figure 6.4 Residual plot of Model 5

One of the important assumptions in the regression analysis is relating to the error terms (E_i). The assumption asserts that the errors are normally independently distributed with 0 mean and constant variance (Draper and Smith, 1981; Gunst and Mason, 1980). To check the validity of the above assumption calls for a normal probability plot. If errors are normally distributed, the data points should lie approximately on the straight line. For this type of plot, the minimum sample size should be 20 (Daniels and Wood, 1971). The plot points conform to the above pattern thus indicating that the error terms are normally distributed in both models (Figure 6.5 and 6.6).

Another form of error normally present in time-series data such as these is correlated errors or a serial correlation. In fact, this is one of the reservations echoed by several authors against using monthly data in the regression analysis (Reigner, 1964; Reinhart et al., 1963). In this context, the Durbin-Watson test statistic (D.W.) provides a convenient method of detecting the presence of such correlation in the data by comparing D. W. values against the postulated bounds (Table 6.1). For a two-predictor model and n = 36, the lower (D_l) and upper (D_u) postulated bounds are 1.35 and 1.59. The null hypothesis Ho: E=0, (i.e. errors are uncorrelated), cannot be rejected if D.W. > D_u, as in this case. Therefore, it can be concluded that errors are uncorrelated and thus a serial correlation is not present.

6.2 Prediction of Water Yield Changes

Models 2 and 5 were employed to predict the monthly runoff for the entire period including four years of the post-logging period for

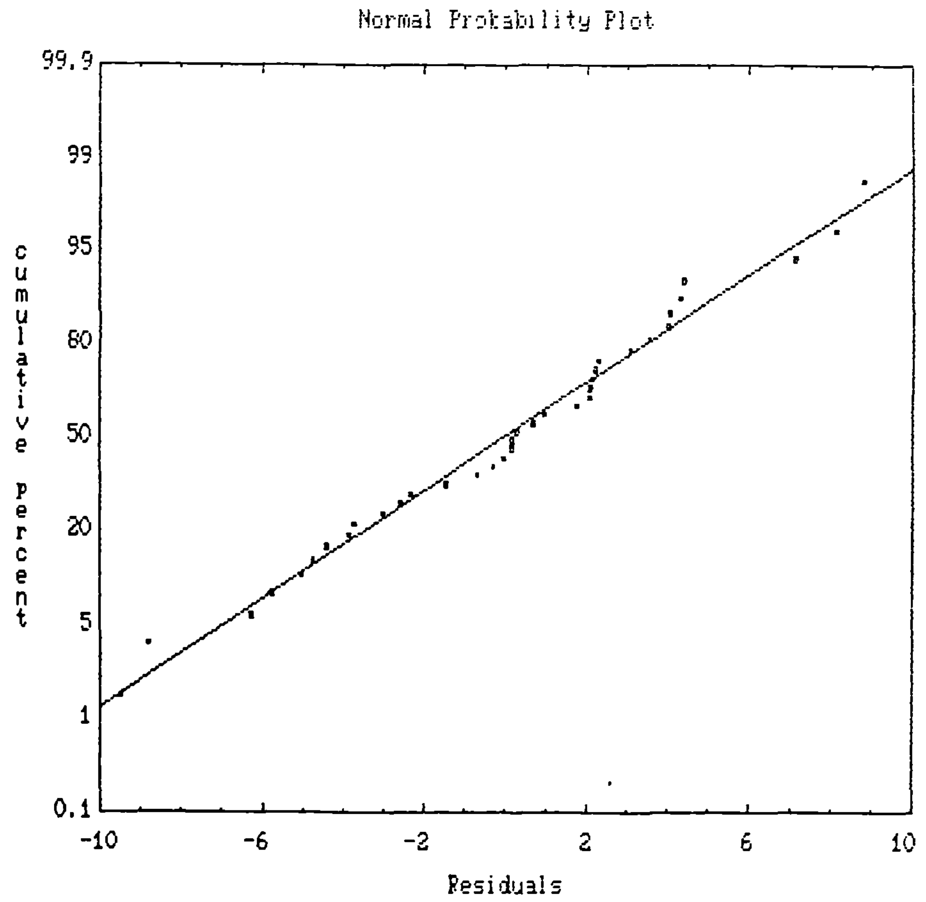


Figure 6.5 Normal probability plot of Model 2

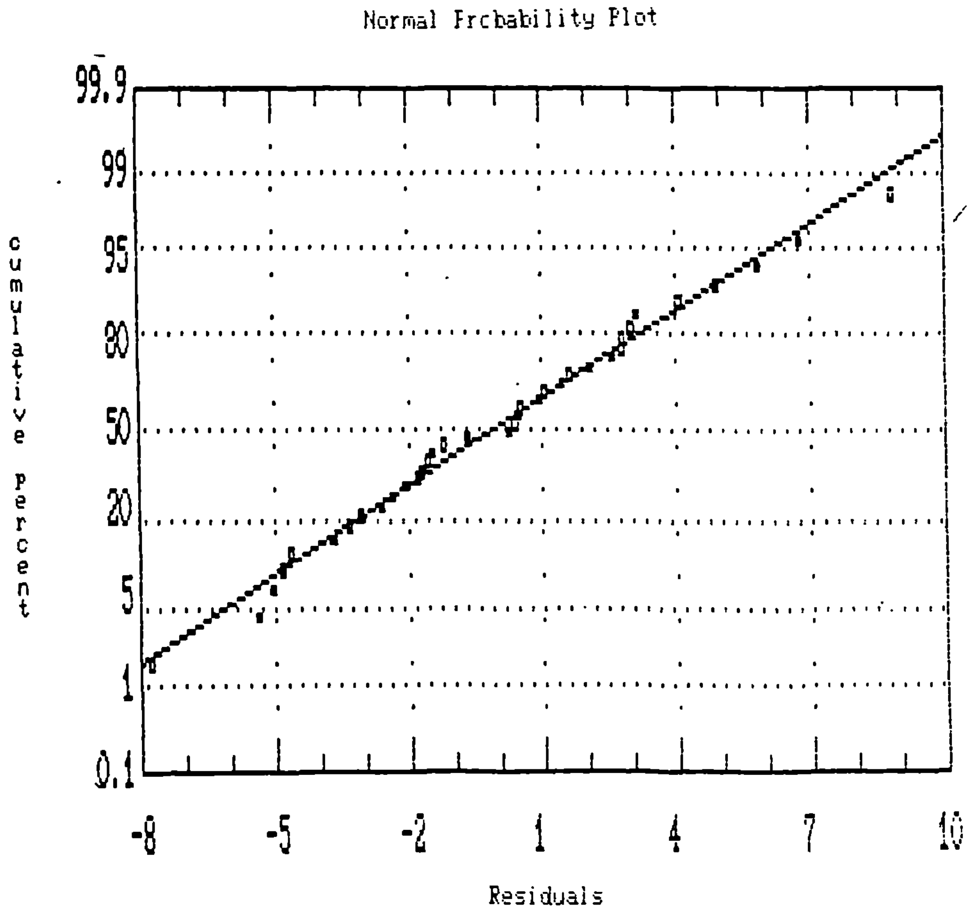


Figure 6.6 Normal probability plot of Model 5

the respective catchments. Subsequently, their deviations from the observed values are computed, representing the differences in water yield after both catchments have been logged (Figures 6.7, 6 8; Appendix 18). The yield of C1 substantially increased immediately after the forest harvesting. The monthly increase is reliable within the s. e. of estimate amounting to 4.5 mm. Apparently, the water yield increase persisted up to the fourth year after treatment with the average monthly increase amounting to 14 mm. Specifically, the annual water yield increase following treatment amounts to 165 mm (70%), 142 mm (55%), 175 (72%) and 155 (67%) in the first, second, third and fourth year, respectively. The mean annual increase over the four-year period is 160 mm/year or approximately 66%.

Similarly, C3 demonstrated an increase in monthly runoff immediately following the treatment, although a few months assumed negative deviations (Figure 6.8). Therefore, in examining the increments, it is instructive to observe annual yield over the year rather than monthly values which are sometimes subjected to seasonal fluctuation. The water yield increase persisted up to the fourth year following treatment as in C1. In particular, the annual yield increase in C3 in the first four years amounted to 87, 70, 106 and 94 mm or 37, 28, 44 and 41% per year, respectively (Table 6 5). The mean annual increase amounts to 89 mm or 38% and the monthly average is about 7 mm.

The apparent increases in annual water yield need to be tested in terms of statistical significance. A dummy regression technique provides a convenient approach of testing the above treatment effects. The approach involves the comparison of the residual errors from the full model containing a treatment effect with a reduced logging periods in the same regression. In this case, the introduced dummy variable (T) qualitatively serves to denote different phases of treatment in the data set by assigning '0' and '1' for the calibration and post-treatment periods respectively Hence, the full model and reduced model for the two periods take the following form

T = 1 (Full Model)

$Q_t = a_1 + a_2T + (b_1 + b_2T)Q_c + (b_3 + b_4T)P_c + E_i$ Equation 5 1

T = 0 (Reduced Model)

$Q_t = a_1 + b_1Q_c + b_3P_c + E_i$ . . .. Equation 5 2

where:

Q_t = the predicted monthly runoff of the variable Q on the treatment catchment
Q = observed monthly runoff (mm)
t = treated catchments, C1 and C3
c = control catchment
T = dummy variable (T = 0 during calibration phase, T = 1 during post-logging)
a_i and b_i = parameter estimates
E_i = error term

Subsequent multiple linear regressions in the form of Equations 5.1 and 5.2 involving 36 observations for both phases are sought and their parameter estimates are listed in Table 6 2. The full models for C1 and C3 apparently explained 94 and 91% of the variation in the monthly runoffs of the respective catchments. Relatively high r^2 and low standard error of estimates for both regression equations suggest the adequacy of the model as previously discussed

In the above regression models, the dummy variable has been introduced in the models in an additive form (addition of T to the intercept) and in a multiplicative form (T multiplied by Q_2 and P_2) Accordingly, the coefficient a_2 is called a differential intercept whilst coefficients b_2 and b_4 are a differential slope, they can be

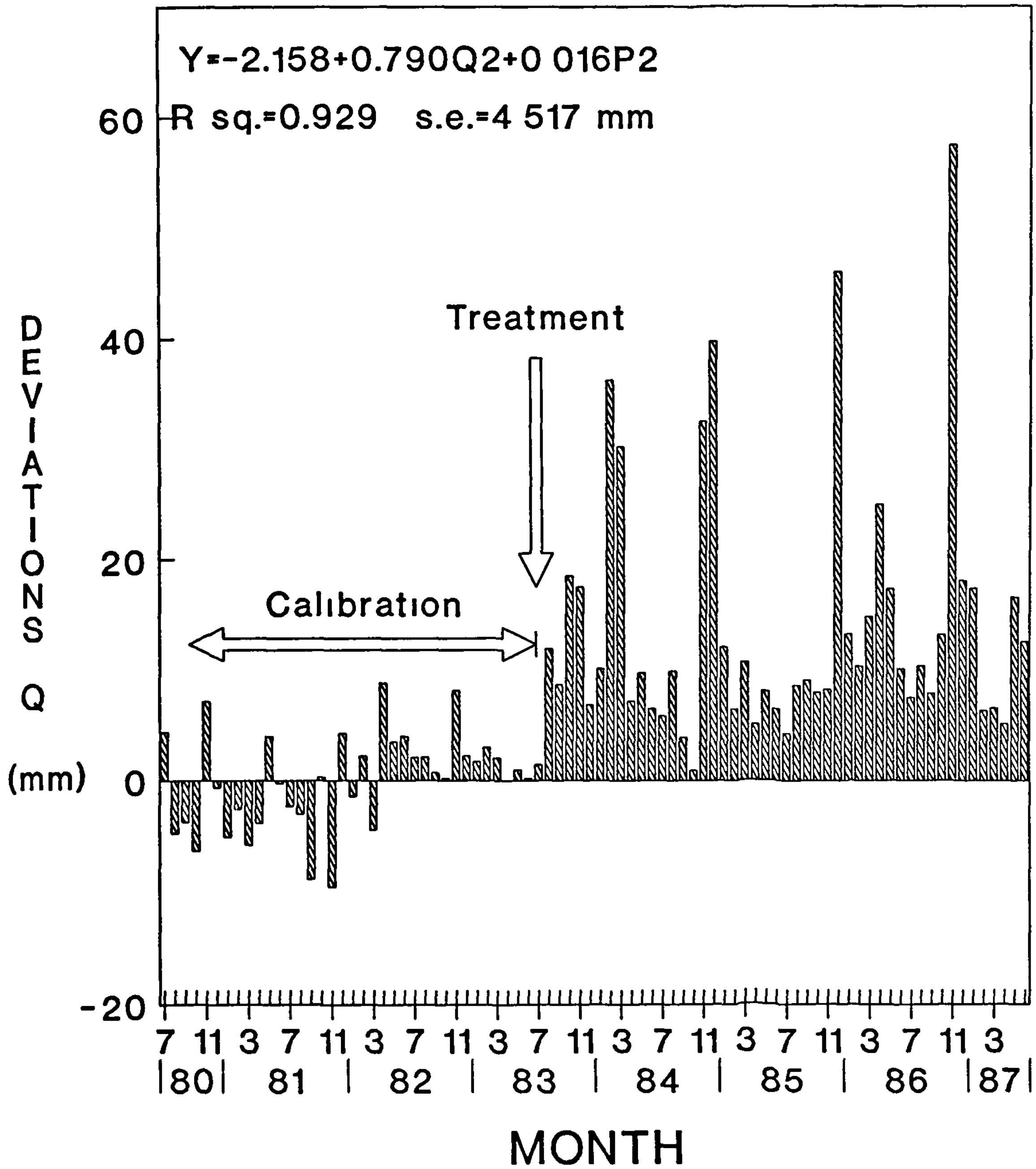


Figure 6.7 Deviations between observed and predicted runoffs (mm for catchment 1

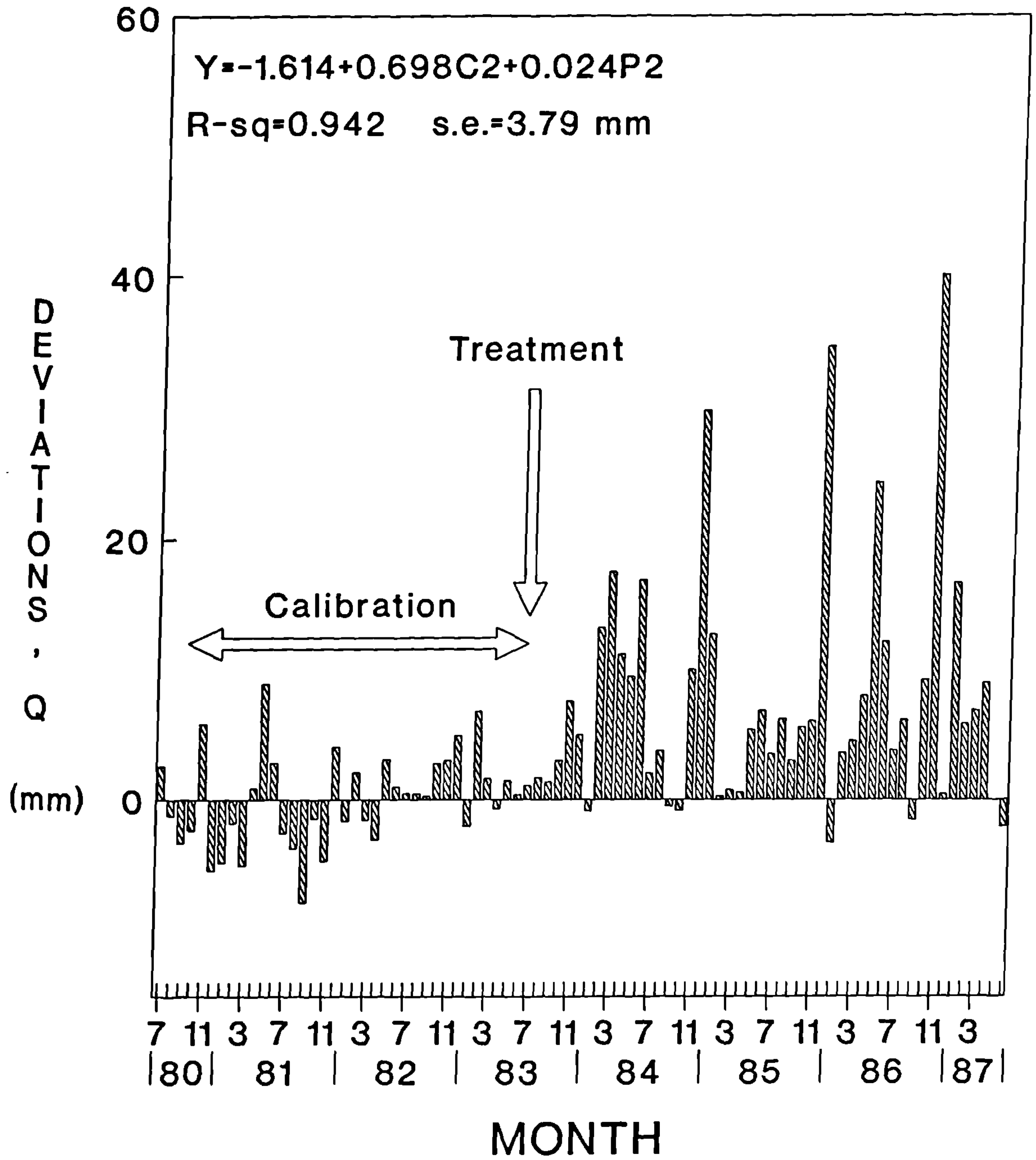


Figure 6.8 Deviations between observed and predicted runoffs (mm) for catchment 3

used in place of the standard analysis of variance as well as the analysis of covariance, respectively (Gujarati, 1970 and 1988) However, the dummy variable approach also allows the testing of intercept and slope simultaneously using the F-statistics on the null

Table 6.2 Regression statistics and parameter estimates of Full and Reduced Models

Model	a_1	a_2	b_1	b_2	b_3	b_4	r^2	s e	D W
Dependent = C_1									
T=1	-2 158	-0 093	0 790	0 533	0 016	0 002	0 939	5 592	1 952
			(10 339)**	(4 513)**	(1 371)ns	(0 126)ns			
T=0	-2 158		0 790		0 016		0 808	9 704	0 919
			(9 519)**		(2 314)*				
Dependent = C_3									
T=1	-1 614	2 560	0 698	0 441	0 024	-0 030	0 911	5 564	1 903
			(9 186)**	(3 755)**	(1 976)*	(-1 645)ns			
T=0	-1 614		0 698		0 024		0 845	7 165	1 329
			(11 444)**		(1 876)*				

* significant at p<0 01
** significant at p<0 001
ns not significant

hypothesis that the treatments have no effect on the monthly runoff (i.e Ho: $a_2 = b_2 = b_4 = 0$) as follows

$$F = \frac{(SS_1 - SS_2)/(df_1 - df_2)}{EMS}$$

where:

SS_1 = the sum of squares due to regression for the full model
SS_2 = the sum of squares due to regression for the reduced model
df_1 = degree of freedom of regression for the full model
df_2 = degree of freedom of regression for the reduced model
EMS = error mean square of the full model

If the F-statistic does not lead to rejection of the above null hypothesis, then the treatment operation does not have any significant effect on water yield. The computation of the F-statistics are based on the values from the analysis of variance tables for respective models (Table 6 3)

Table 6.3 Analysis of Variance for the Regressions

Dependent Q_1, Full Model (T = 1)

Source	Sum of squares	DF	Mean square	F-ratio	p-value
Model	31851.0	5	6370 20	203 726	0 0001
Error	2063.72	66	31 268		
Total	33914.7	71			

R-square = 0 939 Standard error of estimates = 5 592
Adj. R-square = 0 935 Durbin-Watson statistic = 1 952

Dependent=Q_1, Reduced Model (T = 0)

Source	Sum of squares	DF	Mean square	F-ratio	p-value
Model	27417.1	2	13708 5	145 575	0 0001
Error	6497.62	69	94.168		
Total	33914.7	71			

R-square = 0 808 Standard error of estimates = 9 704
Adj. R-square = 0 803 Durbin-Watson statistic = 0 919

Dependent = Q_3, Full Model (T = 1)

Source	Sum of squares	DF	Mean square	F-ratio	p-value
Model	20820 8	5	4164.17	134 520	0 0001
Error	2043 08	66	30 956		
Total	22863 9	71			

R-square = 0.911 Standard error of estimates = 5 564
Adj. R-square = 0.904 Durbin-Watson statistic = 1 903

Dependent = Q_3, Reduced Model (T = 0)

Source	Sum of squares	DF	Mean square	F-ratio	p-value
Model	19321.3	2	9660 66	188 162	0 0001
Error	3542 61	69	51 342		
Total	22863 9	71			

R-square = 0.845 Standard error of estimates = 7 165
Adj. R-square = 0 841 Durbin-Watson statistic = 1 329

Table 6.4 The F-Statistics for the full and reduced models

	$F_{(cal)}$	$F_{(tab)}$ at $p < 0.001$
C1	47.3	4 13 (3 ; 66)
C3	16.1	4.13 (3 ; 66)

Evidently, the above F-tests indicate that the observed increases in water yield are highly significant for both catchments particularly in C1 as shown by a relatively large F-value, 47 as compared with C3 (Table 6.4).

The significant increase in water yield evident from the above result reinforces the earlier analyses discussed in Chapter 4, in particular, the flow duration curves, runoff coefficients, and the baseflow recession curves analyses. In addition, the earlier results also reveal the fact that the magnitude of the increases differed between the two catchments in that C1 consistently indicated a higher response than C3 in all of the above analyses

The observed differences in water yield response can be chiefly attributed to a different percentage of forest cover removed from the two catchments in which C1 recorded a slightly larger percentage of forest removal, by 7% Despite this relatively small difference in forest removal, it translated into more than 55% higher in water yield response based on the annual mean. Conceivably, this can be explained by the actual number of trees being extracted or damaged in the process of harvesting As lower cutting regimes had been prescribed in C1, a greater number of trees were eventually cut which, in turn, may have resulted in more damage to the residual trees. Logging damage to residual trees in the hill dipterocarp forest has been exceptionally high and can amount to as much as 43% of stems > 10 cm dbh (Phillips, 1987), or even higher as reported by Burgess (1971). Unfortunately, the enumeration of the residual damage conducted together with the botanical survey is not ready for the present analysis. While the degree and type of damage incurred may vary, quite often serious damage may lead to trees dying or to a large portion of canopy being snapped off. In addition, a higher density of skid trail is normally required in order to provide adequate access to a larger number of trees This is indicated in C1 with the skid trail density being 60% higher than that of C3 despite the fact that the density of the logging roads was similar In turn, this resulted in more trees having to be removed or possibly damaged in the construction of these trails. The underlying fact is that C1 was commercially logged which invariably vitiated many of the regulations normally prescribed in the logging exercise

On the other hand, since catchment C3 was subject to a supervised logging, only prescribed trees were taken out following quite stringent cutting regimes and thus, as expected, fewer trees were harvested. Thus a much lower density of skid trails was involved while the damage to the residual trees was kept to a minimum. In this instance, the buffer strip or riparian zone of a minimum distance of 20 m from each side of the stream was instituted and strictly enforced and hence the ground disturbance has been limited to certain areas such as logging roads, skid trails and landings.

One interesting point which emerges from the result of this analysis relates to the variability of the runoff response It is quite evident that the prevailing rainfall pattern influences the magnitude and extent of water yield response In fact, the differentials in the annual water yield increases following treatment closely follow the annual rainfall pattern for both catchments (Figures 5.1, 6.7 and 6 8) The first and third year after treatment recorded a higher annual rainfall which accordingly was reflected in the magnitude of water yield increase in both catchments Similarly, values for the second and fourth years portrayed a rather low rainfall that was reflected in a relatively lower yield of C1 and C3 Thus, undoubtedly, the rainfall regime during and following treatment largely determines the magnitude of any increase.

6.3 Comparison with Other Tropical Studies

To compare the above response with a similar setting locally, the Sg. Tekam study may provide a useful comparison on the effect of forest logging followed by clearance (DID, 1986, Abdul-Rahim, 1988) At Sg. Tekam in the harvesting and clearance of sub-catchment B, representing about 60% of the total area, the water yield increase after the first three years amounted to 145 mm, 155 mm and 137 mm per year. The above increases, by and large, are comparable with the responses observed in C1 which underwent a 40% cut However, in interpreting the above results, two factors are worth pointing out The first is that the forest cover in Sg. Tekam Basin prior to logging consisted essentially of logged-over or secondary forest and secondly, the area is located in a lower rainfall zone in Peninsular Malaysia Intuitively, the above two factors have some bearing on the hydrological response treatment.

The normal conclusion of temperate results is that the greatest increase occurs in the first year following treatment but this is not observed in the present study nor in the Sg Tekam catchment In fact, the increase tends to persist for a few years before the runoff reverts back to the normal level, if ever this happens. The above anomaly could be ascribed to the fact that the growth of the rainforest, particularly the dipterocarp species present in Peninsular Malaysia, is remarkably slow and takes a longer time to return to a stable condition. However, the undergrowth on the forest floor and the pioneer species establish themselves much quicker and are thus beneficial in covering up the ground disturbance.

As mentioned earlier, little quantitative data are available on the effect of selective logging practice per se from the tropics on water yield. Most of the documented studies so far normally deal with the effect of clearcutting of natural forests followed by either reforestation or conversion to agricultural land use (Bosch and Hewlett, 1982; Oyebande, 1988, Bruijnzeel, 1986). One exception has been the Babinda study located in tropical north-east Australia where Gilmour (1977) has documented some effects of forest logging followed by clearance. However, the result here did not indicate any significant change in monthly streamflow except after forest clearance. The author ascribed the above phenomenon to the rather extensive character of the type of logging practised, which left a fair amount of canopy and perhaps the forest floor largely intact. In another recent study conducted in a high rainfall region of Zambia (c. 1400 mm), Mumeka (1986) reported increases in water yield following the clearance of *Brachystegia* woodland to agricultural land use. The average annual increase ranged from 194 to 230 mm or 56 and 74% for the two treated catchments, respectively.

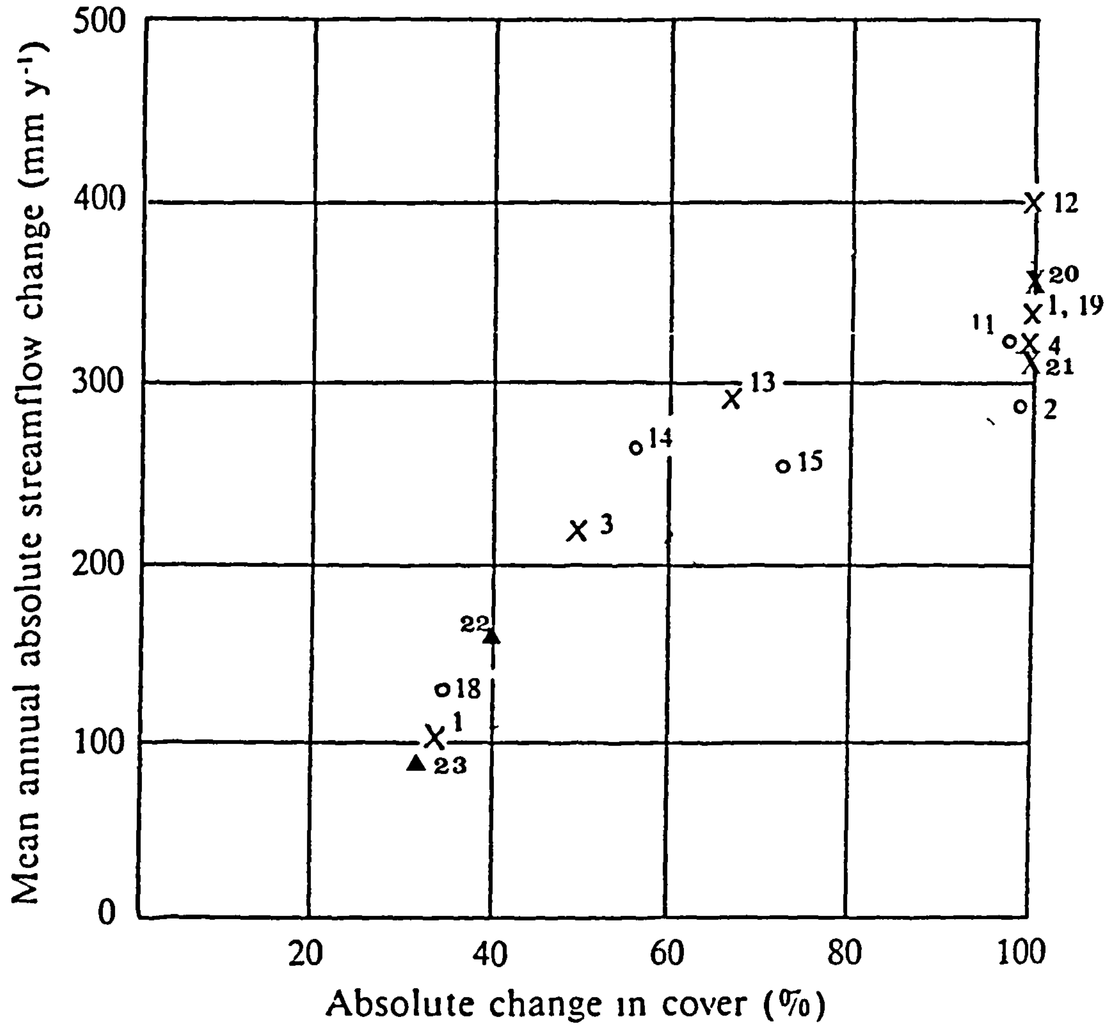
The present study, on the other hand, revealed a significant increase in monthly runoff and thus the annual yield following selective logging, ranging from 70 mm to 175 mm after extracting 33 to 40% of the forest cover The above increase is equivalent to approximately 3 to 4 mm for every percentage of the forest cover removed and corresponds to 300 to 400 mm for a 100% removal or clearcutting. Taking an average value of 350 mm, the figure is in agreement with the mean values of the Sg Tekam Basin, 314 mm and 358 mm, which underwent a complete clearance (Table 6 5, DID, 1986, Abdul-Rahim, 1988). It is clear, however, that this projection is much lower than that of Oyebande (1988) who suggested a value of 5 0 mm for every percentage of forest removed. In the latter analysis, the author summarized the results of nine tropical catchment studies to fit a regression line which encompassed studies on both afforestation and clearcutting practice (Figure 6 9). However, the plot also included results of South Africa studies, even though these do not fall under the humid tropics region according to the definition of Chang and Lau (1983). Further, the results of the Sg Tekam study have not been included. Another reservation relating to the above conclusions is the inclusion of the result of Fritsch (1983) in French Guyana which largely influenced the fitting of the regression lines. In fact, the value quoted from this study only represented the first year of observation (Table 6 5) Moreover, the small size of the catchment used could form another reservation

Hibbert (1967) suggested that the upper limit of water yield increase is 4.5 mm per year for each percentage of forest cover reduction. Nevertheless, the author further maintained that most treatments produced less than 2.5 mm increase per year with the first year response varying from 34 mm to 457 mm Obviously, the above review mainly considered studies from temperate areas with the exception of a few studies from Africa

Table 6 5 Forest cover transformation in the humid tropics and changes in water yield

Location	Type of transformation	Catchment sizes (ha)	M A P.* (mm)	Elevation (m a s.l)	Changes in water yield (mm/yr) 1st yr	2nd yr	3rd yr	4th yr	u	Reference
Babinda, Queensland	Lowland rain forest to grass (35%) & scrub (35%)	18 3	4035	10-200	+264 (7 0%)	+323[a] (13 4%)			+293	Gilmour, 1977
Lien-Hua-Chi, Taiwan	Clearcutting of mixed evergreen hill forest, regeneration	5 9	2100	725-785	+448 (58%)	+204[b] (13 4%)			+326	Hsia & Koh, 1983
Kimakia, Kenya	Montane rain forest/ bamboo to Pinus plantation, agriculture intercropping (3 yrs) until canopy closed	36 4	2198	2440	+457	+229	+178		+328	Blackie, 1979
Mbeya, Tanzania	Evergreen montane forest (1/3 grass & shrub) to agricultural land use (50% annual cropping & 50% grazing land)	20 2	1900	2428					+220	Blackie, 1979
St Emilie, French Guyana	Primary lowland rain forest to plantation of Eucalyptus	1 0	3230	<100	+408 (25 9%)					Fritsch, 1983
Sg Tekam(A), Malaysia	Secondary dipterocarp forest to cocoa plantation	37 7	1878	72 5	+110 (117%)	+706[c] (157%)	+353 (94%)	+263 (158%)	+358	DID, 1986, DID, 1989
Sg Tekam(B), Malaysia	Secondary dipterocarp forest to oil palm (60%) and cocoa (40%) plantation	96 9	1878	68 5	+145 (85%)	+155 (142%)	+137 (97%)	+822[c] (470%)	+314	DID, 1986, DID, 1989
Berembun (1), Malaysia	Selective logging (40%) of primary dipterocarp forest	13 3	2126	221	+165[a] (70%)	+142 (55%)	+175[a] (72%)	+155 (67%)	+160	This study
Berembun (3), Malaysia	Selective logging (33%) of primary dipterocarp forest	30 6	2126	236	+87[a] (37%)	+70 (28%)	+106[a] (44%)	+94 (41%)	+89	This study

*Mean annual rainfall [a]Wet year [b]Dry year [c]100% clearance



o Afforestation x Clear cutting ▲ Selective Logging

Figure 6.9 Average yield changes following forest cover transformation

(Source: Oyebande, 1988)

1 Kericho, Kenya	2 Kimakia, Kenya
3 Mbeya, Tanzania	4 Lien-Hua-Chi, Taiwan
11 Ibadan, Nigeria	12 Amazon, French Guiana
13 Babinda, Australia	14 Dehra Dun, India
19 Transvaal, S Africa	18 Tierkloof, S Africa
20 Sg Tekam A, Malaysia	21 Sg Tekam B, Malaysia
22 Berembun 1, Malaysia	23 Berembun 3, Malaysia

Considering results of recent studies in the tropics, the water yield response in the first four years after logging could amount to 500 to 800 mm as observed in Lien-Hua-Chi, Taiwan and Sg Tekam, Malaysia In questioning the conclusion of Hibbert (1967) that water yield response to afforestation and deforestation is unpredictable, Bosch and Hewlett (1982) concluded that coniferous, deciduous hardwood forest, brush and grass cover manifest, in that order, a decreasing influence on water yield compared with bare ground When inferring results from studies under tropical forests, the rainforest (dipterocarp forest) apparently produces a comparable response to the coniferous forests, if not, perhaps, even larger However, to summarize the specific ranking as such, more research results from studies in the tropics are required that represent various rainfall regimes and forest types In addition, future studies should include as many components of the hydrological cycle as possible together with detailed accounts of processes operating in order to explain and understand catchment responses fully in a rigorous manner as suggested by Pereira (1973)

While the present results confirm and update the findings of paired watershed studies conducted elsewhere, both in tropical and temperate areas, the present analysis only covers the first four years of the post-treatment period Undoubtedly, a much longer duration of observation is needed to quantify the subsequent catchment response on water yield and to find out whether the catchment would revert back to a pre-calibration regime when the forest ultimately recovers

The implications of the present investigation to forest management and watershed management are several One is that selective forest logging may produce substantial amounts of water available to other uses downstream considering the present rate of logging in any country Nevertheless, more important are the problems of environmental degradation that ensue with the increase in water yield, such as greater on-site erosion, sedimentation and impairment of water quality (Wiersum, 1984) Although the above parameters are part of this hydrological research project at FRIM, the present analysis does not cover the effects of treatment on water quality and sedimentation. In fact, detailed analyses on the impacts of selective logging on the above parameters are being conducted by fellow colleagues at FRIM as Masters theses (Zulkifli, In prep and Baharuddin, In prep) Hopefully, then, the completion of this rigorous research programme at FRIM may lead to the formulation and establishment of watershed management guidelines to be enforced in Malaysian forested watersheds specifically, and in other regions of similar climatic characteristics and forest types

6 4 Conclusion

The present paired watershed investigation indicates that a short calibration period of three years can be successfully employed to detect and predict water changes resulting from forest cover manipulation. A shorter calibration period affords fast results with reasonably low standard error of estimate, thereby reducing the cost of research maintenance

Up to this point, the results show that selective logging of rainforests produces a significant increase in the water yield proportionate to the percentage of forest removal, thus reinforcing the earlier results discussed in the preceeding chapter By and large, the present results conform to and up-date the findings of other paired watershed studies conducted elsewhere, and particularly those in the tropics

The question of whether or not the observed increase in yield is associated with changes in stormflow parameters will be explored in the next chapter Specifically, it deals with the analysis of time-based stormflow hydrographs in terms of stormflow volume and peak discharge by employing the similar concept of the paired watershed Determinant factors influencing the above variables will be identified and subsequently applied in a regression model to predict changes resulting from forest logging

CHAPTER 7

STORMFLOW RESPONSE TO FOREST LOGGING

Logging and clearance of forest has been associated with increased flooding downstream in addition to sedimentation and impairment of water quality As the exploitation of rainforest still continues in most tropical countries, the perceived threat to the environment still exists. While adequate scientific information has been progressively assembled on the effect of forest clearance on the flood potential, quantitative data are woefully scarce in the tropics, for most of the previous studies have mainly dealt with the input-output relationships of the drainage basin (Bruijnzeel, 1986, Bonell, 1989). Intuitively, great concern on the above potential effects are being felt considering the inherent unfavourable physical factors of countries in the tropics - high rainfall intensity, greater rainy days and easily erodable soils. Without rigorous research input, prediction of the impact of the above phenomena becomes difficult and potentially misleading, particularly for application purposes. Therefore, the present analysis attempts to shed some light on this crucial yet controversial issue not only for Malaysia but also for the humid tropics as a whole.

7 1 Analysis of Stormflow Hydrographs

A streamflow hydrograph is a graph showing the flow rate as a function of time in a particular catchment. It provides useful information about a drainage basin and, in effect, serves as an integral expression of the physiographic and climatic characteristics that govern the relation between rainfall and runoff (Chow et al , 1988). Two types of hydrographs are particularly important the annual hydrograph and the storm hydrograph. The present analysis, however, mainly deals with the latter category which is essentially the result of storm rainfall. The terminologies normally used to define storm hydrograph variables follow the scheme of Hewlett and Hibbert (1967) and have been employed in many forest hydrological studies elsewhere (Hsia, 1987; Pearce et al , 1976, Leitch and Flinn, 1986).

Generally, the shape of the storm hydrograph is influenced by two sets of factors namely, catchment factors and weather factors (Ward, 1967; Raudviki, 1979, Hewlett, 1982). Catchment factors that influence the total volume of runoff as well as the shape of the hydrograph are the area of catchment, elevation, topography, shape and slope, orientation, geology, vegetation cover and drainage network. On the other hand, climatic factors which influence the storm hydrograph and eventually runoff are the nature of precipitation, rainfall intensity and duration, areal rainfall distribution, rate of evaporation and intensity, rainfall distribution with time and direction of storm movement as indicated by Raudkivi (1979).

7.1.1 Stormflow hydrograph separation

Storm hydrograph analysis usually begins with hydrograph separation into various components. Several techniques or approaches have been proposed and employed, all of which are at best subjective and arbitrary procedures. Among techniques commonly used in hydrological analyses are the Template Method (Linsley, et al ,1949, Wilson, 1974), Master Depletion Curves (Barnes, 1959), Storm-event

Separation (Hewlett and Hibbert, 1967, Ward, 1967) and several other methods as employed by Wisler and Brater (1957) and Clark and Bruce (1966). Because of the subjectiveness of the methods available, Jones (1975) divided them into two basic groups namely 'graphical or intuitive approaches' and the 'objective approach' which is based on pre-determined criteria The former approaches have dominated much of the hydrological literature and these separate hydrographs by graphical rules formulated by the originator of the method The latter method or storm-event separation as advocated and proposed by Hewlett and Hibbert (1967) is generally based on some kind of quantitative criteria, though it is equally as arbitrary as the other methods. Nevertheless, this method has received greater acceptance in the last three decades and has been employed in hydrological analyses, particularly by geographers, foresters, land-use hydrologists and soil scientists (Walling, 1971; Harr, et al , 1975, Gilmour, 1977; Pearce, et al , 1980, Hsia, 1987) In addition, this method is more suitable for direct computer processing of the digitized hourly values (Hibbert and Cunningham, 1967)

7.1.2 Storm-event hydrograph separation

The method of hydrograph separation proposed by Hewlett and Hibbert (1967) avoided much of the controversy over the relative importance of overland flow and throughflow in the formation of the storm hydrograph by using a storm event or time-based separation (Gregory and Walling, 1973). A storm hydrograph is divided into stormflow -synonymous with quickflow or direct runoff - and baseflow or delayed flow components by a line drawn upwards from the point of hydrograph rise at a gradient of 0 0055 l/sec/ha/hr In other words, the method assumes that after a rainstorm begins on a relatively small drainage basin of less than 250 ha, for discharge expressed as in rate per unit area, baseflow rises at a fixed rate until it intercepts the falling limb of the storm hydrograph. Dunne and Leopold (1978) also considered a comparable approach by assuming a linear separation of the two variables as the simplest method. Although slight modifications have been introduced over the years, for example using a different gradient, essentially the approach has remained the same (Whyman, 1986, Bren et al., 1987, Higgins et al., 1989). A similar demarcation of storm runoff but with a slightly more complicated approach has been adopted by Bethalamy (1972). The method assumes that any increase in the baseflow is related to the rise of the storm hydrograph. A convenient computer programme has also been prepared for the above analysis as employed by Jones (1975). Bruijnzeel (1983) adopted an entirely different method of separation using a hydrochemical approach when working in forested watersheds in Indonesia. Regardless of the method used, the important underlying factor is that, once chosen, it should be consistently employed to ensure compatibility in subsequent analysis (Hewlett, 1982; Dunne and Leopold, 1978; Linsley, Kohler and Paulhus, 1949).

7.1.3 Unit hydrograph analysis

Another classical approach to hydrograph analysis is the unit hydrograph method as proposed by Sherman (1932) and which can be defined as a direct runoff hydrograph resulting from 1 inch (usually taken as 1 cm in SI units) of excess rainfall generated uniformly over the drainage basin area at a constant rate for an effective duration. Although the word unit is originally used to denote a unit of time, it has often been interpreted as a unit depth of excess rainfall (Chow et al., 1988). The method, however, depends upon several basic assumptions including the fact that the excess rainfall is uniformly distributed throughout the catchment area and has a constant intensity, the base time of the hydrograph of a given duration is constant and the ordinates are directly proportional to the total amount of direct runoff represented by each hydrograph.

However, under a natural condition, the above assumptions cannot be perfectly satisfied and are unlikely to be experienced in practice (Bruce and Clark, 1966; Chow et al , 1988). In this context, reservations against the method arise from the fact that it depends on the Hortonian infiltration approach, wherein not only are all catchments considered as contributing to runoff, but all of the rainfall excess over infiltration is considered as being overland flow (Horton, 1945, Kirby, 1969, Jones, 1975). Nevertheless, it has been widely accepted as an invaluable tool for studying hydrograph form for the last 50 years (Low, 1971, Gregory and Walling, 1973, Newson, 1975; Raudkivi, 1979) Unit hydrographs may be of considerable value in situations where records are limited and prediction is the main aim (Ward, 1967), but are of limited use in areas where groundwater runoff predominates (De Zeeuw, 1973)

In forested or wildland watersheds characterized by permeable soil and high infiltration capacity where sub-surface flow tends to dominate (Dunne, 1978; Pearce et al., 1986), the concept of the unit hydrograph is less applicable. Furthermore, the unit hydrograph does not account for soil moisture-evapotranspiration relationships that invariably indicate the moisture status at any point of time, for it only provides an estimate of a single event (Kenneth Brooks, personal communication). The present analysis adopts the approach of storm-

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Personal communication Kenneth Brooks, University of Minnesota, USA based hydrograph analysis (Hewlett and Hibbert, 1967) that involves portrayal and analysis of a series of hydrographs produced by a particular catchment under a variety of storms and antecedent conditions and which ultimately undergoes landuse changes In this study, the hydrographs are considered in their natural physical form or as a discharge per unit area per unit time by eliminating areal bias, and this permits a reliable comparison between other catchments (Jones, 1975).

7.1.4 Selection of storm hydrographs and derivation variables

Not all storm hydrographs recorded at the three catchments in Berembun Experimental Watershed (BEW) are amenable to detailed analysis as many of them suffer some deficiency such as discontinuous hydrograph traces, mismatch in the time sequence between the onset of rainfall events and the hydrograph and incompleteness of rainfall charts. In addition, the analysis only considers simple hydrographs as they represent the frequent type of storm hydrograph emanating from these catchments; thus complex hydrographs are disregarded. Furthermore, this approach facilitates direct comparison between catchments in the subsequent analysis Although the amount of storm rainfall, to a certain extent, dictates the magnitude of the corresponding hydrograph, various sized storms are considered as long as they produced an appreciable size of storm hydrograph Another restrictive criterion is pertaining to the need for a common time base between the two treated catchments and the control both for the calibration and post-treatment periods.

Selected hydrographs are separated using the approach of Hewlett and Hibbert (1967) as described earlier on. The adoption of this

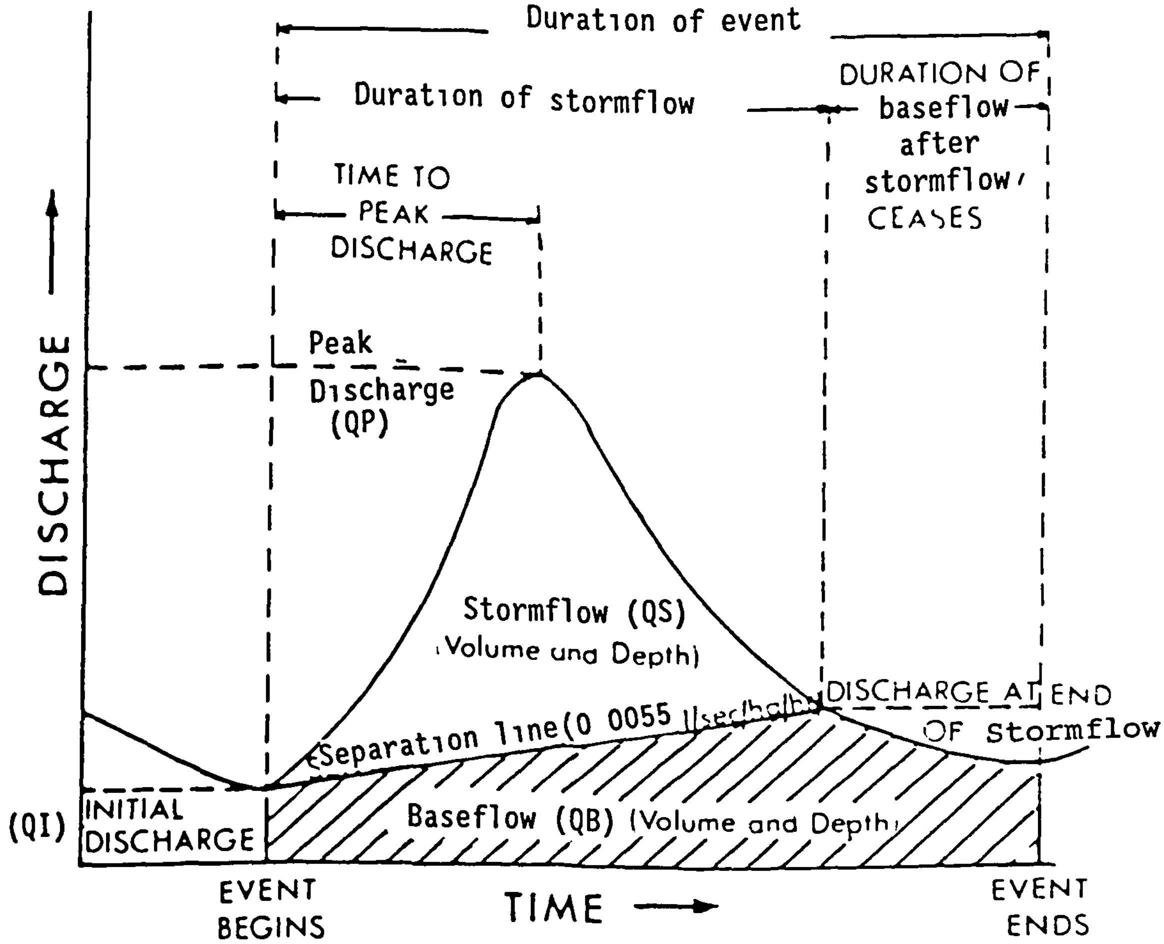

Figure 7.1 Hydrograph separation method (Hewlett and Hibbert, 1967) and stormflow parameters

7.2 Statistical Analysis of Stormflow Variables

The span of hydrograph charts and rainfall records used for this analysis range from 1979 to 1986, including more than three years of the post-treatment phase. However, the actual number of storm hydrographs selected based on the above mentioned criteria for C1, C2, and C3 amount to 145, 145 and 86, respectively (Appendices 19 and 20). A summary of their statistical measures for all variables is given in Table 7.1, categorized into the calibration and post-treatment phases.

The parameter QI included in the analysis is to provide some indication of the antecedent moisture condition prior to the onset of stormflow. As QI in this case is normally extracted along the recession limb, it is assumed to represent the prevailing moisture condition of a particular catchment at that time. Several authors have considered and employed QI to represent similar conditions in the stormflow analysis (Pearce and Taylor, 1982; Wheater at al., 1982; Hsia, 1987; Leith and Flinn, 1986).

As the central purpose of this analysis is to determine the response of stormflow parameters or flood potential resulting from selective logging operations, three variables have been identified as the response variables namely the stormflow volume (QS), peak discharge (QP) and initial discharge (QI). The other variables are considered as independent or predictor variables. Peak discharge emanating from a small forested catchment usually bears no causal relation to downstream flood stages as the latter mainly depend on the storage geometry of the channel. Conversely, the volume of the stormflow does tend to add proportionately downstream although with some expected damping and lagging effects (Hewlett, 1979; 1982a).

		CALIBRATION						POST-TREATMENT				
Variable	Unit	N	Mean	Ranges	Median	Skew	.	N	Mean	Ranges	Median	Skew
Catchment 1												
PT	mm	81	26.0	(3.5 - 116.0)	21.0	1.827	:	64	29.9	(7.5 - 113.5)	25.0	1.778
PI	mm/hr	75	19.3	(0.764 - 162.5)	22.3	1.369	:	61	31.5	(2.02 - 263 9)	19.9	3.529
QS	mm	81	1.811	(0.031 - 20.744)	0.716	3.846	:	64	3.322	(0.026 - 59 614)	0.831	5.188
QP	l/s/ha	81	1.876	(0.113 - 16.193)	1.005	3.338	:	64	3.664	(0.095 - 112.525)	1.176	7.924
QI	l/s/ha	81	0 056	(0.000 - 0.232)	1.006	1.618	:	64	0.099	(0.017 - 0.647)	0 076	3 575
RF	%	81	4.681	(0.346 - 23.982)	3.462	2.141	:	64	6.841	(0.111 - 47 856)	3.528	2.930
Catchment 2												
C2												
PT	mm	81	27.6	(3.5 - 116.0)	22.0	1.948	:	64	29.1	(6.5 - 113.5)	25.0	1.806
PI	mm/hr	75	20 7	(0.76 - 162.5)	12.7	3.368	:	61	29.7	(1.78 - 263.9)	16.4	3.656
QS	mm	81	3.521	(0.082 - 43.941)	1.556	4.527	:	64	3.174	(0.055 - 24.192)	1.233	2.327
QP	l/s/ha	81	3.571	(0.150 - 25.238)	2.283	3.083	:	64	2.847	(0.119 - 24.286)	1.570	3.075
QI	l/s/ha	79	0 08	(0.0 - (0.229)	0.076	0.535	:	64	0.066	(0.007 - 0.240)	0 064	1.787
RF	%	81	9.735	(0.617 - 49.650)	8.114	2.159	:	64	8.380	(0.457 - 40.903)	5.779	1.578
Catchment 3												
PT	mm	55	26 6	(3.5 - 116.0)	22.5	2.03	:	31	32.7	(7.5 - 83 0)	29.5	1.178
PI	mm/hr	50	19.0	0.76 - 81.6)	11.6	1.558	:	30	32.5	(4.38 - 263.9)	20.3	3.909
QS	mm	55	2.194	(0.050 - 24.232)	1.286	4.557	:	31	3.546	(0.155 - 65.453)	0.791	4.742
QP	l/s/ha	55	1.914	(0.041 - 22.582)	0.914	4.805	:	31	2.894	(0.182 - 29.848)	1.221	3.872
QI	l/s/ha	55	0.049	(0.004 - 0.248)	0.034	2.298	:	31	0.018	(0.018 - 0.281)	0.076	1.275
RF	%	55	6.603	(0.827 - 28.014)	5.667	1.613	:	31	6.375	(0.884 - 86.370)	2.585	4.725

Subsequently, the analysis of stormflow response is carried out in three stages. Firstly, descriptive statistics of all variables are computed to characterize storm rainfall and stormflow variables. Secondly, statistical relations between predictor variables and independent variables are sought using the stepwise regression method to fit the general model as follows:

$$\ln Q = \ln K + a \ln A \ldots + n \ln D \quad \ldots\ldots\ldots\ldots\ldots\ldots (7.1)$$

where Q is either QS or QP or QI, K is a regression constant, A to D are independent variables and a to d are regression coefficients.

Thirdly, based on the above results, data from C1 and C3 are fit to the likely model against data from C2 whilst the adequacy of the model will be rigorously tested. Subsequently, the models will be tested to determine whether there are any significant changes following forest logging on the variables under study.

The paired catchment concept will be applied in the overall analysis by regression of stormflow variables of treated catchments against the same variable of the control catchment in addition to other predictor variables as identified by the earlier analysis. The basis of this approach has been discussed in detail in Chapter 4. A similar approach has been adopted by Higgins et al. (1989), albeit with some transposition of steps, in their analysis of the effects of range management strategies on stormflow parameters.

7.2.1 Transformation of data

Most variables indicate that the data are highly skewed for all catchments in both periods with the exception, to a certain extent, of storm rainfall (Table 7.1). Peak frequencies of most of the variables lie in the lower range values, in particular QS and QP. The positive skew nature of these variables can be portrayed and verified by frequency distribution curves (Figure 7.2 and 7.4). Due to the asymmetrical distribution or non-normal characteristics, these variables essentially require some kind of transformation or normalization before subsequent analysis can be carried out. A transformation entails a mathematical change of data into a form that more closely approximates to the normal curve or symmetrical distribution which normally governs many assumptions in statistical analyses (Gregory, 1963). In this case, natural logarithmic transformations are appropriate as the data exhibit a positive skew thus stabilizing the variance (Figure 7.3 and 7.5) (Hsia, 1987; Swindel et al., 1983). Although some parameters still exhibit a tendency towards a positive skew, the transformed distributions are markedly more symmetrical than before the transformation.

There are apparently some changes in mean value of parameters after the post-treatment phase particularly in C1 and C3, but they will not be quantified and discussed in this section. However, apparent changes will be implicitly examined in the analysis of regression to document treatment changes. Nevertheless, at this point it is worth commenting on the response factor of these catchments as indicated by the RF ratio. During the calibration period, RF values for the three catchments are rather low ranging from 5 to 10%. The maximum RF for C1, C2 and C3 amounts to 24%, 50% and 28%, respectively. After the treatment, although the mean RF changes very little, the maximum values for C1 and C3 increase moderately, amounting to 48 and 86%. A rather low RF during the calibration and post-treatment periods clearly indicates that a greater portion of storm rainfall does not appear as quickflow but

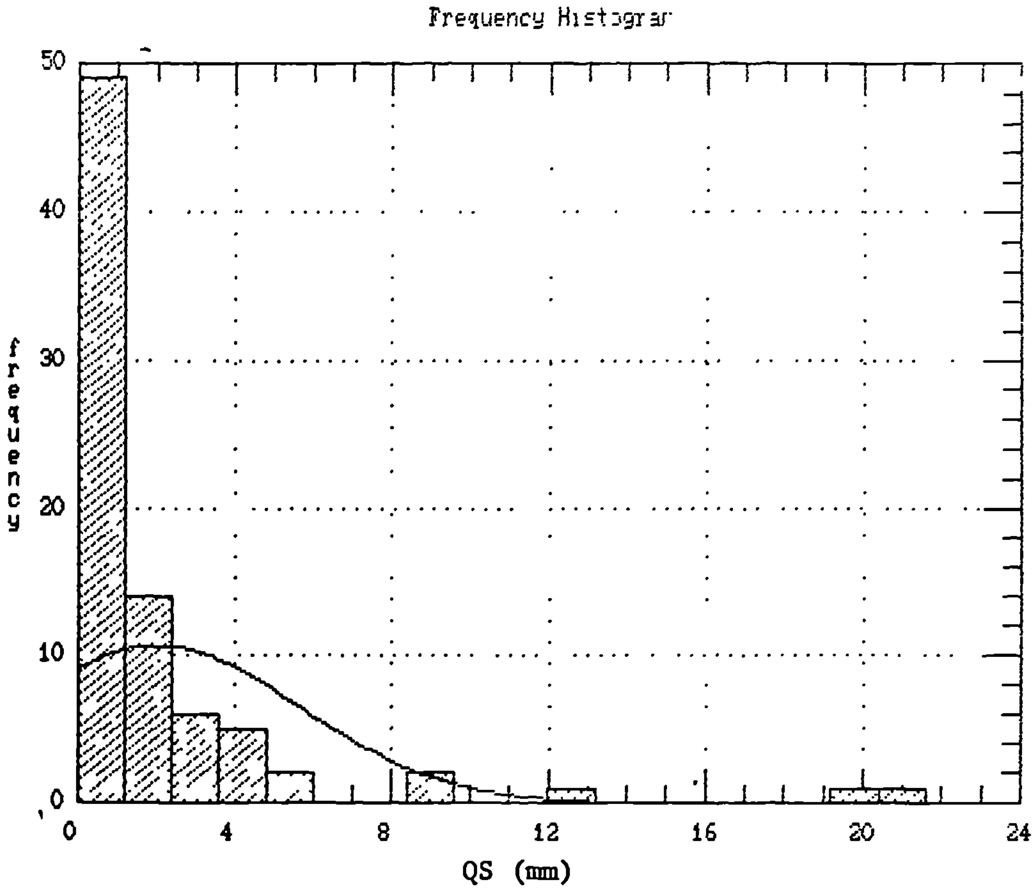

Figure 7.2 Frequency histogram of QS before data transformation in Catchment 1 during calibration

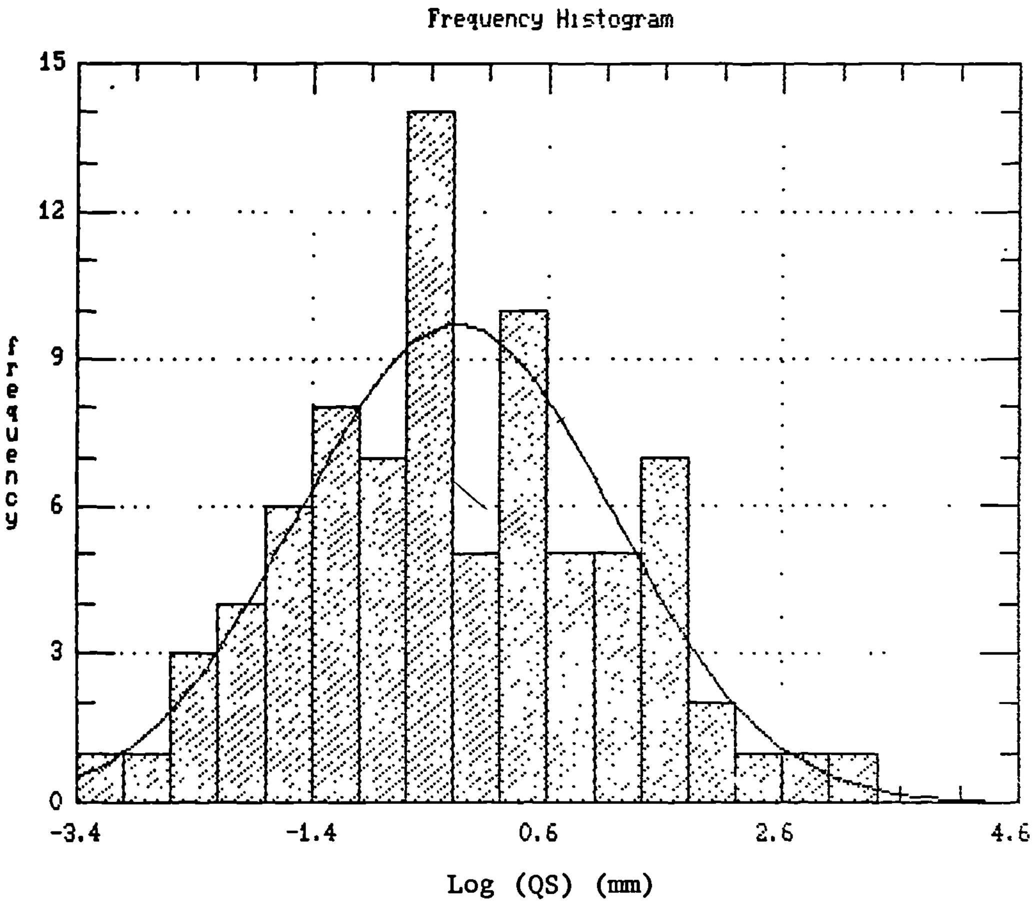

Figure 7.3 Frequency histogram of QS after data transformation in Catchment 1 during calibration

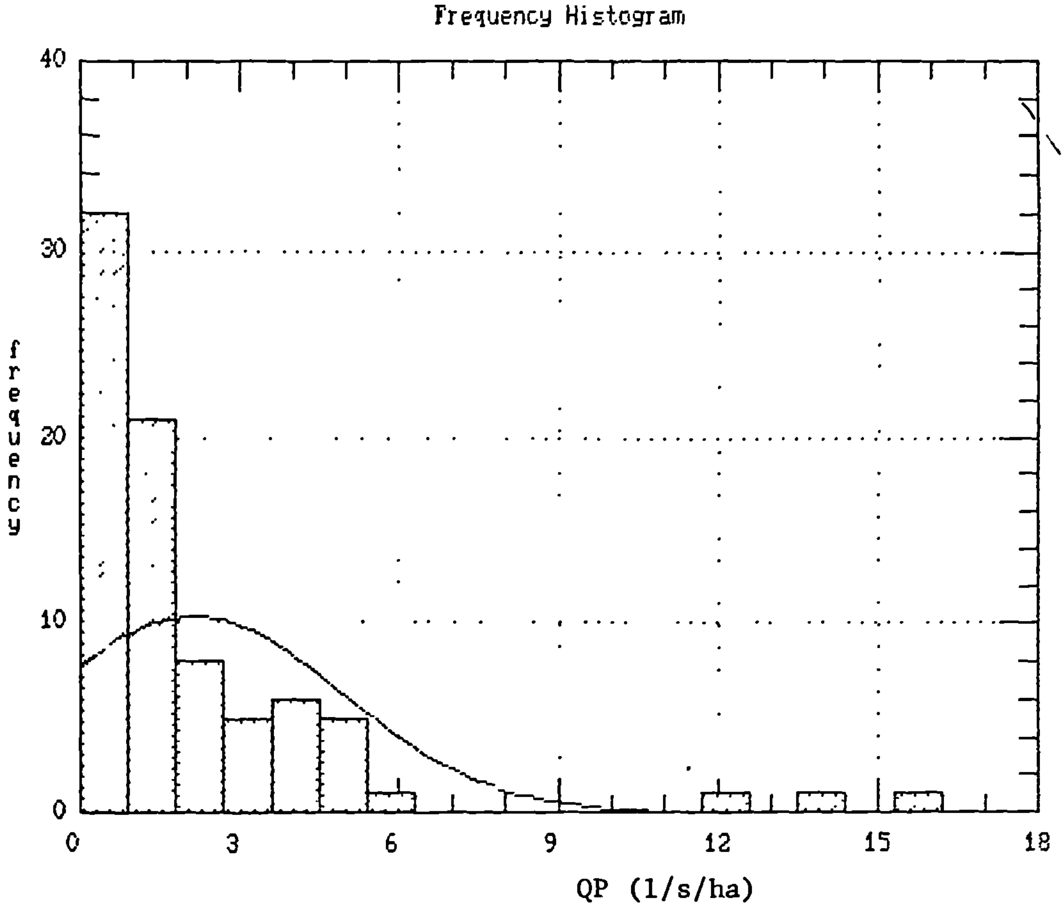

Figure 7.4 Frequency histogram of QP before data transformation in Catchment 1 during calibration

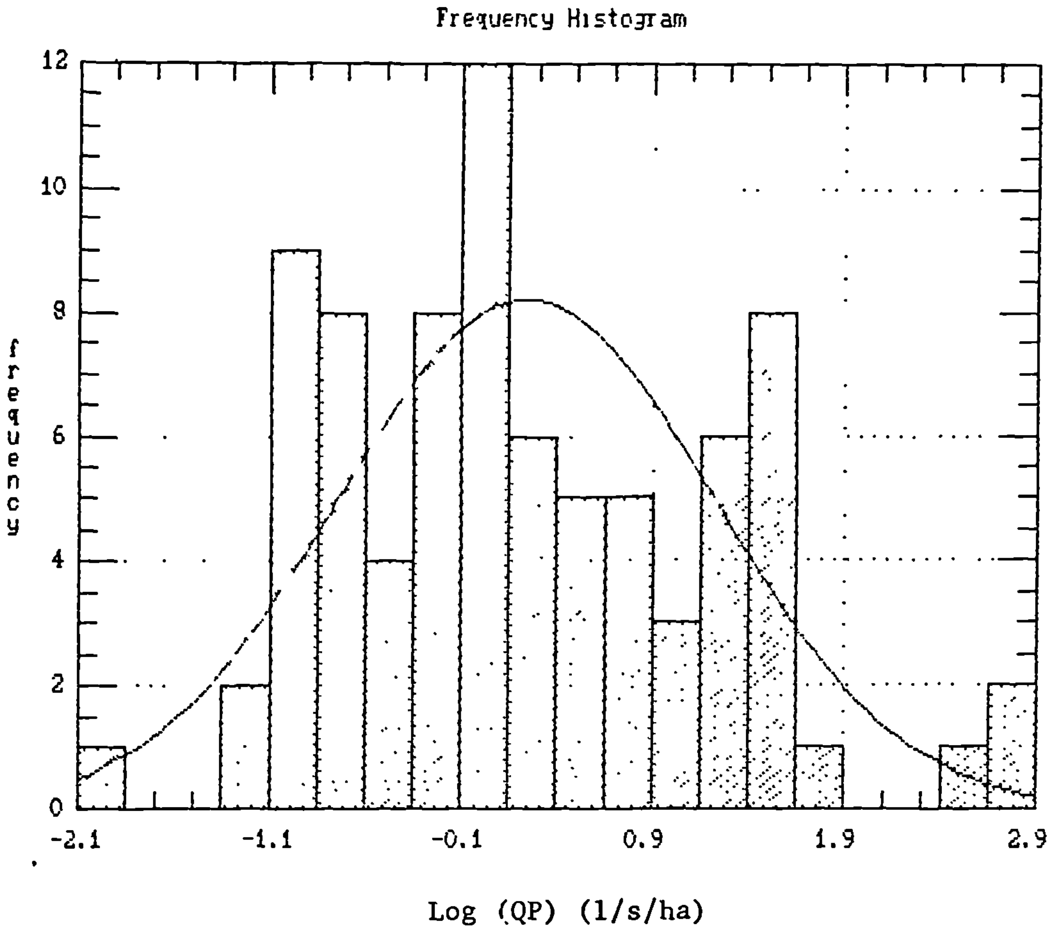

Figure 7.5 Frequency histogram of QP after data transformation in Catchment 1 during calibration

instead may transmit through other means of sub-surface flow. Hsia (1987) reported a much higher mean RF amounting to 19% for a forested catchment before treatment and observed that the maximum increase amounted to 92% in Taiwan. Conceivably a shallow soil mantle of 1.0 m may have accentuated the above high response under a quite humid condition of the site. A contrasting situation is observed in Babinda, Australia in which a widespread overland flow occurs under the undisturbed forest condition (Bonell et al., 1983). The above phenomena apparently can be ascribed to the prevailing rainfall intensity which frequently exceeds the saturated hydraulic conductivity of the soil profile beyond the depth of 0.2 m. Bruijnzeel (1983) observed a quickflow percentage of 8 - 9% based on his work in a forest plantation underlain by volcanic soil in Indonesia. It is quite evident therefore that the physical characteristics of the soil mantle in addition to the prevailing climatic conditions largely govern the magnitude and occurrence of stormflow variables in forest environments. A low RF ranging from 2% to 42% has been observed in forested catchments in temperate areas whilst a selection cut catchment attained RF values of 11% to 60% (Miller et al., 1988).

7.2.2 Selection of variables for regression models

The second step in data analysis involves identifying significant predictor variables to fit in the regression models using the stepwise regression procedure. Selected stormflow and storm rainfall variables elicited from storm hydrographs and hyetographs are categorized into the response or dependent variables and the predictor or independent variables as listed in Table 7.2.

Table 7.2 Storm rainfall and stormflow variables considered in regression models

Type of variable	Variable	Unit	Notation
Dependent or Response	Stormflow volume	mm	QS_t
	Peak discharge	l/s/ha	QP_t
	Initial discharge	l/s/ha	QI_t
Independent or Predictor	Stormflow volume	mm	QS_c
	Peakflow discharge	l/s/ha	QP_c
	Initial discharge	l/s/ha	QI_c
	Storm rainfall	mm	PT
	Storm intensity	mm/hr	PI

$_t$refers to treated catchments (C1 or C3) thus for catchment 1 QS_t is written as QS_1
$_c$refers to control catchment (C2)

The forward stepwise regression is sought in which a model begins with no variable and then adding one at a time as long as the new variable adds significantly to the model. At the same time, the procedure checks at each stage whether the previously selected variables are still significant, otherwise they would be removed. The procedure is carried out at the 95% confidence level with F-ratio of 4.0 (Table 7.3).

Results of the above analysis clearly indicate that total storm rainfall (PT) and the corresponding variable of interest are significant in describing the variation in the models with reasonably high r^2 which accounts for more than 70 to 90% of the variations. However, for QI, the storm rainfall is not a significant variable thus the model assumes a simple regression model. It is of interest to note that the initial discharge and storm intensity are not significant in the model except in QP_1 where initial discharge is marginally significant. In fact similar relationships have been observed in forested catchments in Taiwan (Hsia, 1987), and in the Piedmont region of Georgia (Hewlett et al., 1984) and Wisconsin, USA Higgins et al.(1989). On the other hand, Wheater et al. (1982) found that QI was important and significant when working on southwest England based on a unit hydrograph analysis.

Table 7.3 Results of Stepwise Regression

Dependent Variable	N	Variables entered into model[1] First	Second	Third	Final R-sq.
QS_1	145	PT (0.9001)[2]	QS_2 (0.9004)		0.8856
QS_3	86	QS_2 (0.9157)	PT (0.8981)		0.8906
QP_1	145	QP_2 (0.9236)	PT (0.8687)	QI_2 (0.2666)	0.9016
QP_3	86	QP_2 (0.9306)	PT (0.8479)		0.9036
QI_1	145	QI_2 (0.5535)			0.3064
QI_3	86	QI_2 (0.4588)			0.2105

[1] F-to-enter and F-to-remove is 4.00
[2] Partial correlation

7.2.3 Fitting data to selected regression models

The third stage involves fitting data to selected models for predicting changes in stormflow response resulting from treatment operations. Once again, a dummy regression technique is employed to detect and examine potential changes in response variables as similarly applied in the water yield analysis described in Chapter 6. A dummy variable T = 0 has been assigned to the calibration period or reduced model and T = 1 for the full model with a treatment. Accordingly, the selected regression model for each response factor between the treated and control catchments assumes a common model specification except for QI as mentioned earlier:

Full model for stormflow volume and peak discharge,

$$\ln (QS, QP)_t = a_1 + a_2T + (b_1 + b_2T)\ln (QS, QP)_c + (b_4 + b_5T)\ln PT + E_i \quad \ldots . \, (7.2)$$

and the full model for QI takes the following form:

$$\ln (QI)_t = a_1 + a_2T + (b_1 + b_2T) \ln (QI)_c + E_i \quad \ldots\ldots\ldots (7.3)$$

where a_i's and b_i's are intercepts and regression coefficients and subscripts t and c denote treated and control catchments, respectively. When T is set equal to 0, a reduced model results:

$$\ln (QS, QP)_t = a_1 + b_2\ln (QS, QP)_c + b_4PT + E_i \quad \ldots\ldots\ldots\ldots (7.4)$$

and,

$$\ln (QI)_t = a_1 + b_2 \ln (QI)_c + E_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7.5)$$

Although the stepwise regression of variable QP_1 suggests an inclusion of QI in the model, QI has been dropped from the final model as its addition only increases r^2 by less than 0.5%. Hence, the model specification for QP_1 is basically similar to the rest of the models except for QI (Table 7.4).

The above approach is based on the fact that stormflow variables from two similar adjacent catchments under the same forest cover will correlate highly before either catchment undergoes treatment. As in the present case, most models account for 70 to 90% of the variation in the response variables coupled with a relatively low standard error of estimates (Table 7.4).

Table 7.4 Values of intercepts and coefficients for regression models

Dependent Variable	a_1	a_2	b_1	b_2	b_3	b_4	r^2	s.e.	D. W.	n	F	Eqtn. No.
QS_1	-4.0449 (-10.54)**	1.2256 (1.59)ns	0.4404 (6.85)**	0.2706 (2.43)*	1.1726 (9.03)**	-0.4473 (-1.62)ns	0.8932	0.4522	1.574	145	2.31+	7.6
QS_3	-2.6454 (-5.08)**	-1.7437 (-1.85)ns	0.6038 (7.04)**	-0.1243 (-0.95)ns	0.8523 (4.95)**	0.4667 (1.52)ns	0.9079	0.3829	1.759	86	ns	7.7
QP_1	-1.9421 (-7.17)**	0.4117 (0.84)ns	0.6924 (10.14)**	0.0814 (0.83)ns	0.5113 (-0.08**	-0.0826 (-0.49)ns	0.9031	0.3294	1.821	145	ns	7.8
QP_3	-1.7843 (-4.76)**	-0.4623 (-1.37)ns	0.8562 (9.81)**	-0.1471 (-1.23)ns	0.3853 (2.77)**	0.2158 (1.55)ns	0.9036	0.3331	1.674	86	ns	7.9
QI_1	-1.7258 (-3.15)**	-0.1767 (-0.51)ns	0.8851 (10.27)**	-0.3300 (-2.72)**			0.5816	0.4617	1.409	143	47.1**	7.10
QI_3	-1.0788 (-3.15)**	-0.5284 (-0.51)ns	0.7985 (10.27)**	-0.4015 (-2.72)**			0.4130	0.6050	1.870	86	ns	7.11

** significant at $p < 0.01$

* significant at $p < 0.05$

+ significant at $p < 0.10$

ns not significant

The effect of treatment on stormflow parameters was tested by two methods: first the significance of each dummy variable introduced in the model is tested and secondly, the F-test with the null hypothesis Ho: $a_2 = b_2 = b_4 = 0$ is used. The significance of a dummy variable in the first test can be assessed by t-values provided by the regression procedure (Table 7.4). If neither of the dummy variables (i.e. a_2, b_2 and b_4) shows as significant in the model, then the F-test will not be carried out. In this case, it actually indicates that the variable in question has not changed after the treatment operation. On the other hand, if one or more forms of dummy variables are significant, the F-test will be applied to confirm the apparent changes as follows:

$$F = \frac{(SS_1 - SS_2)/(df_1 - df_2)}{EMS}$$

where legends for the above notations have been given in Chapter 6.

7.3 Treatment Effects on Stormflow Variables

The results of the above analysis reveal that the effects of selective logging on stormflow parameters are variable and hence careful interpretation of these apparently contradictory findings is required (Figure 7.4). It is also evident that both catchments respond differently to the treatment operation in terms of stormflow volume and peak discharge. Quite surprisingly, peak discharge (QP) did not show any significant change following forest logging in both catchments whilst stormflow volume exhibits a quite variable response. C1 shows a significant change in stormflow volume at $p < 0.10$ level with a F-value of 2.31 (Table 7.4), but this was not significant at higher levels of probability, ($p < 0.05$ or 0.01) which are normally used in statistical tests. Thus, an indication of stormflow volume increase in C1 is statistically weak at best, otherwise it may not be significant at all. Conversely, stormflow volume of C3 did not reveal any significant change due to treatment as neither differential intercept nor slope indicates significance at $p < 0.05$ (Table 7.4). The initial discharge (QI) of C1 indicates a highly significant increase following treatment with an F-value of 47.1 at $p < 0.01$ and d.f of 2 and 80. On the contrary, C3 did not exhibit any significant difference at all. Accordingly, the increase in QI after treatment amounts to 31.0% based on the mean value. The corresponding increase in QS of C1 could be as high as 39.0%, but its low level of significance renders it inappropriate to quantify the percentage increase.

In explaining the above results a few pertinent factors need to be considered. These include the degree of disturbance in both catchments taking into account the different percentage of forest removed, typical characteristics of stormflow parameters under the present conditions in addition to inherent physical properties of the soils underlying these catchments.

The results suggest that stormflow parameters would not be drastically altered unless a substantial removal of forest cover is effected such as in clearcutting of the forest or forest logging followed by transformation to a different land use. Under such conversion, QP may increase up to two-fold as observed in the Sg. Tekam Basin, Malaysia (DID, 1986; DID, 1989). In the present case, even with up to 40% of reduction in forest cover, QP did not seem to be affected whilst at the same level, QS tends to show some significant effects, although these are statistically rather weak.

This in turn indicates that under the present environment, QP is less sensitive than is normally expected relative to QS. Under normal circumstances, peak discharges are mainly dependent on the storage geometry of the channel above the point of measurement (Hewlett, 1982a; Swindel et al., 1983). However, the stormflow volumes do tend to add proportionately downstream, but may not be on an equivalent basis as discharges tend to be lagged or damped as they flow downstream.

As described earlier, minimal disruption of the forest floor resulting from logging activities has been observed apart from damage to residual trees as well as the ground disturbance in the construction of forest roads, skid trails and landings. Furthermore, selection of trees to be harvested based on prescribed dbh affords a uniform distribution of trees over the catchment rather than their being limited to a certain area or location. Therefore, the flow channel remains practically undisturbed during the logging operation and thus stream geometry changes very little. However, as pulses of discharge flow downstream from different parts of the catchment resulting from a storm event, stormflow volume may have proportionately accumulated to a significant volume as observed in C1. Nevertheless, a similar mechanism may not have accentuated fully in C3 as there is more forest cover remaining behind coupled with less ground disturbance, thus favouring a greater subsurface flow or recharge to baseflow. This is further amplified by the antecedent moisture condition of C3 which did not reveal any significant change as compared with C1. Evidently therefore, the above results are consistent and thus strongly reinforce the earlier findings that observed increases in total water yield are largely associated with the augmentation of baseflow.

In this respect, Swindel et al. (1983) maintained that forest operations on watersheds entailing minimal disturbance into drainage channels, no displacement of soil litter, and only subdued effects on the residual understorey, produce no discernible increase in peakflow rate. Similarly they further observed that stormflow increases following forest operations are normally mitigated by dispersing harvests over managed forest landscapes.

The construction of logging roads and landings may modify peakflow discharge by two important processes: compaction of road surfaces may reduce infiltration and thus permit rapid surface runoff and roads may intercept subsurface flow as well as capture surface runoff and channel it more directly to streams (Ziemer, 1981). Although in this study, there is no special attempt to quantify the effect of road construction, its effect could have been confounded in the overall effect on stormflow variables. The inference from the earlier results is that the relatively small percentage of forest road in these catchment does not seem to accentuate peakflow discharge following treatment. Ziemer (1981) reported no change in stormflow parameters when a forest road system occupied 5% of a forested watershed in Northern California. In other studies, a significant increase in peakflow was only significant when roads and permeable areas occupied more than 12% of the watershed (Harr et al., 1975; Harr, 1970). There has been little research on this matter in the tropics except the on-going study at Danum Valley, Sabah, Malaysia (Greer et al., 1989; Douglas et al., 1990).

Another pertinent factor relating to the above response could be the comparatively low response factor (RF) of this watershed, ranging from 4% to 10%. Given these values, these catchments could not be considered as 'flashy' watersheds as compared with those watersheds in New Zealand and Australia which attained RF values on average of 40% and 47% (Pearce and McKerchar, 1979; Bonell et al., 1981). On the other hand, the proportion of quickflow or stormflow volume in Indonesia and Kenya is equally low, amounting to 5 to 7% and 8 to 9%, based on monthly data, respectively (Bruijnzeel, 1983; Dagg and Pratt, 1962). This may lead to the reasonable belief that a greater proportion of storm rainfall transmits through other pathways such as deep subsurface or baseflow. In this context, Ward (1984) examined four major pathways into which storm rainfall may be partitioned, particularly in headwater catchments, namely direct or channel precipitation (Q_p), overland flow (Q_o), shallow subsurface flow or throughflow (Q_t), and deep subsurface flow or groundwater flow (Q_g) (Appendix 21). Although these are terminologies used to define the above stormflow mechanisms, many authors subscribe to the above basic pathways in relation to the concept of the variable source area (Bruijnzeel, 1983; Bonell et al., 1981; Hewlett and Hibbert, 1967; Freeze, 1972; Kirby, 1978). Central to the above hypothesis is the concept of runoff contributing area which expands and contracts seasonally and during storms, depending on antecedent wetness, soil physical properties , water table elevations and storm magnitude (Pearce et al., 1986).

Based on field observation in a plantation forest in Indonesia, Bruijnzeel (1983) maintained that stormflow consisted of a mix of all the above variables, but cautioned that overland flow has never been observed on the forest floor. In fact, Horton overland flow only occurred on compacted areas produced by trails and landings. He further asserted that subsurface contributions are variable depending on basin wetness before and during storms and that the variable source model seems applicable in tropical areas. However, Hsia (1987) suggested that stormflow production in a forested area is the result of two simultaneous processes dominated by channel expansion or saturation overland flow and subsurface stormflow. Similarly, in many parts of New Zealand, Horton overland flow is not the principal mechanism generating storm runoff but rather it is direct precipitation on saturated variable source area, also depending on the soil hydraulic conductivity and the form of catchment hillslopes (Pearce and McKerchar, 1979). The important role of soil hydraulic properties in evaluating the stormflow mechanism has been frequently emphasized by several workers (Bonell, 1989; Bonell et al., 1981, Bruijnzeel, 1989a).

7.4 Conclusion

The stormflow analysis evidently reinforces the earlier findings that the increase in total water yield resulting from selective logging is largely associated with augmentation of baseflow. The result also reveals that stormflow parameters (stormflow volume and peak discharge) apparently require a substantial reduction in forest cover before a significant effect can be detected. The important implication of this finding is that under a proper forest management system, such as selective forest logging where a minimal ground disturbance occurs and the stream channel remains intact, the risk of potential flooding downstream following logging seems negligible. However, the antecedent moisture condition represented by the initial discharge (QI) is expected to indicate a significant change following commercial forest logging.

Stormflow runoff mechanisms under a humid rainforest could be as variable as in other areas, and could even be more complex due to the inherent climatic extremes and deep soil mantle. This in turn suggests that further rigorous field observation is needed. Additional recommendations pertaining to the hydrological effects of forest activities in the humid tropics in relation to the present study are assembled in the concluding chapter.

CHAPTER 8

GENERAL CONCLUSION

The present study can be said to have achieved the objectives set out at the beginning of this research programme. Findings from the study contribute towards a better understanding of the hydrological response of tropical watersheds and modifications imposed upon them in a number of ways. The research undoubtedly updates the growing scientific knowledge on tropical hydrology not only in the academic sense, but more importantly for forest managers and policy makers.

Despite some criticisms of the use of experimental watersheds in the past, this approach still unquestionably offers one of the best alternatives for the quantification of treatment effects, and has been used in this context for the last 50 to 60 years. Furthermore, by resorting to a shorter calibration period, as purposely adopted in this study, quick results can be obtained and at a much reduced cost. Nonetheless, an important pre-requisite with this approach is satisfactory site selection of watersheds in order to avoid problems of substantial leakage or underflow out of the watershed which can otherwise render costly results doubtful.

As expected, monitoring of the humid tropics environment, including that of Malaysia, exhibits hydrological and climatic characteristics which are different from other zones, notably in terms of more intense rainfall and abundant global radiation throughout the year. In addition, vegetation cover and soil conditions are different. An exceptionally large number of storms is evident and characterised by an extreme intensity and short duration resulting in mean monthly intensity often exceeding the threshold level of the rainfall erosive capacity. However, the question remains as to whether watersheds in the tropics are so different in their hydrological response and roles in protecting soils when disturbance occurs, that responses are quite different from those in other parts of the world. This frequently asked question has been adequately addressed by the first three objectives of this study. In general, the preceeding analyses revealed that differences are more in degree than in kind although some variables definitely require specific treatment and elaboration in the tropics, for example forest evapotranspiration. The forest evapotranspiration of this site assumes a conservative value and shows minimal variation over the year.

Results on treatment effects from this study, particularly on water yield changes, clearly confirm and reinforce findings of many other studies conducted in the tropics as well as in temperate areas. The magnitude and rate of the total yield increase largely depends on the amount of cover removed and the rainfall regime during and immediately after forest treatment, and to a lesser extent, the soil characteristics of the area. However, the specific influence of the prevailing rainfall regime on water yield increment proves difficult to quantify separately under the present research method unless a more rigorous hydrological process study is undertaken. In this instance, the magnitude of water yield changes resulting from cover manipulations is as variable as in temperate areas while qualitatively both tropical forest and coniferous forest seem to yield a similar magnitude of response as compared with other forest types.

While concrete evidence on the total yield changes has been presented, interesting results emerged on the effects of selective logging on baseflow and stormflow variables. This study indicates that the observed increase in water yield is largely associated with the augmentation of baseflow. This result is further supported by insignificant effects of treatment on peakflow discharges and stormflow volumes especially for the supervised logging method. The main reason for such responses is essentially the extensive nature of the selective logging operation which left a substantial forest area intact. Thus there was less ground disturbance whilst retention of the buffer strip ensures minimum disturbance to the flow channel. Accordingly, the former condition permits significant infiltration or reasonable recharge to baseflow. The observed increase in initial discharge (QI) as an index of soil moisture storage is interpreted as resulting from a considerable reduction in forest evapotranspiration due to forest canopy removal. Therefore, it can be inferred that stormflow parameters would not be drastically altered, with negligible effect on potential flooding downstream, unless a substantial area of forest is removed as in clearcutting. Similarly, a reasonably small percentage of forest road network, constructed as in this study, does not appear to cause any change on stormflow parameters.

The above response on stormflow variables can cause far reaching effects not only on hydrological processes but also on nutrient export and sedimentation processes, both on- and off-sites. The latter two analyses are, however, beyond the scope of this study, but rigorous studies located at the same sites have been undertaken by colleagues at FRIM as mentioned earlier.

Another interesting finding derived from this research study pertains to the effectiveness of the supervised selective logging method as compared with the unsupervised one in terms of hydrological responses. Apart from the retention of a buffer strip and the small percentage area to be covered by forest roads, other conservation measures such as installation of cross drains, culverts and proper forest road planning proved beneficial and effective in reducing undesirable hydrological impacts of forest logging, thereby ameliorating potential environmental consequences. This therefore answers the questions posed by the fourth objective of this study and these conclusions are in fact crucial at the present moment as the Forest Department of Peninsular Malaysia is in the process of formulating specific guidelines for forest logging in watershed areas, to follow broad guidelines which have already been formulated and introduced. Therefore, results of this study in addition to other relevant findings stemming from FRIM's research programme are indeed timely for the above purpose. While this study can be seen as providing the first scientific evidence on hydrological responses to selective logging in Malaysia, hopefully the findings could serve as a concrete basis for the formulation of sound watershed management quidelines in Malaysia in the near future.

One of the basic goals of hydrological science and thus watershed research is to understand hydrological responses to both atmospheric inputs as well as human activities. Development of such understanding has proven to be elusive due to the complexity of the processes involved in addition to inherent climatic and physical factors. While adequate research endeavour has been focussed on theoretical aspects of the problems, too often the application of research findings has lagged behind and even been neglected, particularly in the humid tropics. Therefore, further areas of research are necessary and relevant in the context of the phase of development and population pressures in the tropics.

Lately, forest plantations have emerged as a viable alternative land use in the tropics, in particular in degraded lands, marginal lands and logged over forest. A national programme has been underway in Malaysia since 1982 to establish a total of 188,000 ha of plantation within a time span of 15 years. While the present study elucidates the hydrological effects of forest operations, research is needed on the hydrology of plantations, including effects of conversion from natural forests. A new study on the effects of plantation establishment on various aspects of hydrology including nutrient balance, soil erosion and sedimentation, water quality and micro-climate has recently been established by FRIM at Bukit Tarik, Selangor.

There are significant gaps in our understanding of detailed hydrological processes in tropical rainforests as many of the previous studies have essentially been based on input-output studies. Many details covering process mechanisms of storm runoff operating in rainforests are still not fully understood. Therefore, process studies help to assist in the understanding of storms and fluxes of water movement so that interpretations of other results are better developed.

Upland watersheds constitute a large area of the tropical region. In Peninsular Malaysia, about 36% of the land area exceeds the 20° or 36% slope limit which is in fact the limit for agricultural practice. However, there is a strong tendency to go beyond this limit for future economic development. In the development of such areas due consideration must be given to their hydrological functions and environmental stability, thus pointing to the need for applied research commensurate with the scale of development. Further, an assessment of the role of undisturbed buffer strips under such conditions is imperative as is evaluation of their use in the broader context. Accordingly, the question of the cut-off points in terms of watershed size and storm events when land treatment ceases to be an important contribution to floods and river sediment could be examined.

In conclusion, there has been a considerable build-up in research activity in the humid tropics which should address many of these issues. In particular, the situation in the Asia-Pacific region looks very promising with a number of important initiatives and projects underway. The ASEAN - US Watershed Project and the International Hydrology Programme/UNESCO have been responsible for many meetings and seminars concerned particularly with the uplands of the ASEAN countries and research activity in the whole area is developing well. The expanding activities of FRIM, DID and universities in Malaysia and the major project in the Danum Valley, Sabah should ensure that research results relating to hydrologic responses to land use change should soon be available to assist in important land management decisions.

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APPENDIX 1

Location : Catchment 1

Parent Rock : Granite

Soil Series : Berembun

Profile

A	0-4 cm; Dark yellowish brown (10 YR 4/4); Coarse sandy clay loam, weak fine granular to crumby structure; loose, fine roots abundant, many medium roots.
AB	3-20 cm; Yellowish brown (10 YR 5/6); coarse sandy clay loam; weak, fine to medium subangular blocky structure, friable, many fine and medium roots, abrupt smooth boundary.
B21t	20-45 cm; Yellowish brown (10 YR 5/8); medium sandy clay loam, moderate medium subangular blocky structure; slightly firm, cutan continuous, many medium roots; clear smooth boundary
B22t	45-80 cm; Brownish yellow (10 YR 6/8); coarse sandy clay, strong to moderate coarse subangular blocky structure; firm, cutan continuous, few medium roots, gradual boundary
B23t	>80 cm; Brownish yellow (10 YR 6/8); coarse sandy clay; strong to moderate coarse subangular blocky; firm, non-plastic, non-sticky; cutan continuous; no roots; gradual boundary

APPENDIX 2

<u>Location</u> : Catchment 2

<u>Parent Rock</u> : Granite

<u>Soil Series</u> : Berembun

<u>Profile</u>

A	0-5 cm; Dark brown (10 YR 3/3); Medium to fine sandy clay loam, fine crumby structure; loose, fine roots abundant, micro pores abundant
AB	5-20 cm; Yellowish brown (10 YR 5/6); coarse sandy clay loam; weak, fine to medium subangular blocky structure, friable, many fine root but few medium roots, clear boundary; few micro pores
B21t	20-55 cm; Yellowish brown (10 YR 5/6); coarse sandy clay loam, moderate medium to coarse subangular blocky structures; slightly firm, cutan patchy, many fine roots, few medium roots; smooth abrupt boundary
B22t	55-100 cm; Yellowish brown (10 YR 5/8); coarse sandy clay, moderate, medium to coarse subangular blocky structures; slightly firm, cutan continuous, few medium roots, smooth gradual boundary
B23t	>100 cm; Yellowish brown (10 YR 5/6); coarse sandy clay; moderate to coarse subangular blocky structures; firm, slightly sticky; cutan continuous; rare medium roots; smooth clear boundary

APPENDIX 3

Location : Catchment 3

Parent Rock : Granite

Soil Series : Berembun

Profile

A	0-3 cm; Dark brown (10 YR 3/3); medium sandy clay loam, weak fine granular to crumby structure; loose, fine roots abundant, many medium roots.
AB	3-20 cm; Yellowish brown (10 YR 5/6); coarse sandy clay loam; weak, fine to medium subangular blocky structure, friable, many fine and medium roots, abrupt smooth boundary.
B21t	20-45 cm; Yellowish brown (10 YR 5/8); medium sandy clay loam, medium moderate subangular blocky structure; firm, cutan continuous, few medium roots; gradual boundary
B22t	45-80 cm; Brownish yellow (10 YR 6/8); coarse sandy clay, strong to moderate coarse subangular blocky structure; firm, cutan continuous, few medium roots, gradual boundary
B23t	>80 cm; Brownish yellow (10 YR 6/8); coarse sandy clay; strong to moderate coarse subangular blocky; firm, firm; cutan continuous; no roots; gradual boundary

APPENDIX 4

List of tree species in Berembun Experimental Watershed

DIPTEROCARPS : MERANTI GROUP

Shorea acuminata
Shorea bracteolata
Shorea dasyphylla
Shorea hopeifolia
Shorea leprosula
Shorea macroptera
Shorea maxima
Shorea ovalis
Shorea parvifolia

DIPTEROCARP: NON-MERANTI GROUP

Anisoptera laevis
Anisoptera scaphula
Hopea dryobalanoides
Neobalanocarpus heimii
Parashorea densiflora
Vatica pauciflora

NON DIPTEROCARPS : LIGHT HARDWOOD

FULLY MARKETABLE

Calophyllum biflorum
Calophyllum ferrugineum var ferrugineum
Calophyllum gracillimum
Calophyllum rubiginosum
Calophyllum rupicolum
Campnosperma coriaceum
Canarium littorale
Canarium pilosum
Canarium pseudosumatranum
Dacryodes costata
Dacryodes incurvata
Dacryodes laxa
Dacryodes longifolia
Dacryodes rostrata
Dacryodes rugosa
Durio griffithii
Dyera costulata
Endospermum malaccense
Gonystylus maingayi
Madhuca malaccensis
Mangifera griffithii
Mangifera indica
Mangifera magnifica
Mangifera quadrifida
Neesia synandra
Palaquium hexandrum
Palaquium hispidum
Palaquium mangayi
Palaquium obovatum
Payena lucida
Pentaspadon motleyi
Pentaspadon velutinus
Pouteria malaccensis
Santiria griffithii
Santiria laevigata
Santiria tomentosa
Scaphium linearicarpum
Scaphium macropodum
Scutinanthe brunnea
Sindora coriacea
Triomma malaccensis
Xylopia ferruginea
Xylopia malayana

PARTIALLY MARKETABLE

Actinodaphne glomerata
Actinodaphne sequipedalis
Actonodaphne pruinosa
Alstonia spatulata
Anthocephallus chinensis
Antiaris toxicaria
Artocarpus elasticus
Artocarpus lowii
Artocarpus scortechinii
Beilschmeidia palembanica
Cinnamomum iners
Cryptocarya rugulosa
Cryptocarya scortechinii
Dehaasia incrassata
Dehaasia longipetiolata
Diospyros andamanica
Diospyros apiculata
Diospyros areolata
Diospyros buxifolia
Diospyros latisepala
Diospyros penangiana
Diospyros pyrrhocarpa
Diospyros scortechinii
Diospyros sumatrana
Diospyros venosa
Diospyros wallichii
Dracontomelon dao
Endiandra maingayi
Endiandra praeclara
Gymnacranthera eugeniifolia
Gymnacranthera forbesii
Horsfieldia macrocoma var. canarioides
Horsfieldia sucosa
Horsfieldia superba
Horsfieldia tomentosa
Horsfieldia wallichii
Knema furfuracea
Knema hookeriana
Knema patentinervia
Knema pseudolaurina
Litsea grandis
Macaranga conifera
Myristica elliptica
Myristica gigantea
Myristica maingayi
Myristica maxima
Nothaphoebe panduriformis
Nothaphoebe umbellata
Parartocarpus bracteatus
Parkia speciosa
Pentace triptera
Phoebe elliptica
Prainea limpato
Sandoricum koetjape
Sapium baccatum
Sapium discolor
Strombosia javanica

NON-DIPTEROCARPS : MEDIUM HARDWOOD;

FULLY MARKETBALE

Artocarpus dadah
Artocarpus fulvicortex
Artocarpus integer v silvestris
Artocarpus lanceifolius
Artocarpus nitidus sp. griffithii
Artocarpus rigidus
Dillenia reticulata
Dillenia sumatrana
Heritiera javanica
Koompassia malaccensis

PARTIALLY MARKETABLE

Atuna excelsa
Castanopsis inermis
Cratoxylum formosum
Drimycarpus luridus
Elateriospermum tapos
Eugenia Sp. 13
Eugenia Sp. 7
Eugenia Sp. A
Eugenia claviflora
Eugenia diospyrifolia
Eugenia fastigiata
Eugenia garcinifolia
Eugenia inophylla
Eugenia operculata
Eugenia papillosa
Eugenia ridleyi
Eugenia syzygiodes
Eugenia tumida
Eugenia valdevenosa
Gluta lanceolata
Gluta malayana
Lithocarpus curtisii
Lithocarpus cyclophorus
Lithocarpus ewyckii
Lithocarpus gracilis
Lithocarpus lucidus
Lithocarpus rassa
Lithocarpus wallichii
Lithocarpus wrayi
Maranthes corymbosa
Melanochyla angustiloba
Melanochyla caesia
Melanochyla fulvinervis
Ochanostachys amentacea
Parinari costata
Parinari oblongifolia
Pimelodendron griffithianum
Pometia pinnata v alnifolia
Quercus gemilliflora
Terminalia calamansanai
Terminalia citrina
Terminalia subspatulata
Xanthophyllum affine
Xanthophyllum eurhynchum
Xanthophyllum griffithii
Xanthophyllum rufum
Xanthophyllum stipitatum
Xanthophyllum sulphureum

NON-DIPTEROCARPS : HEAVY HARDWOOD .

FULLY MARKETABLE

Cynometra malaccensis
Dialium platysepalum
Intsia palembanica

PARTIALLY MARKETABLE

Fagraea gigantea
Irvingia malayana
Mesua asamica
Mesua ferrea
Mesua nervosa
Mesua nuda
Mesua recemosa
Mesua roses
Nephelium eriopetalum
Nephelium glabrum
Vitex gamosepala
Vitex pinnata
Vitex quinata
Vitex vestita
Xerospermum noronhianum

APPENDIX 5

RATING TABLE FOR : BC 1 (R.L. 448)
UNIT : Litre/sec.

RTBC1

mm	8	9	0	1	2	3	4	5	6	7
440/ 450	0.00	00.02	00.04	00.05	00.07	00.09	00.11	00.13	00.14	00.16
450/ 460	0.18	00.20	00.22	00.23	00.25	00.27	00.28	00.30	00.32	00.33
460/ 470	0.35	00.38	00.40	00.43	00.45	00.48	00.50	00.53	00.55	00.58
470/ 480	0.60	00.63	00.66	00.69	00.72	00.75	00.78	00.81	00.84	00.87
480/ 490	0.90	00.96	01.01	01.07	01.12	01.18	01.23	01.29	01.34	01.40
490/ 500	1.45	01.52	01.59	01.66	01.73	01.80	01.87	01.94	02.01	02.08
500/ 510	2.15	02.26	02.36	02.47	02.57	02.68	02.78	02.89	02.99	03.10
510/ 520	3.20	03.33	03.46	03.59	03.72	03.85	03.98	04.11	04.24	04.37
520/ 530	4.50	04.65	04.8	04.95	05.1	05.25	05.4	05.55	05.7	05.85
530/ 540	6.00	06.17	06.34	06.51	06.68	06.85	07.02	07.19	07.36	07.53
540/ 550	7.70	07.91	08.12	08.33	08.54	08.75	08.96	09.17	09.38	09.59
550/ 560	9.80	10.02	10.24	10.46	10.68	10.9	11.12	11.34	11.56	11.78
560/ 570	12.0	12.27	12.54	12.81	13.08	13.35	13.62	13.89	14.16	14.43
570/ 580	14.7	14.99	15.28	15.57	15.86	16.15	16.44	16.73	17.02	17.31
580/ 590	17.6	17.92	18.24	18.56	18.88	19.2	19.52	19.84	20.16	20.48
590/ 600	20.8	21.16	21.52	21.88	22.24	22.6	22.96	23.32	23.68	24.04
600/ 610	24.4	24.79	25.18	25.57	25.96	26.35	26.74	27.13	27.52	27.91
610/ 620	28.3	28.75	29.2	29.65	30.1	30.55	31.0	31.45	31.9	32.35
620/ 630	32.8	33.29	33.78	34.27	34.76	35.25	35.74	36.23	36.72	37.21
630/ 640	37.7	38.25	38.8	39.35	39.9	40.45	41.0	41.55	42.1	42.65
640/ 650	43.2	43.81	44.42	45.03	45.64	46.25	46.86	47.47	48.08	48.69
650/ 660	49.3	49.9	50.5	51.1	51.7	52.3	52.9	53.5	54.1	54.7
660/ 670	55.3	55.88	56.46	57.04	57.62	58.2	58.78	59.36	59.94	60.52
670/ 680	61.11	61.7	62.3	62.9	63.5	64.1	64.7	65.3	65.9	66.5
680/ 690	67.1	68.19	69.28	70.37	71.46	72.55	73.64	74.73	75.82	76.91
690/ 700	78.0	78.7	79.4	80.1	80.8	81.5	82.2	82.9	83.6	84.3
700/ 710	85.0	85.7	86.4	87.1	87.8	88.5	89.2	89.9	90.6	91.3
710/ 720	92.0	93.0	94.0	95.0	96.0	97.0	98.0	99.0	100.0	101.0
720/ 730	102.0	103.0	104.0	105.0	106.0	107.0	108.0	109.0	110.0	111.0
730/ 740	112.0	113.0	114.0	115.0	116.0	117.0	118.0	119.0	120.0	121.0
740/ 750	122.0	123.0	124.0	125.0	126.0	127.0	128.0	129.0	130.0	131.0
750/ 760	132.0	133.0	134.0	135.0	136.0	137.0	138.0	139.0	140.1	141.0
760/ 770	142.0	143.0	144.0	145.0	146.0	147.0	148.0	149.0	150.0	151.0
770/ 780	152.0	153.2	154.4	155.6	156.8	158.0	159.2	160.4	161.1	162.8
780/ 790	164.0	165.2	166.4	167.6	168.8	170.0	171.2	172.4	173.6	174.8
790/ 800	176.0	177.2	178.4	179.6	180.8	182.0	183.2	184.4	185.6	186.8
800/ 810	188.0	189.2	190.4	191.6	192.8	194.0	195.2	196.4	197.6	198.8
810/ 820	200.0	201.4	202.8	204.2	205.6	207.0	208.4	209.8	211.2	212.6
820/ 830	214.0	215.4	216.8	218.2	219.6	221.0	222.4	223.8	225.2	226.6
830/ 840	228.0	229.4	230.8	232.2	233.6	235.0	236.4	237.8	239.2	240.6
840/ 850	242.0	243.6	245.2	246.8	248.4	250.0	251.6	253.2	254.8	256.4
850/ 860	258.0	259.6	261.2	262.8	264.4	266.0	267.6	269.2	270.8	272.4
860/ 870	274.0	275.6	277.2	278.8	280.4	282.0	283.6	285.2	286.8	288.4
870/ 880	290.0	291.8	293.6	295.4	297.2	299.0	300.8	302.6	304.4	306.2
880/ 890	308.0	309.8	311.6	313.4	315.2	317.0	318.8	320.6	322.4	324.2
890/ 900	326.0	327.9	329.8	331.7	333.6	335.5	337.4	339.2	341.2	343.1
900/ 910	345.0	347.0	349.0	351.0	353.0	355.0	357.0	359.0	361.0	363.0
910/ 920	365.0	367.0	369.0	371.0	373.0	375.0	377.0	379.0	381.0	383.0
920/ 930	385.0	387.0	389.0	391.0	393.0	395.0	397.0	399.0	401.0	403.0
930/ 940	405.0	407.0	409.0	411.0	413.0	415.0	417.0	419.0	421.0	423.0
940/ 950	425.0	427.2	429.4	431.6	433.8	436.0	438.2	440.4	442.6	444.8
950/ 960	447.0	449.2	451.4	453.6	455.8	458.0	460.2	462.4	464.6	466.8
960/ 970	469.0	471.3	473.6	475.9	478.2	480.5	482.8	485.1	487.4	489.7
970/ 980	492.0	494.4	496.8	499.2	501.6	504.0	506.4	508.9	511.2	513.6
980/ 990	516.0	518.4	520.8	523.2	525.6	528.0	530.4	532.8	535.2	537.6
990/1000	540.0	542.4	544.8	547.2	549.6	552.0	554.4	556.8	559.2	561.6
1000/1010	564.0	566.4	568.8	571.2	573.6	576.0	578.4	580.8	583.2	585.6
1010/1020	588.0	590.6	593.2	595.8	598.4	601.0	603.6	606.2	608.8	611.4
1020/1030	614.0	616.8	619.6	622.4	625.2	628.0	630.8	633.6	636.4	639.4
1030/1040	642.0	644.8	647.8	650.4	653.2	656.0	658.8	661.6	664.4	667.2
1040/1050	670.0	672.8	675.6	678.4	681.2	684.0	686.8	689.6	692.4	695.2

APPENDIX 6

RATING TABLE FOR : BC 2 (R.L. 450)
UNIT : Litre/sec.

RTBC2

mm	0	1	2	3	4	5	6	7	8	9
450	0.00	00.02	00.04	00.05	00.07	00.09	00.11	00.13	00.14	00.16
460	0.18	00.20	00.22	00.23	00.25	00.27	00.28	00.30	00.32	00.33
470	0.35	00.38	00.40	00.43	00.45	00.48	00.50	00.53	00.55	00.58
480	0.60	00.63	00.66	00.69	00.72	00.75	00.78	00.81	00.84	00.87
490	0.90	00.96	01.01	01.07	01.12	01.18	01.23	01.29	01.34	01.40
500	1.45	01.52	01.59	01.66	01.73	01.80	01.87	01.94	02.01	02.08
510	2.15	02.26	02.36	02.47	02.57	02.68	02.78	02.89	02.99	03.10
520	3.20	03.33	03.46	03.59	03.72	03.85	03.98	04.11	04.24	04.37
530	4.50	04.65	04.8	04.95	05.1	05.25	05.4	05.55	05.7	05.85
540	6.00	06.17	06.34	06.51	06.68	06.85	07.02	07.19	07.36	07.53
550	7.70	07.91	08.12	08.33	08.54	08.75	08.96	09.17	09.38	09.59
560	9.80	10.02	10.24	10.46	10.68	10.9	11.12	11.34	11.56	11.78
570	12.0	12.27	12.54	12.81	13.08	13.35	13.62	13.89	14.16	14.43
580	14.7	14.99	15.28	15.57	15.86	16.15	16.44	16.73	17.02	17.31
590	17.6	17.92	18.24	18.56	18.88	19.2	19.52	19.84	20.16	20.48
600	20.8	21.16	21.52	21.88	22.24	22.6	22.96	23.32	23.68	24.04
610	24.4	24.79	25.18	25.57	25.96	26.35	26.74	27.13	27.52	27.91
620	28.3	28.75	29.2	29.65	30.1	30.55	31.0	31.45	31.9	32.35
630	32.8	33.29	33.78	34.27	34.76	35.25	35.74	36.23	36.72	37.21
640	37.7	38.25	38.8	39.35	39.9	40.45	41.0	41.55	42.1	42.65
650	43.2	43.81	44.42	45.03	45.64	46.25	46.86	47.47	48.08	48.69
660	49.3	49.9	50.5	51.1	51.7	52.3	52.9	53.5	54.1	54.7
670	55.3	55.88	56.46	57.04	57.62	58.2	58.78	59.36	59.94	60.52
680	61.11	61.7	62.3	62.9	63.5	64.1	64.7	65.3	65.9	66.5
690	67.1	68.19	69.28	70.37	71.46	72.55	73.64	74.73	75.82	76.91
700	78.0	78.7	79.4	80.1	80.8	81.5	82.2	82.9	83.6	84.3
710	85.0	85.7	86.4	87.1	87.8	88.5	89.2	89.9	90.6	91.3
720	92.0	93.0	94.0	95.0	96.0	97.0	98.0	99.0	100.0	101.0
730	102.0	103.0	104.0	105.0	106.0	107.0	108.0	109.0	110.0	111.0
740	112.0	113.0	114.0	115.0	116.0	117.0	118.0	119.0	120.0	121.0
750	122.0	123.0	124.0	125.0	126.0	127.0	128.0	129.0	130.0	131.0
760	132.0	133.0	134.0	135.0	136.0	137.0	138.0	139.0	140.1	141.0
770	142.0	143.0	144.0	145.0	146.0	147.0	148.0	149.0	150.0	151.0
780	152.0	153.2	154.4	155.6	156.8	158.0	159.2	160.4	161.1	162.8
790	164.0	165.2	166.4	167.6	168.8	170.0	171.2	172.4	173.6	174.8
800	176.0	177.2	178.4	179.6	180.8	182.0	183.2	184.4	185.6	186.8
810	188.0	189.2	190.4	191.6	192.8	194.0	195.2	196.4	197.6	198.8
820	200.0	201.4	202.8	204.2	205.6	207.0	208.4	209.8	211.2	212.6
830	214.0	215.4	216.8	218.2	219.6	221.0	222.4	223.8	225.2	226.6
840	228.0	229.4	230.8	232.2	233.6	235.0	236.4	237.8	239.2	240.6
850	242.0	243.6	245.2	246.8	248.4	250.0	251.6	253.2	254.8	256.4
860	258.0	259.6	261.2	262.8	264.4	266.0	267.6	269.2	270.8	272.4
870	274.0	275.6	277.2	278.8	280.4	282.0	283.6	285.2	286.8	288.4
880	290.0	291.8	293.6	295.4	297.2	299.0	300.8	302.6	304.4	306.2
890	308.0	309.8	311.6	313.4	315.2	317.0	318.8	320.6	322.4	324.2
900	326.0	327.9	329.8	331.7	333.6	335.5	337.4	339.2	341.2	343.1
910	345.0	347.0	349.0	351.0	353.0	355.0	357.0	359.0	361.0	363.0
920	365.0	367.0	369.0	371.0	373.0	375.0	377.0	379.0	381.0	383.0
930	385.0	387.0	389.0	391.0	393.0	395.0	397.0	399.0	401.0	403.0
940	405.0	407.0	409.0	411.0	413.0	415.0	417.0	419.0	421.0	423.0
950	425.0	427.2	429.4	431.6	433.8	436.0	438.2	440.4	442.6	444.8
960	447.0	449.2	451.4	453.6	455.8	458.0	460.2	462.4	464.6	466.8
970	469.0	471.3	473.6	475.9	478.2	480.5	482.8	485.1	487.4	489.7
980	492.0	494.4	496.8	499.2	501.6	504.0	506.4	508.9	511.2	513.6
990	516.0	518.4	520.8	523.2	525.6	528.0	530.4	532.8	535.2	537.6
1000	540.0	542.4	544.8	547.2	549.6	552.0	554.4	556.8	559.2	561.6
1010	564.0	566.4	568.8	571.2	573.6	576.0	578.4	580.8	583.2	585.6
1020	588.0	590.6	593.2	595.8	598.4	601.0	603.6	606.2	608.8	611.4
1030	614.0	616.8	619.6	622.4	625.2	628.0	630.8	633.6	636.4	639.4
1040	642.0	644.8	647.8	650.4	653.2	656.0	658.8	661.6	664.4	667.2
1050	670.0	672.8	675.6	678.4	681.2	684.0	686.8	689.6	692.4	695.2

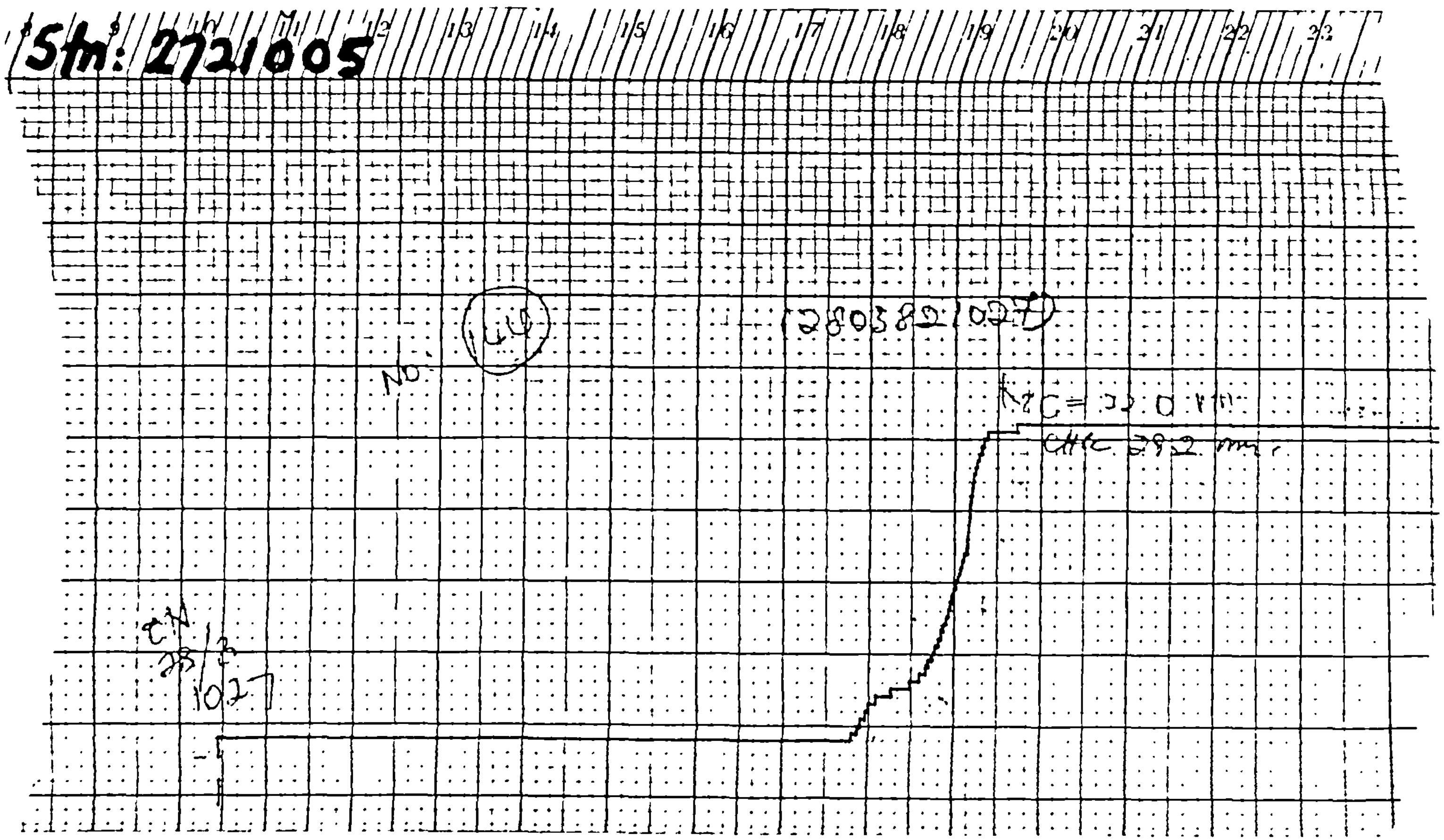
APPENDIX 7

RATING TABLE FOR : BC 3 (R.L. 458)
UNIT : Litre/sec.

RTBC3

mm	8	9	0	1	2	3	4	5	6	7
450/ 460	0.00	00.02	00.04	00.05	00.07	00.09	00.11	00.13	00.14	00.16
460/ 470	0.18	00.20	00.22	00.23	00.25	00.27	00.28	00.30	00.32	00.33
470/ 480	0.35	00.38	00.40	00.43	00.45	00.48	00.50	00.53	00.55	00.58
480/ 490	0.60	00.63	00.66	00.69	00.72	00.75	00.78	00.81	00.84	00.87
490/ 500	0.90	00.96	01.01	01.07	01.12	01.18	01.23	01.29	01.34	01.40
500/ 510	1.45	01.52	01.59	01.66	01.73	01.80	01.87	01.94	02.01	02.08
510/ 520	2.15	02.26	02.36	02.47	02.57	02.68	02.78	02.89	02.99	03.10
520/ 530	3.20	03.33	03.46	03.59	03.72	03.85	03.98	04.11	04.24	04.37
530/ 540	4.50	04.65	04.8	04.95	05.1	05.25	05.4	05.55	05.7	05.85
540/ 550	6.00	06.17	06.34	06.51	06.68	06.85	07.02	07.19	07.36	07.53
550/ 560	7.70	07.91	08.12	08.33	08.54	08.75	08.96	09.17	09.38	09.59
560/ 570	9.80	10.02	10.24	10.46	10.68	10.9	11.12	11.34	11.56	11.78
570/ 580	12.0	12.27	12.54	12.81	13.08	13.35	13.62	13.89	14.16	14.43
580/ 590	14.7	14.99	15.28	15.57	15.86	16.15	16.44	16.73	17.02	17.31
590/ 600	17.6	17.92	18.24	18.56	18.88	19.2	19.52	19.84	20.16	20.48
600/ 610	20.8	21.16	21.52	21.88	22.24	22.6	22.96	23.32	23.68	24.04
610/ 620	24.4	24.79	25.18	25.57	25.96	26.35	26.74	27.13	27.52	27.91
620/ 630	28.3	28.75	29.2	29.65	30.1	30.55	31.0	31.45	31.9	32.35
630/ 640	32.8	33.29	33.78	34.27	34.76	35.25	35.74	36.23	36.72	37.21
640/ 650	37.7	38.25	38.8	39.35	39.9	40.45	41.0	41.55	42.1	42.65
650/ 660	43.2	43.81	44.42	45.03	45.64	46.25	46.86	47.47	48.08	48.69
660/ 670	49.3	49.9	50.5	51.1	51.7	52.3	52.9	53.5	54.1	54.7
670/ 680	55.3	55.88	56.46	57.04	57.62	58.2	58.78	59.36	59.94	60.52
680/ 690	61.11	61.7	62.3	62.9	63.5	64.1	64.7	65.3	65.9	66.5
690/ 700	67.1	68.19	69.28	70.37	71.46	72.55	73.64	74.73	75.82	76.91
700/ 710	78.0	78.7	79.4	80.1	80.8	81.5	82.2	82.9	83.6	84.3
710/ 720	85.0	85.7	86.4	87.1	87.8	88.5	89.2	89.9	90.6	91.3
720/ 730	92.0	93.0	94.0	95.0	96.0	97.0	98.0	99.0	100.0	101.0
730/ 740	102.0	103.0	104.0	105.0	106.0	107.0	108.0	109.0	110.0	111.0
740/ 750	112.0	113.0	114.0	115.0	116.0	117.0	118.0	119.0	120.0	121.0
750/ 760	122.0	123.0	124.0	125.0	126.0	127.0	128.0	129.0	130.0	131.0
760/ 770	132.0	133.0	134.0	135.0	136.0	137.0	138.0	139.0	140.1	141.0
770/ 780	142.0	143.0	144.0	145.0	146.0	147.0	148.0	149.0	150.0	151.0
780/ 790	152.0	153.2	154.4	155.6	156.8	158.0	159.2	160.4	161.1	162.8
790/ 800	164.0	165.2	166.4	167.6	168.8	170.0	171.2	172.4	173.6	174.8
800/ 810	176.0	177.2	178.4	179.6	180.8	182.0	183.2	184.4	185.6	186.8
810/ 820	188.0	189.2	190.4	191.6	192.8	194.0	195.2	196.4	197.6	198.8
820/ 830	200.0	201.4	202.8	204.2	205.6	207.0	208.4	209.8	211.2	212.6
830/ 840	214.0	215.4	216.8	218.2	219.6	221.0	222.4	223.8	225.2	226.6
840/ 850	228.0	229.4	230.8	232.2	233.6	235.0	236.4	237.8	239.2	240.6
850/ 860	242.0	243.6	245.2	246.8	248.4	250.0	251.6	253.2	254.8	256.4
860/ 870	258.0	259.6	261.2	262.8	264.4	266.0	267.6	269.2	270.8	272.4
870/ 880	274.0	275.6	277.2	278.8	280.4	282.0	283.6	285.2	286.8	288.4
880/ 890	290.0	291.8	293.6	295.4	297.2	299.0	300.8	302.6	304.4	306.2
890/ 900	308.0	309.8	311.6	313.4	315.2	317.0	318.8	320.6	322.4	324.2
900/ 910	326.0	327.9	329.8	331.7	333.6	335.5	337.4	339.2	341.2	343.1
910/ 920	345.0	347.0	349.0	351.0	353.0	355.0	357.0	359.0	361.0	363.0
920/ 930	365.0	367.0	369.0	371.0	373.0	375.0	377.0	379.0	381.0	383.0
930/ 940	385.0	387.0	389.0	391.0	393.0	395.0	397.0	399.0	401.0	403.0
940/ 950	405.0	407.0	409.0	411.0	413.0	415.0	417.0	419.0	421.0	423.0
950/ 960	425.0	427.2	429.4	431.6	433.8	436.0	438.2	440.4	442.6	444.8
960/ 970	447.0	449.2	451.4	453.6	455.8	458.0	460.2	462.4	464.6	466.8
970/ 980	469.0	471.3	473.6	475.9	478.2	480.5	482.8	485.1	487.4	489.7
980/ 990	492.0	494.4	496.8	499.2	501.6	504.0	506.4	508.9	511.2	513.6
990/ 1000	516.0	518.4	520.8	523.2	525.6	528.0	530.4	532.8	535.2	537.61
1000/1010	540.0	542.4	544.8	547.2	549.6	552.0	554.4	556.8	559.2	561.6
1010/1020	564.0	566.4	568.8	571.2	573.6	576.0	578.4	580.8	583.2	585.6
1020/1030	588.0	590.6	593.2	595.8	598.4	601.0	603.6	606.2	608.8	611.4
1030/1040	614.0	616.8	619.6	622.4	625.2	628.0	630.8	633.6	636.4	639.4
1040/1050	642.0	644.8	647.8	650.4	653.2	656.0	658.8	661.6	664.4	667.2

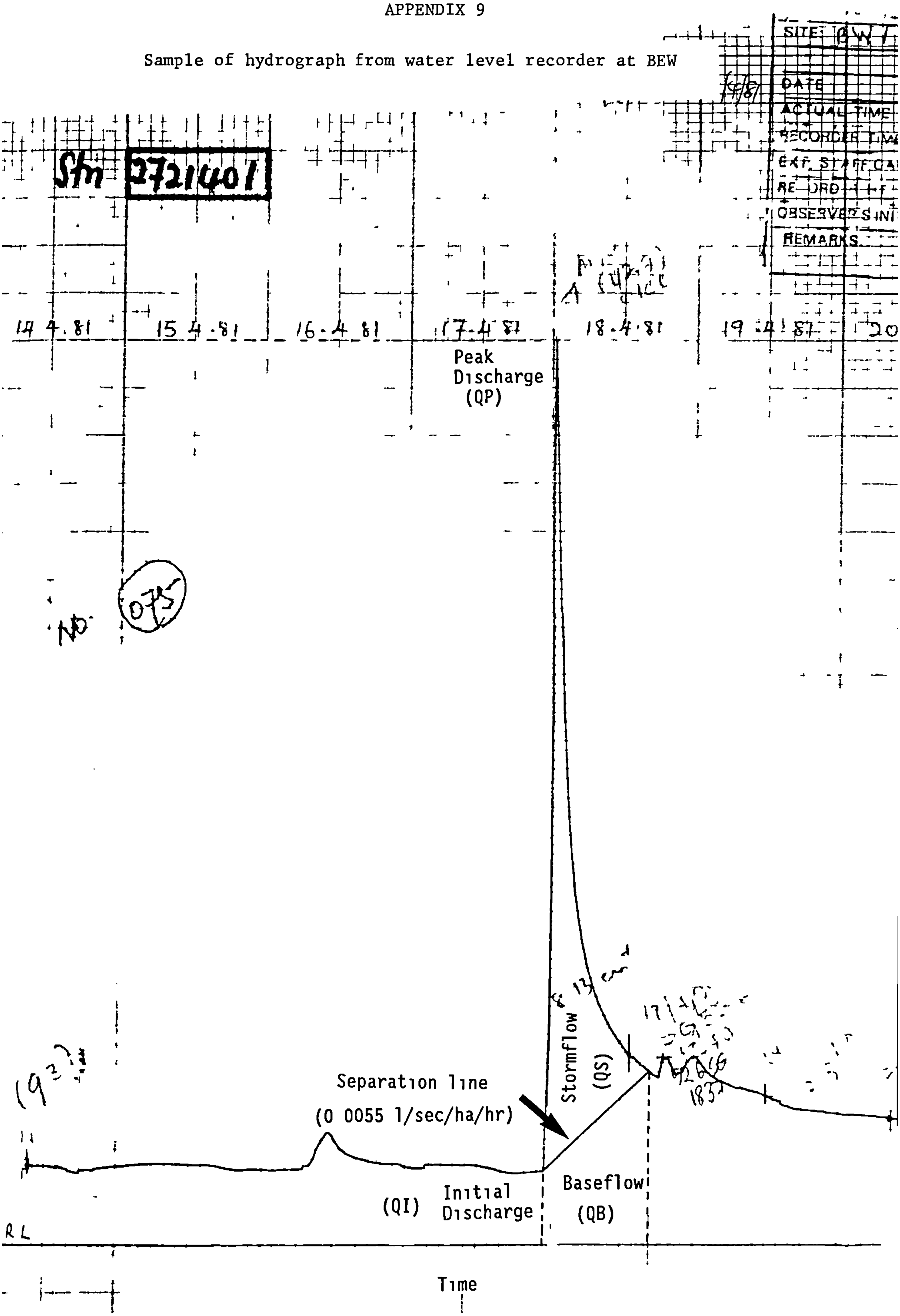
Sample of rainfall chart from recording raingauge at BEW



Storm Rainfall chart of 28.3.1983 (Daily)
Storm started : 1748 hr. Ended: 1923
Total : 21.5 mm

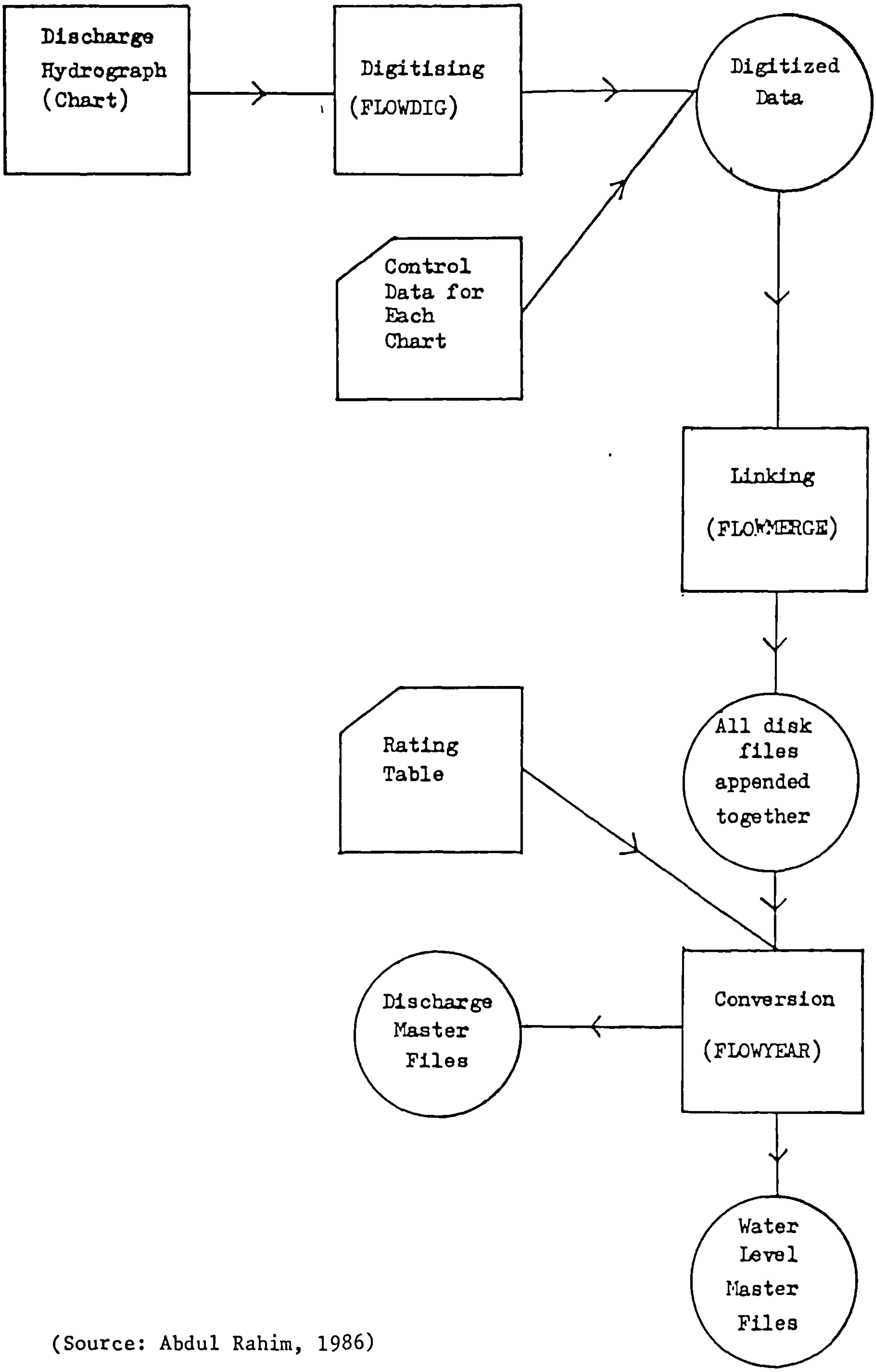
APPENDIX 9

Sample of hydrograph from water level recorder at BEW



APPENDIX 10

Flowchart for Processing Discharge Hydrograph



(Source: Abdul Rahim, 1986)

APPENDIX 11

Logging Specifications in catchment 3 of Berembun Experimental Watershed (BEW), Berembun Forest Reserve, Negeri Sembilan

I. Road Planning

Proper planning can minimise the amount of land in roads and considerably reduce the undesirable impacts of soil erosion, silted stream and impairment of water quality. Accordingly, proper road construction and maintenance will do much to prevent soil erosion and sedimentation of streams. For this, road survey on the catchment 3 has been carried out by the Engineering Unit of Forestry Department of Peninsular Malaysia. The purpose is to locate a proper logging road system with respect to appropriate access, adequate protection measure and one which is economical. The road system on this catchment will cover approximately 6% of the area.

II. Road Construction

1. Main and branch road should be 4.0 to 4.5 m wide and road grades should not exceed 20%, preferably between 10-15%.

2. Roads should follow topographic contours, whenever possible, to avoid steep grades and extensive cutting and filling.

3. Whenever roads must ascend steep grades, they should be constructed in a winding manner with a minimum curve radius of 15 m. Although this may result in greater road length and higher initial costs, factors of increased safety, reduced maintenance cost viz. wear and tear on vehicles and reduced erosion are sompensated for.

4. Stream crossings should be made <u>ONLY</u> where necessary and at right angles to water course. The approaches to these crossings should be on aminimum slope. Proper bridges or culverts are required at these crossings. (Detailed specification of bridge and culvert may be obtained from the Engineering Unit of Forestry Department, Kuala Lumpur).

5. Maintain a strip of undisturbed forest or filter strip between road and stream. The width of filter strip can be determined by the following procedure but minimum width is being 20 m: Width of filter strip (m) = 8.0 (0.6 X % slope)

6. Sloping road surfaces should be blade-ditched to a minimum of 12-25 cm below road surfaces. These ditches should be provided with a series of cross drains or pole culverts at 30 m of maximum interval in order to dissipate the surface runoff into the filter strip. Rip-rap (collection of stones/rocks acts as energy absorber) can be placed at cross drains outlets.

7. Skid trails

Most of the above specifications, in principle, also apply to the construction of skid trails with the exception of their width. Minimum skid trails are recommended and if possible, repeated use of the same trails should encouraged. No skidding down or across the channel should be permitted and skid trails that converge in a downslope direction should be avoided.

III. Logging Operation

1. No logging is allowed within 20 m from live streams so that a continous filter is maintained.
2. Cutting regimes that have been imposed must be followed strictly.
3. Trees should be felled away from stream channels without disturbing the filter strip.
4. Trees should be felled in a 'herring bone pattern' or perpendicular to the road enabling their extraction with a minimum turning and disturbance to the soil.
5. Whenever possible, turning of crawler tractors should be made in openings and then backed up to the loads.
6. Logs should be pulled out endwise and not pivoted around live trees or clumps of under growth.

IV. Landing

1. The landing site should be far away from water courses and adequately surrounded by at least 10 m of buffer strip.
2. Adequate drainage on approach roads must be provided and frequently maintained.
3. The servicing of machines on site should be done in such a way that old oil, etc. should be drained into containers and properly disposed.
4. Revegetate landings immediately following completion of forest operations.

V. Maintenance of Logging Roads

1. Stabilise and protect any fill and bank disturbance with logs, rocks, rip-rap or other protective materials.

2. Restrict traffic on logging roads during unfavourable weather when possible

3. Regrade roads to remove deep ruts when severe rutting occurs.

4. Never allow skidding on main roads.

5. Established earthen water bars at appropriate intervals after completion of forest operation.

6. Inspect the road system at regular schedule, clean ditches, culverts and inlets and outlets to culverts.

Hydrology Section
Forest Research Institute
Kepong, Selangor
November, 1982.

APPENDIX 12

Monthly and Annual Rainfall of Three Recording Raingauges in BEW

YEAR*	STN.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1980	C/S					120.0	47.0	180.5	156.0	237.0	207.0	275.0	166.5	1389.0
	21B	23.5	159.5	181.5	148.5	95.0	47.5	119.5	215.5	250.0	203.5	323.0	184.5	1951.5
	32A	27.0	167.0	199.0	167.0	97.5	46.0	166.5	193.5	278.0	217.0	326.0	198.0	2082.5
1981	C/S	43.5	230.5	162.0	326.0	333.5	43.5	31.5	40.0	318.0	93.0	234.5	168.5	2024.5
	21B	60.0	251.0	172.5	379.0	371.5	39.5	23.0	45.5	327.0	102.1	229.0	157.5	2157.6
	31A	60.0	276.5	156.5	370.0	368.5	42.0	16.5	34.5	383.0	81.5	232.0	141.5	2162.5
1982	C/S	22.5	53.5	264.5	405.5	105.5	121.0	108.5	80.5	104.0	281.0	333.0	72.0	1951.5
	21B	19.5	35.5	279.0	352.5	86.5	129.0	102.0	70.0	89.5	266.0	377.5	106.0	1913.0
	32A	24.0	53.5	302.0	352.0	91.5	146.5	85.0	78.0	69.0	299.0	336.0	135.0	1971.5
1983	C/S	75.5	20.5	7.0	99.0	116.5	125.5	174.5	166.5	170.0	219.0	240.0	155.0	1569.0
	21B	101.5	22.5	5.0	131.0	71.0	120.0	195.5	171.5	212.5	249.5	252.0	171.5	1703.5
	32A	87.5	17.0	6.5	109.0	93.0	129.5	164.5	163.0	182.5	206.0	238.0	168.5	1565.0
1984	C/S	156.0	390.5	187.0	117.5	215.0	111.0	127.5	99.5	156.0	205.0	412.0	213.5	2390.5
	21B	173.5	417.5	216.5	127.5	227.5	102.5	110.5	107.5	145.5	234.5	493.0	261.5	2617.5
	32A	182.0	376.0	189.0	105.5	204.0	110.0	114.5	123.5	163.5	216.5	519.5	224.5	2528.5
1985	C/S	60.0	186.5	134.5	112.0	215.0	8.5	144.5	19.0	123.0	233.5	306.0	319.0	1861.5
	21B	59.5	167.5	131.0	119.5	265.5	12.5	168.0	28.0	132.0	229.5	312.5	347.0	1972.5
	32A	42.0	171.5	101.0	114.0	208.5	14.0	163.0	20.0	124.5	195.5	305.0	302.5	1761.5
1986	C/S	182.6	118.5	262.5	280.5	259.0	38.0	123.5	46.0	226.5	272.5	276.5	244.5	2330.6
	21B	245.0	141.0	291.5	283.0	289.0	38.0	146.5	46.5	268.5	298.0	279.5	267.0	2593.5
	32A	226.0	96.5	244.9	299.0	268.0	39.0	115.0	37.5	223.5	265.5	275.5	206.0	2296.4
1987	C/S	75.0	6.5	124.5	186.0	278.0	113.5	32.5	114.0	193.5	294.0	277.5	156.5	1851.5
	21B	68.5	9.0	141.0	293.5	319.5	142.5	38.0	196.5	204.5	309.5	290.0	173.5	2186.0
	32A	54.0	7.0	124.0	226.0	250.0	114.5	35.0	172.5	193.5	292.0	252.0	137.5	1858.0

APPENDIX 13

Storm Intensity Frequency of Climate Station, BEW

Class	Freq	Rel. Freq.
10	384	54
30	182	25.6
50	64	9
70	60	5.6
90	14	1.9
110	2	0.2
130	4	0.5
150	8	1.1
170	1	0.1
190	2	0.2
210	2	0.2
230	0	0
250	0	0
270	3	0.4
290	0	0
310	1	0.1
330	0	0
350	0	0
370	2	0.2
390	0	0
410	0	0
430	0	0
450	1	0.1

APPENDIX 14

Frequency of Storm Duration of Climate Station

Class	Freq.	Rel. Freq.
15	242	34.1
45	235	33.0
75	102	14.3
105	41	5.7
135	40	5.6
165	18	2.5
195	12	1.6
225	7	0.9
255	5	0.7
285	0	0.0
315	2	0.2
345	3	0.4
375	1	0.1

APPENDIX 15

Baseflow recession curve data for catchment 1, BEW

DAY	1980		1981				1982				1983		AVG
0				1.12		1.07							1.10
1		0.96		0.96		0.96							0.96
2		0.87		0.84		0.90							0.87
3		0.84		0.81		0.87							0.84
4		0.84				0.81							0.83
5		0.78	0.78			0.78							0.78
6			0.72			0.72							0.72
7			0.69			0.70		0.67					0.69
8			0.66			0.66		0.65					0.66
9			0.63			0.60		0.60					0.61
10								0.58			0.58	0.55	0.57
11					0.53			0.54			0.55	0.50	0.53
12	0.40				0.43		0.44			0.48	0.50	0.48	0.46
13	0.27				0.33		0.37			0.37	0.48	0.42	0.37
14	0.23				0.30		0.37			0.33	0.43	0.38	0.34
15	0.20				0.28		0.35			0.31	0.40	0.35	0.32
16	0.18				0.23		0.33			0.29	0.38	0.32	0.29
17	0.15				0.22		0.29		0.23	0.27		0.28	0.24
18					0.20		0.21		0.24	0.25		0.25	0.23
19					0.16		0.18		0.18	0.24		0.14	0.18
20					0.13		0.17		0.18	0.21			0.17

APPENDIX 16

Monthly soil water at SM1, SM2, and SM3

MON	YEAR	SM1	SM2	SM3	C/S	S21
OCT	81	25.46	32.14	27.65	93.00	102.10
NOV	81	33.03	32.80	31.33	234.50	229.00
DEC	81	28.13	28.58	25.80	168.50	157.50
JAN	82	24.71	29.89	26.68	22.50	19.50
FEB	82	25.46	28.67	24.64	53.50	35.50
MAR	82	27.80	31.45	31.22	264.50	279.00
APR	82	31.33	31.28	28.83	405.50	352.50
MAY	82	28.46	28.67	26.32	105.50	86.50
JUN	82	29.86	32.78	24.46	121.00	129.00
JUL	82	29.45	28.32	26.68	108.50	102.00
AUG	82	29.12	33.53	27.75	80.50	70.00
SEP	82	27.03	28.67	28.47	104.00	89.50
OCT	82	35.41	35.62	34.21	281.00	266.00
NOV	82	34.75	34.40	32.90	333.00	377.50
DEC	82	30.23	31.45	27.63	72.00	106.00
JAN	83	29.90	28.67	28.83	75.50	101.50
FEB	83	26.92	25.19	23.93	20.50	22.50
MAR	83	23.93	22.24	25.24	7.00	5.00
APR	83	30.12	28.84	28.23	99.00	131.00
MAY	83	30.56	26.58	27.87	116.50	71.00
JUN	83	25.59	24.85	24.16	125.50	120.00
JUL	83	30.78	30.06	28.23	174.50	195.50
AUG	83	32.87	32.49	32.18	166.50	171.50
SEP	83	31.66	33.53	27.87	170.00	212.50
OCT	83	32.54	35.58	32.54	219.00	249.50
NOV	83	31.88	34.88	31.34	240.00	252.00
DEC	83	30.23	34.36	30.86	155.00	171.50
JAN	84	31.88	32.49	34.33	156.00	173.50
FEB	84	33.21	29.54	32.54	390.50	417.50
MAR	84	30.01	28.15	29.91	187.00	216.50
APR	84	33.32	27.63	32.18	117.50	127.50
MAY	84	33.21	32.84	34.69	215.00	227.50
JUN	84	31.22	30.06	32.42	111.00	102.50
JUL	84	33.76	34.40	32.18	127.50	110.50
AUG	84	29.12	31.62	28.83	99.50	107.50
SEP	84	32.76	29.02	27.99	156.00	145.50
OCT	84	30.89	32.84	28.59	205.00	234.50
NOV	84	32.54	34.58	33.14	412.00	493.00
DEC	84	34.42	34.75	35.53	213.50	261.00

APPENDIX 16b

Monthly soil water at SM1, SM2, and SM3

MON	YEAR	SM1	SM2	SM3	C/S	S21
JAN	85	28.90	24.84	26.55	60.00	59.50
FEB	85	30.56	28.15	29.79	186.00	167.50
MAR	85	30.34	27.28	27.51	134.50	131.00
APR	85	27.36	31.62	32.54	112.00	119.50
MAY	85	35.08	31.45	29.55	215.00	265.50
JUN	85	28.46	28.49	27.27	8.50	12.50
JUL	85	31.00	28.32	29.79	144.50	168.00
AUG	85	26.26	25.54	25.96	19.00	28.00
SEP	85	27.25	27.63	27.16	123.00	132.00
OCT	85	33.76	29.71	32.18	229.00	229.50
NOV	85	32.54	32.14	33.38	312.50	312.50
DEC	85	32.32	33.71	31.94	347.00	347.00
JAN	86	32.14	34.14	30.72	182.60	245.00
FEB	86	33.47	33.92	31.64	118.50	141.00
MAR	86	32.80	33.58	31.95	262.50	291.00
APR	86	32.92	33.58	29.80	280.50	283.00
MAY	86	33.36	33.14	31.54	259.00	289.00
JUN	86	31.02	29.47	29.18	38.00	38.00

APPENDIX 17

PENMAN POTENTIAL EVAPOTRANSPIRATION EQUATIONS

Penman's equations for the estimation of potential evapotranspiration are as follows:

$$R_n = R_A\,(a + b\frac{n}{N})(1-r) - \sigma T_m^4\,(0.56 - 0.092\sqrt{e_d})(0.1 + 0.9\frac{n}{N}) \quad ..(1)$$

$$H = R_n/L$$

$$Ea = 0.35\,(e_m - e_d)(1 + 0.526U) \quad \text{(Penman 1948)} \quad (2)$$

$$\Delta = \frac{5326.4}{T_m^2}\,e_m \quad (3)$$

$$PE = \frac{\Delta H + \gamma Ea}{\Delta + \gamma} \quad (4)$$

where R_n = Net radiation in gm. cal/cm²/day

R_A = mean daily extra terrestrial radiation in gm.cal/cm²/day
= 804 gm.cal/cm /day

H = mean daily heat budget at surface in mm water/day

a, b = empirical constants converting sunshine hours to short wave radiation
a = 0.24 ; b = 0.51

T_m = mean air temperature in degrees absolute (°K) for day (month).

L = latent heat of vaporisation (cal/mm.cm²) given empirically by
$L = 75.56 - 0.0581\ T_m$

r = albedo, the reflection coefficient of the surface

n = actual duration of bright sunshine in hours for day (month)

N = maximum possible mean daily duration of bright sunshine in hours

σ = Lummer and Pringsheim constant; 117.74×10^{-9} gm. cal/cm²/°K⁻⁴

e_m = saturation vapour pressure in mm Hg at mean air temperature for day (month)

e_d = saturation vapour pressure in mm Hg at mean dew point temperature for day (month)

U = mean wind velocity in m/sec for day (month) at two metres above ground level

Δ = slope of saturation vapour pressure curve of air at absolute temperature T_m, in mm Hg/°C

γ = psychrometric constant; 0.49 mm Hg/°C

PE = potential evapotranspiration in mm water/day

(Source: DID, 1977)

APPENDIX 18a

Observed and estimated monthly runoff (mm) of catchments 1 and 3 with respective residuals

Month	Q1	Q2	Q3	Q1EST	RES1	Q3EST	RES3
0780	7.30	3.90	6.50	2.89	4.41	3.94	2.56
08	5.20	10.80	9.80	9.93	-4.73	11.04	-1.24
09	17.30	24.10	17.80	21.01	-3.71	21.15	-3.35
10	19.10	30.60	22.20	25.37	-6.27	24.58	-2.38
11	43.50	42.00	41.20	36.35	7.15	35.38	5.82
12	34.50	43.40	27.70	35.17	-0.67	33.07	-5.37
01	15.00	26.80	13.70	20.00	-5.00	18.53	-4.83
02	19.40	25.30	20.20	21.97	-2.57	22.01	-1.81
03	13.10	23.00	13.50	18.86	-5.76	18.54	-5.04
04	46.10	58.00	48.80	49.92	-3.82	47.88	0.92
05	66.20	73.30	67.70	62.21	3.99	58.87	8.83
06	25.00	33.90	25.80	25.27	-0.27	23.00	2.80
0781	12.50	21.00	11.00	14.81	-2.31	13.60	-2.60
08	5.70	12.80	4.70	8.70	-3.00	8.41	-3.71
09	34.40	50.60	33.70	43.21	-8.81	41.48	-7.78
10	16.40	21.00	14.00	16.12	0.28	15.47	-1.47
11	22.40	38.30	25.90	31.88	-9.48	30.57	-4.67
12	33.50	36.40	31.60	29.20	4.30	27.54	4.06
01	7.30	13.40	6.50	8.75	-1.45	8.21	-1.71
02	3.80	4.00	4.10	1.59	2.21	2.02	2.08
03	4.60	8.30	9.20	9.00	-4.40	10.80	-1.60
04	50.30	47.90	37.10	41.50	8.80	40.20	-3.10
05	16.00	16.70	15.20	12.46	3.54	12.10	3.10
06	15.70	14.80	12.80	11.66	4.04	11.78	1.02
0782	14.20	15.90	12.40	12.09	2.11	11.91	0.49
08	10.80	12.30	9.10	8.71	2.09	8.64	0.46
09	5.40	6.80	5.50	4.69	0.71	5.26	0.24
10	16.00	17.20	19.50	15.82	0.18	16.70	2.80
11	51.00	49.10	44.60	42.86	8.14	41.63	2.97
12	21.00	24.20	22.70	18.71	2.29	17.80	4.90
01	14.40	16.60	10.30	12.63	1.77	12.39	-2.09
02	2.30	1.30	6.60	-0.76	3.06	-0.17	6.77
03	0.00	0.00	0.12	-2.08	2.08	-1.50	1.62
04	0.00	0.00	0.80	0.00	0.00	1.49	-0.69
05	0.00	0.00	1.50	-0.99	0.99	0.07	1.43
06	0.00	0.00	1.60	-0.18	0.18	1.23	0.37
0783	5.10	3.30	6.40	3.67	1.43	5.32	1.08
08	22.10	12.10	12.60	10.23	11.87	10.90	1.70
09	21.30	14.20	14.70	12.57	8.73	13.34	1.36
10	31.20	13.60	16.80	12.70	18.50	13.80	3.00
11	43.90	30.90	33.50	26.41	17.49	25.94	7.56
12	21.70	17.90	19.90	14.81	6.89	14.95	4.95
01	24.40	17.20	13.60	14.29	10.11	14.51	-0.91
02	89.90	61.90	64.70	53.63	36.27	51.52	13.18
03	65.50	42.70	50.80	35.15	30.35	33.34	17.46
04	24.20	21.60	27.60	17.01	7.19	16.50	11.10
05	30.40	24.20	30.10	20.71	9.69	20.68	9.42
06	20.70	18.50	30.60	14.15	6.55	13.74	16.86

APPENDIX 18b

Observed and estimated monthly runoff (mm) of catchments 1 and 3 with respective residuals

Month	Q1	Q2	Q3	Q1EST	RES1	Q3EST	RES3
0784	20.60	19.10	16.40	14.75	5.85	14.35	2.05
08	19.60	12.80	13.60	9.73	9.87	9.88	3.72
09	18.30	17.90	13.80	14.38	3.92	14.34	-0.54
10	24.80	28.10	22.70	23.91	0.89	23.57	-0.87
11	97.90	75.00	72.40	65.23	32.67	62.46	9.94
12	76.20	43.40	64.70	36.44	39.76	34.90	29.80
01	28.50	22.30	28.00	16.44	12.06	15.37	12.63
02	25.75	23.60	19.10	19.25	6.50	18.84	0.26
03	29.30	23.60	18.70	18.65	10.65	17.98	0.72
04	17.70	16.20	13.10	12.61	5.09	12.53	0.57
05	28.90	23.60	26.50	20.87	8.03	21.16	5.34
06	12.10	9.60	12.20	5.63	6.47	5.39	6.81
0785	16.20	14.30	15.70	11.91	4.29	12.36	3.34
08	8.10	1.50	6.30	-0.51	8.61	0.10	6.20
09	9.10	0.00	4.40	0.02	9.08	1.51	2.89
10	16.40	8.60	15.20	8.42	7.98	9.83	5.37
11	29.80	23.50	28.00	21.56	8.24	22.21	5.79
12	97.40	60.60	83.31	51.44	45.96	48.94	34.37
01	41.83	33.80	24.30	28.59	13.24	27.80	-3.50
02	24.62	17.86	17.69	14.28	10.34	14.20	3.49
03	41.62	30.61	30.96	26.83	14.79	26.68	4.28
04	54.37	33.94	36.52	29.32	25.05	28.80	7.72
05	49.64	37.63	55.61	32.34	17.30	31.52	24.09
06	27.06	23.45	27.69	16.99	10.07	15.67	12.02
0786	22.67	18.85	18.69	15.15	7.52	15.03	3.66
08	14.98	7.65	11.19	4.65	10.33	4.83	6.36
09	25.78	19.75	16.77	17.87	7.91	18.55	-1.78
10	39.13	29.33	34.84	25.93	13.20	25.94	8.90
11	92.66	41.35	75.66	35.12	57.54	33.89	41.77
12	76.73	71.42	54.80	58.67	18.06	54.60	0.20
01	23.90	9.60	23.00	6.56	17.34	6.72	16.28
02	10.30	7.50	9.60	3.92	6.38	3.84	5.76
03	13.30	8.30	14.30	6.73	6.57	7.53	6.77
04	19.70	15.40	24.40	14.50	5.20	15.60	8.80
05	43.10	30.60	25.40	26.51	16.59	26.22	-0.82
06	27.40	18.50	12.50	14.81	12.59	14.69	-2.19

Stormflow parameters of catchment 1 against catchment 2, BEW

Date	QS2	QI2	QP2	RF2	S21	PI	QI1	QS1	QP1	RF1
791111	3.325	0.079	3.776	19.00	17.50	19.02	0.025	1.622	1.700	9.271
791117	2.558	0.079	2.700	21.31	12.00	4.00	0.033	1.289	1.187	10.741
791122	2.352	0.114	3.179	17.42	13.50		0.047	0.761	1.016	5.636
800705	5.520		5.381	11.38	48.50	10.78	0.002	4.733	3.783	9.758
800821	11.794		7.167	10.17	116.00	16.57	0.003	8.900	4.110	7.672
800903	1.208	0.017	1.250	3.36	36.00	36.00	0.022	0.765	0.847	2.126
800907	2.807	0.043	2.438	10.80	26.00	52.00	0.019	1.396	1.467	5.371
800909	3.833	0.060	4.267	8.16	47.00	47.00	0.031	2.721	2.625	5.790
800917	1.320	0.033	1.712	6.77	19.50	9.75	0.026	0.765	0.830	3.925
800921	1.135	0.048	1.550	6.13	18.50	37.00	0.030	0.638	0.779	3.447
800928	1.556	0.055	2.233	6.92	22.50	5.63	0.037	1.164	1.517	5.172
801011	5.839	0.076	4.419	20.49	28.50	6.63	0.049	4.323	3.357	15.170
801015	0.173	0.114	1.038	0.79	22.00	3.67	0.078	0.644	0.615	2.929
801111	0.295	0.090	0.538	2.68	11.00	5.50	0.047	0.179	0.350	1.627
801203	0.472	0.143	0.886	3.63	13.00	7.78	0.096	0.219	0.519	1.687
801204	0.318	0.157	0.855	3.35	9.50	3.17	0.124	0.157	0.493	1.649
801207	1.037	0.119	2.490	5.06	20.50	8.20	0.078	0.157	0.572	0.764
801215	1.379	0.095	2.438	3.58	38.50	12.83	0.058	0.492	1.100	1.279
801216	1.392	0.126	1.631	11.60	12.00	4.00	0.075	0.627	0.995	5.221
801222	3.173	0.102	3.436	10.24	31.00		0.065	1.361	2.047	4.389
810101	0.401	0.107	0.886	4.46	9.00	18.00	0.058	0.112	0.299	1.243
810102	0.130	0.131	1.040	0.62	21.00	4.67	0.061	0.736	0.898	3.503
810202	5.760	0.131	5.467	10.67	54.00	20.22	0.023	2.270	2.891	4.205
810215	0.494	0.088	0.793	3.09	16.00	8.00	0.045	0.434	1.121	2.713
810216	6.240	0.090	5.269	13.28	47.00	18.80	0.031	4.092	4.204	8.706
810219	1.093	0.138	1.957	6.43	17.00	11.33	0.047	0.671	1.079	3.949
810228	1.556	0.079	2.083	5.99	26.00	7.81	0.043	0.806	1.142	3.098
810314	0.700	0.055	0.824	4.25	16.50	9.88	0.019	0.363	0.420	2.197
810324	2.400	0.076	2.857	9.60	25.00	50.00	0.047	1.382	1.672	5.529
810330	2.030	0.048	2.857	10.68	19.00	4.22	0.030	0.797	1.100	4.193
810417	43.941	0.067	25.238	49.65	88.50	20.58	0.047	20.012	16.193	22.613
810422	12.768	0.107	9.500	22.80	56.00	17.23	0.092	8.882	6.169	15.860
810509	0.349	0.102	0.762	3.49	10.00	6.67	0.063	0.333	0.680	3.330

APPENDIX 19D

Stormflow parameters of catchment 1 against catchment 2

Date	QS2	QI2	QP2	RF2	S21	PI	QI1	QS1	QP1	RF1
810518	0.463	0.171	0.917	5.79	8.00	13.79	0.140	0.089	0.396	1.108
810520	23.489	0.131	18.905	27.16	86.50	20.74	0.113	20.744	14.328	23.982
810524	3.619	0.138	4.800	8.83	41.00	41.00	0.134	2.822	4.250	6.882
810529	5.157	0.143	7.167	17.78	29.00		0.113	1.310	2.199	4.519
810530	4.526	0.179	5.638	17.08	26.50		0.162	2.039	3.100	7.696
810627	0.551	0.171	1.286	6.89	8.00	13.79	0.068	0.180	0.396	2.249
810903	0.235	0.021	1.107	0.70	33.50	6.59	0.005	1.020	0.830	3.046
810905	1.038	0.033	1.250	10.93	9.50	14.18	0.011	0.330	0.466	3.477
810907	2.469	0.076	3.050	9.87	25.00	6.67	0.045	1.222	1.467	4.887
810909	6.802	0.055	6.460	16.20	42.00	84.00	0.031	4.678	4.567	11.138
810910	1.283	0.095	1.712	9.87	13.00	162.50	0.092	0.510	0.915	3.925
810914	24.276	0.083	19.071	32.80	74.00	18.14	0.065	12.554	12.370	16.965
810915	2.746	0.060	2.283	22.89	12.00	7.19	0.075	0.150	0.350	1.249
811102	0.082	0.052	0.150	1.37	6.00	3.00	0.041	0.034	0.124	0.559
811116	3.860	0.038	3.638	9.90	39.00	12.30	0.017	2.170	2.108	5.563
811117	0.504	0.067	0.512	2.72	18.50	4.11	0.049	0.336	0.420	1.814
811118	0.088	0.107	1.010	0.65	13.50	7.38	0.054	0.314	0.443	2.327
811119	3.977	0.102	3.050	11.36	35.00		0.061	2.142	1.868	6.119
811120	0.233	0.131	0.638	3.88	6.00		0.096	0.074	0.319	1.231
811125	1.162	0.079	1.752	7.26	16.00	16.00	0.047	0.651	0.830	4.066
811126	0.898	0.102	1.933	5.28	17.00	34.00	0.075	0.369	0.729	2.169
811127	3.833	0.102	4.419	13.45	28.50	9.50	0.092	1.402	1.840	4.918
811204	8.448	0.079	6.845	17.97	47.00	9.40	0.058	5.337	3.451	11.355
820326	1.750	0.021	1.357	6.03	29.00	12.89	0.005	1.198	1.016	4.130
820327	0.611	0.067	1.179	3.82	16.00	23.88	0.041	0.206	0.420	1.290
820328	1.785	0.048	2.133	8.11	22.00	11.00	0.030	0.646	1.016	2.938
820331	6.508	0.055	9.631	12.51	52.00	52.00	0.022	4.935	5.167	9.490
820403	6.350	0.052	7.274	14.77	43.00	19.82	0.021	2.690	3.271	6.257
820408	0.766	0.114	1.550	3.83	20.00	29.85	0.118	0.363	0.995	1.817
820412	2.031	0.055	2.931	6.77	30.00	8.77	0.063	1.114	2.169	3.715
820428	1.931	0.114	4.267	6.66	29.00	4.52	0.100	1.249	4.017	4.307

Stormflow parameters of catchment 1 against catchment 2

Date	QS2	QI2	QP2	RF2	S21	PI	QI1	QS1	QP1	RF1
820514	0.286	0.067	0.662	2.04	14.00	7.00	0.054	0.221	0.506	1.580
820616	2.211	0.055	2.921	6.70	33.00	12.00	0.047	0.684	1.392	2.072
820703	0.408	0.060	0.612	2.33	17.50	4.77	0.045	0.247	0.443	1.410
820717	1.408	0.048	1.671	5.99	23.50	3.62	0.039	0.623	0.953	2.649
820725	0.658	0.026	1.071	5.06	13.00	26.00	0.058	0.088	0.350	0.678
820814	1.045	0.031	1.143	5.10	20.50	12.97	0.033	0.407	0.713	1.987
820901	2.795	0.017	3.243	11.18	25.00	50.00	0.027	0.836	1.417	3.345
821002	1.722	0.012	2.386	14.35	12.00	48.00	0.018	0.370	0.544	3.084
821024	0.803	0.017	1.179	5.74	14.00	82.35	0.019	0.314	0.559	2.246
821025	4.392	0.067	4.869	11.56	38.00	45.78	0.031	3.164	3.736	8.327
821026	4.230	0.033	5.902	15.11	28.00	10.18	0.068	1.593	2.199	5.690
821027	0.216	0.076	0.495	2.16	10.00	23.81	0.087	0.106	0.396	1.064
821028	0.557	0.114	0.979	5.06	11.00	26.19	0.087	0.170	0.545	1.549
821101	7.987	0.229	8.393	15.82	50.50	8.78	0.232	4.340	5.120	8.595
821102	1.404	0.138	2.283	14.78	9.50	12.67	0.208	0.524	1.467	5.512
821121	4.783	0.076	7.810	12.59	38.00	50.67	0.063	2.739	4.612	7.208
830107	5.914	0.055	8.276	11.16	53.00	26.50	0.047	3.338	4.567	6.298
830808	9.998	0.076	8.160	27.77	36.00		0.068	7.190	6.169	19.972
830918	2.254	0.031	1.143	9.02	25.00	8.33	0.087	1.488	1.255	5.951
831018	0.257	0.033	0.319	1.98	13.00	6.50	0.043	0.201	0.309	1.549
831022	0.535	0.038	0.562	3.96	13.50	6.75	0.043	0.322	0.443	2.387
831025	2.746	0.017	2.490	8.72	31.50	16.41	0.047	2.441	2.625	7.748
831105	4.965	0.007	4.052	13.24	37.50	14.53	0.075	4.775	4.017	12.734
831111	6.570	0.083	3.707	14.60	45.00	7.94	0.647	4.934	3.451	10.965
840119	0.241	0.017	0.267	3.22	7.50	93.75	0.041	0.179	0.319	2.387
840202	5.901	0.064	2.386	11.46	51.50	5.72	0.100	4.464	2.269	8.669
840209	11.726	0.143	5.810	15.74	74.50	4.38	0.319	9.262	6.605	12.433
840217	5.563	0.090	8.860	13.91	40.00	20.00	0.118	3.774	7.040	9.434
840304	1.587	0.214	2.183	6.35	25.00	37.31	0.343	0.988	2.169	3.953
840329	1.629	0.071	2.386	5.52	29.50	29.50	0.083	1.532	3.015	5.193
840406	0.329	0.064	0.612	2.74	12.00	13.04	0.068	0.210	0.506	1.749

APPENDIX 19d

Stormflow parameters of catchment 1 against catchment 2

Date	QS2	QI2	QP2	RF2	S21	PI	QI1	QS1	QP1	RF1
840413	0.257	0.079	0.479	2.70	9.50	55.88	0.113	0.141	0.493	1.484
840415	1.410	0.067	1.671	7.62	18.50	15.81	0.058	0.730	1.142	3.943
840623	0.696	0.052	0.688	2.78	25.00	147.06	0.145	1.455	1.517	5.818
840713	1.478	0.031	1.752	4.48	33.00		0.049	0.533	0.585	1.614
840722	0.737	0.010	0.712	3.78	19.50		0.054	0.407	0.479	2.089
840824	1.727	0.038	2.033	7.20	24.00	7.79	0.068	0.806	1.121	3.357
841001	12.370	0.038	10.286	23.12	53.50	26.75	0.043	6.865	5.298	12.833
841017	1.742	0.031	1.671	7.74	22.50	132.35	0.051	0.671	0.974	2.984
841102	8.558	0.095	6.460	21.94	39.00	13.00	0.056	4.605	3.357	11.808
841105	6.418	0.071	4.052	15.65	41.00	19.71	0.100	5.101	4.157	12.441
841119	6.576	0.090	4.952	20.55	32.00	32.00	0.124	5.941	6.061	18.566
841129	17.589	0.076	6.274	40.90	43.00	16.10	0.113	14.259	6.115	33.161
841205	0.669	0.131	3.243	2.27	29.50	70.24	0.156	2.171	4.297	7.358
850207	0.643	0.060	1.429	5.15	12.50	46.87	0.068	0.426	0.680	3.410
850210	1.199	0.064	1.752	4.36	27.50	11.70	0.075	0.824	1.165	2.998
850223	1.125	0.055	0.979	3.63	31.00	7.40	0.058	0.689	0.696	2.223
850308	0.287	0.064	0.295	1.64	17.50	4.20	0.043	0.183	0.241	1.047
850313	0.574	0.071	0.712	3.59	16.00	12.80	0.078	0.326	0.545	2.035
850315	1.824	0.060	1.250	6.76	27.00	10.95	0.104	0.649	0.813	2.405
850412	0.983	0.043	1.040	3.86	25.50	15.00	0.056	0.311	0.532	1.221
850418	0.223	0.043	0.429	1.78	12.50	17.44	0.047	0.143	0.249	1.140
850424	1.037	0.048	0.793	4.15	25.00	18.52	0.054	1.315	1.345	5.259
850513	2.790	0.043	3.500	9.30	30.00	8.38	0.058	1.196	1.672	3.988
851015	0.597	0.010	0.379	2.49	24.00	53.33	0.035	0.254	0.396	1.056
851023	0.219	0.043	0.319	1.07	20.50	30.59	0.033	0.239	0.279	1.165
851030	1.129	0.010	0.886	6.27	18.00	12.41	0.039	0.503	0.615	2.797
851104	0.614	0.043	1.143	1.89	32.50	61.32	0.056	0.837	1.037	2.575
851212	1.268	0.033	1.631	9.06	14.00	8.38	0.249	0.386	0.847	2.760
860310	1.056	0.102	1.983	6.03	17.50	35.00	0.100	0.358	0.847	2.049
860401	4.704	0.083	4.800	9.13	51.50	41.53	0.083	3.166	4.567	6.148

APPENDIX 19e

Stormflow parameters of catchment 1 against catchment 2

Date	QS2	QI2	QP2	RF2	S21	PI	QI1	QS1	QP1	RF1
860411	0.827	0.071	1.469	4.59	18.00	29.03	0.109	0.269	0.598	1.492
860413	2.853	0.090	3.707	10.97	26.00	20.00	0.129	0.671	1.392	2.034
860425	3.072	0.090	5.210	6.47	37.50	208.30	0.118	2.735	3.924	5.757
860502	1.646	0.079	2.700	9.68	17.00	25.37	0.100	0.620	1.517	3.646
860503	11.678	0.102	4.419	25.95	45.00	30.00	0.134	4.733	4.110	10.517
860714	3.120	0.052	4.724	6.93	45.00	84.90	0.068	1.772	2.409	3.938
860726	1.320	0.052	1.752	4.55	29.00	27.10	0.031	0.850	0.881	2.932
860927	16.224	0.021	14.690	19.91	81.50	63.52	0.051	10.150	9.324	12.455
861013	7.104	0.048	5.210	10.85	65.50	21.68	0.058	3.491	2.929	5.330
861018	0.378	0.043	0.429	2.10	18.00	10.28	0.063	0.436	0.559	2.424
861024	0.252	0.043	0.307	1.94	13.00	12.63	0.061	0.122	0.249	0.940
861026	7.611	0.048	5.902	13.59	56.00	14.14	0.068	3.786	3.924	6.761
861030	4.834	0.071	6.117	17.58	27.50	17.51	0.083	3.469	4.250	15.455
861105	1.700	0.102	1.510	5.31	32.00	12.80	0.134	1.011	1.187	3.161
861107	5.925	0.083	7.060	14.63	40.50	14.94	0.124	2.694	3.357	6.653
861109	0.192	0.095	0.612	1.54	12.50	19.84	0.140	0.145	0.506	1.164
861119	0.199	0.071	0.445	2.21	9.00	52.94	0.100	0.074	0.309	0.821
861120	24.192	0.083	24.286	21.31	113.50	108.09	0.124	47.933	50.505	42.232
861124	0.192	0.150	0.688	1.24	15.50	2.02	0.241	0.168	0.545	1.083
861203	2.496	0.095	3.845	6.16	40.50	14.80	0.134	1.041	2.017	2.569

Stormflow parameters of catchment 3 against catchment 2

Date	QS2	QI2	QP2	RF2	S21	PI	QS3	QI3	QP3	RF3
791111	3.325	0.079	3.776	19.00	17.50	19.02	2.655	0.063	1.942	15.171
791122	2.352	0.114	3.179	17.42	13.50		1.380	0.058	1.188	10.219
800903	1.208	0.017	1.250	3.36	36.00	36.00	0.804	0.009	0.397	2.234
800907	2.807	0.043	2.438	10.80	26.00	52.00	1.816	0.012	1.075	6.985
800909	3.833	0.060	4.267	8.16	47.00	47.00	3.972	0.026	1.981	8.452
800917	1.320	0.033	1.712	6.77	19.50	9.75	1.118	0.015	0.574	5.733
800921	1.135	0.048	1.550	6.13	18.50	37.00	0.939	0.019	0.626	5.076
800928	1.556	0.055	2.233	6.92	22.50	5.63	1.960	0.022	1.205	8.710
801011	5.839	0.076	4.419	20.49	28.50	6.63	3.535	0.032	2.201	12.404
810101	0.401	0.107	0.886	4.46	9.00	18.00	0.219	0.058	0.367	2.431
810202	5.760	0.131	5.467	10.67	54.00	20.22	5.437	0.019	4.146	10.068
810215	0.494	0.088	0.793	3.09	16.00	8.00	0.692	0.049	0.737	4.324
810219	1.093	0.138	1.957	6.43	17.00	11.33	0.763	0.034	0.669	4.487
810228	1.556	0.079	2.083	5.99	26.00	7.81	1.811	0.041	1.456	6.965
810314	0.700	0.055	0.824	4.25	16.50	9.88	0.514	0.019	0.360	3.113
810324	2.400	0.076	2.857	9.60	25.00	50.00	2.806	0.047	2.201	11.226
810330	2.030	0.048	2.857	10.68	19.00	4.22	1.073	0.022	0.875	5.645
810509	0.349	0.102	0.762	3.49	10.00	6.67	0.345	0.058	0.459	3.449
810518	0.463	0.171	0.917	5.79	8.00	13.79	0.155	0.022	0.468	1.932
810520	23.489	0.131	18.905	27.16	86.50	20.74	24.232	0.112	18.766	28.014
810524	3.619	0.138	4.800	8.83	41.00	41.00	4.007	0.162	3.842	9.773
810529	5.157	0.143	7.167	17.78	29.00		3.572	0.117	3.910	12.318
810530	4.526	0.179	5.638	17.08	26.50		3.472	0.187	2.888	13.102
811102	0.082	0.052	0.150	1.37	6.00	3.00	0.050	0.011	0.041	0.827
811116	3.860	0.038	3.638	9.90	39.00	12.30	3.158	0.021	1.702	8.098
811117	0.504	0.067	0.512	2.72	18.50	4.11	0.449	0.038	0.375	2.427
811118	0.088	0.107	1.010	0.65	13.50	7.38	0.404	0.083	0.535	2.995
811119	3.977	0.102	3.050	11.36	35.00		4.164	0.070	2.592	11.898
811120	0.233	0.131	0.638	3.88	6.00		0.171	0.072	0.345	2.854
811125	1.162	0.079	1.752	7.26	16.00	16.00	1.025	0.058	0.822	6.408
811126	0.898	0.102	1.933	5.28	17.00	34.00	0.285	0.108	0.468	1.679

APPENDIX 20b

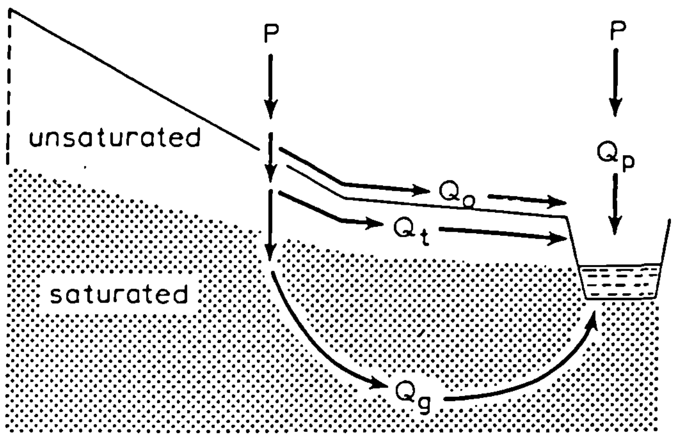
Stormflow parameters of catchment 3 against catchment 2

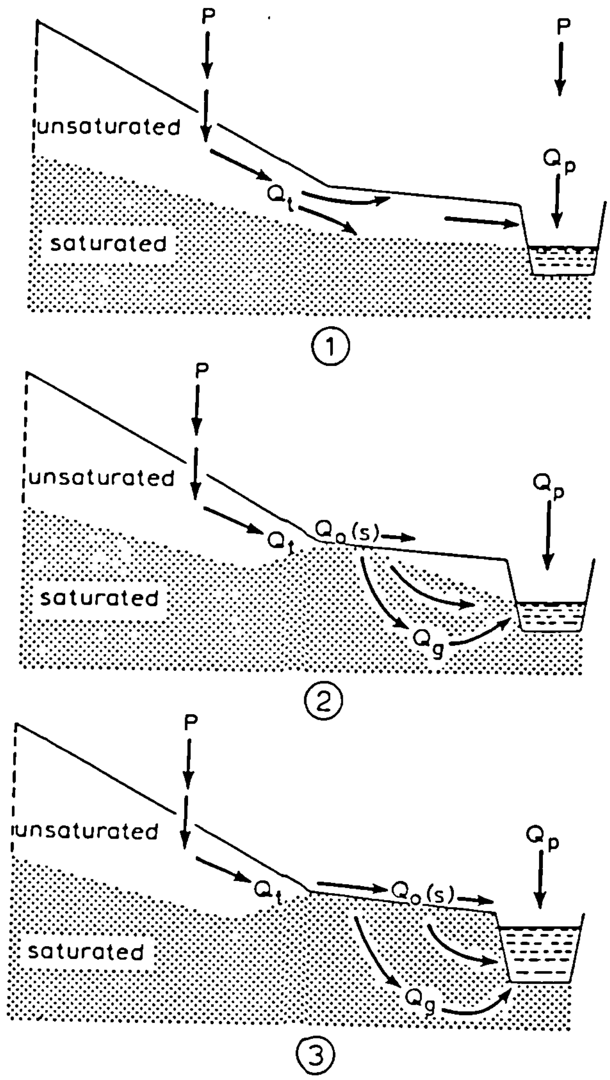
Date	QS2	QI2	QP2	RF2	S21	PI	QS3	QI3	QP3	RF3
811127	3.833	0.102	4.419	13.45	28.50	9.50	2.706	0.072	1.903	9.495
811204	8.448	0.079	6.845	17.97	47.00	9.40	9.014	0.034	3.370	19.179
820326	1.750	0.021	1.357	6.03	29.00	12.89	1.247	0.020	0.798	4.300
820327	0.611	0.067	1.179	3.82	16.00	23.88	0.452	0.058	0.495	2.824
820328	1.785	0.048	2.133	8.11	22.00	11.00	1.259	0.030	1.014	5.724
820331	6.508	0.055	9.631	12.51	52.00	52.00	7.331	0.019	5.123	14.098
820403	6.350	0.052	7.274	14.77	43.00	19.82	5.368	0.025	3.842	12.483
820428	1.931	0.114	4.267	6.66	29.00	4.52	1.603	0.087	1.743	5.528
820514	0.286	0.067	0.662	2.04	14.00	7.00	0.413	0.034	0.423	2.947
820616	2.211	0.055	2.921	6.70	33.00	12.00	2.515	0.032	1.942	7.620
820703	0.408	0.060	0.612	2.33	17.50	4.77	0.660	0.032	0.515	3.771
820725	0.658	0.026	1.071	5.06	13.00	26.00	0.352	0.026	0.338	2.707
820814	1.045	0.031	1.143	5.10	20.50	12.97	1.120	0.024	0.849	5.463
820901	2.795	0.017	3.243	11.18	25.00	50.00	1.422	0.017	1.014	5.688
821002	1.722	0.012	2.386	14.35	12.00	48.00	0.789	0.018	0.679	6.577
821024	0.803	0.017	1.179	5.74	14.00	82.35	0.595	0.018	0.459	4.251
821025	4.392	0.067	4.869	11.56	38.00	45.78	4.200	0.020	3.030	11.052
821026	4.230	0.033	5.902	15.11	28.00	10.18	3.241	0.197	2.555	11.577
821027	0.216	0.076	0.495	2.16	10.00	23.81	0.175	0.038	0.214	1.747
821028	0.557	0.114	0.979	5.06	11.00	26.19	0.323	0.034	0.330	2.940
821101	7.987	0.229	8.393	15.82	50.50	8.78	6.132	0.248	5.123	12.143
821102	1.404	0.138	2.283	14.78	9.50	12.67	0.841	0.172	1.105	8.851
821121	4.783	0.076	7.810	12.59	38.00	50.67	3.515	0.049	2.794	9.250
830107	5.914	0.055	8.276	11.16	53.00	26.50	5.494	0.024	4.044	10.366
830808	9.998	0.076	8.160	27.77	36.00		4.156	0.018	2.040	11.544
830918	2.254	0.031	1.143	9.02	25.00	8.33	0.894	0.101	0.701	3.575
831014	14.006	0.031	13.286	16.87	83.00	20.75	17.898	0.030	16.195	21.564
831022	0.535	0.038	0.562	3.96	13.50	6.75	0.416	0.034	0.345	3.083
831025	2.746	0.017	2.490	8.72	31.50	16.41	2.288	0.030	1.345	7.264
831105	4.965	0.007	4.052	13.24	37.50	14.53	3.981	0.097	3.054	10.616
831111	6.570	0.083	3.707	14.60	45.00	7.94	6.753	0.080	4.179	15.008
840202	5.901	0.064	2.386	11.46	51.50	5.72	4.038	0.063	1.903	7.840

APPENDIX 20c

Stormflow parameters of catchment 3 against catchment 2

Date	QS2	QI2	QP2	RF2	S21	PI	QS3	QI3	QP3	RF3
840209	11.726	0.143	5.810	15.74	74.50	4.38	9.774	0.281	5.366	13.119
840217	5.563	0.090	8.860	13.91	40.00	20.00	2.537	0.219	3.168	6.343
840329	1.629	0.071	2.386	5.52	29.50	29.50	0.989	0.068	1.254	3.352
841001	12.370	0.038	10.286	23.12	53.50	26.75	6.860	0.032	5.157	12.823
841017	1.742	0.031	1.671	7.74	22.50	132.35	0.890	0.041	0.941	3.956
841102	8.558	0.095	6.460	21.94	39.00	13.00	3.094	0.051	3.438	7.933
841105	6.418	0.071	4.052	15.65	41.00	19.71	4.125	0.047	3.054	10.062
841114	5.088	0.090	4.952	18.84	27.00	11.16	5.072	0.152	4.786	18.784
841129	17.589	0.076	6.274	40.90	43.00	16.10	16.191	0.117	5.430	37.655
841205	0.669	0.131	3.243	2.27	29.50	70.24	3.218	0.182	3.505	10.908
850207	0.643	0.060	1.429	5.15	12.50	46.87	0.155	0.080	0.495	1.237
850223	1.125	0.055	0.979	3.63	31.00	7.40	1.187	0.043	0.564	3.828
850313	0.574	0.071	0.712	3.59	16.00	12.80	0.297	0.117	0.535	1.858
850315	1.824	0.060	1.250	6.76	27.00	10.95	0.890	0.080	0.849	3.296
850412	0.983	0.043	1.040	3.86	25.50	15.00	0.890	0.043	0.984	3.490
850424	1.037	0.048	0.793	4.15	25.00	18.52	2.094	0.049	1.271	8.375
850513	2.790	0.043	3.500	9.30	30.00	8.38	1.944	0.043	1.400	6.480
851015	0.597	0.010	0.379	2.49	24.00	53.33	0.416	0.018	0.382	1.734
851023	0.219	0.043	0.319	1.07	20.50	30.59	0.297	0.034	0.242	1.450
851030	1.129	0.010	0.886	6.27	18.00	12.41	0.476	0.034	0.515	2.642
851104	0.614	0.043	1.143	1.89	32.50	61.32	0.773	0.034	0.490	2.378
851208	12.256	0.240	8.160	20.26	60.50	35.41	3.713	0.054	2.865	6.137
851212	1.268	0.033	1.631	9.06	14.00	8.38	0.396	0.117	0.786	2.825





P - Precipitation
P_e - Precipitation excess
Q_p - Direct precipitation
Q_o - Overland flow
Q_t - Throughflow
$Q_o(s)$ - Saturation overland flow
Q_g - Groundwater flow
f - infiltration capacity
i - rainfall intensity

Stormflow pathways in headwater catchment

Source: Ward (1984)