Impact of land use Change on Water Yield and Water Quality in Peninsular Malaysia

by

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Abstract

Economic development and increasing population has brought significant changes in land cover and placed stress on water quantity and water quality within tropical river catchments, including those of Malaysia. There is a need to investigate the impact of land use changes on water yield and water quality in moderate-sized (*c.* 1000 km^2) catchments, such as the Langat and Linggi, since these provide the water resources that cater for the rapid urbanization and industrialization that characterizes Malaysia and most studies so far reported have been for very small catchments (< 25 km^2, frequently < 1 km^2). Findings from these two catchments provides information for local river managers and development planners that will assist in minimizing the negative impacts of development on water resources, while promoting sensible planning within river basins especially newly developed catchments such as the Bernam.

An analysis of land-cover in the Langat, Linggi and Bernam basins indicates that there has been a significant change from forest (primary and secondary selva) to agriculture, especially tree crops (rubber, oil palm), ranging from 7-15% in the three water catchments, and an increase in the urban area that ranges from 183-394% during the period 1984-2002. Despite this, the runoff coefficient shows no significant increase during 42 years of development. The coefficient lies between 22-48%. The outcome is not straightforward and counter intuitive when comparison is made with results from other experimental catchments in the tropics, where there has been shown to be a significant increases (45-70%) in runoff when natural forests have been cleared. It is surmised that the fraction of rainfall leaving the drainage basin through the gauging station remains similar where tree crops are an important replacement for native forest and where urbanization covers less than 20% of the catchments.

However, there is a significant increase in sediment yield of 19% during the development period, which is functionally related to changes in land use cover, both agricultural and urban. Biological oxygen demand (BOD_5), also shows a significant increase where more domestic sewage and industrial waste discharges to the river as a function of higher population and industrial growth since 1990s. Water quality considerations dictate that the catchment must be properly protected and managed to ensure sustainable development. The initial intention to establish a transfer function from a study of catchments undergoing economic development and urbanization that could then be used to predict the effects of development in undeveloped drainage basins on water relations and mitigate them has been relegated in favour of assessing catchment hydrological process-response so that the findings can be used to inform future land use management. In effect, the runoff coefficient remains similar in drainage basins of *c.* 1000 km^2 in this environmental setting where agriculture favours tree crops and where urbanization is, as yet, modest in extent. This study suggests that up-scaling the findings of small catchment studies of forest removal is far from simple, especially in the wet tropics, where the impact of tree crops on water relations may be insufficiently distinguished from primary or secondary forests.

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CHAPTER ONE:
INTRODUCTION

1.1 Introduction

Since its independence in 1957, development in Malaysia [i.e. deforestation, agriculture, urbanization and industrialization] has been focussed on the coastal areas, especially the West Coast of Peninsular Malaysia (**Figure 1.1**). All the main drainage basins, namely, the Klang, Langat, and Linggi, have undergone rapid development since the 1970s, with a view to providing a catalyst for a development corridor and in order to achieve the government's vision to achieve developed country status by the year 2020 (Vision 2020). Vision 2020 has several objectives, such as the end of absolute poverty by 2010, a narrowing of the Chinese-Malay income gap by 2020, to assist Malay entrepreneurship and widen share ownership, to promote equal employment across ethnic groups, and to produce high-value goods closely related to the expansion of new economic growth areas within river basins (Malaysia, 1991). Consequently, many of the West Coast river basins have experienced severe environmental problems, especially those related to water, such as pollution of water bodies, shortages of water and urban flooding (Jamaluddin, 2000).

Since all of these main river basins have already been developed, the government has started to expand the development to other river basins which have a potential to support and accommodate the economic activities of the Kuala Lumpur area. The Bernam Valley, which is situated 73 kilometres northwest of Kuala Lumpur, is one of those river basins which is now subject to extensive land development planning proposals by local governments and the corporate sector. The early stage of development in Bernam was started in 2000 and it is expected that various environmental problems, especially those involving water quantity and quality will occur in Bernam, as they did in the Klang, Langat and Linggi catchments. This is because part of the Bernam Valley is situated in a sensitive area of the Main Range which supplies most of Peninsular Malaysia's water needs.

To minimise the environmental degradation already experienced in the moderate-size Langat and Linggi basins, developers and managers need to be vigilant in dealing with land development and the need for environmental sustainability. In this context, the purpose of any development should "meet the needs of the present without compromising the ability of future generations to meet their own needs generated from environmental resources" (Brundtland Commission, 1987). Because land development in Malaysia has been driven by economic considerations, there is a need to study the hydrological and water quality impacts of rapid land use development so that lessons can be applied to new development areas. In this context, the Langat and Linggi catchments have been examined in order to provide an analogue for the Bernam (refer to Chapter 3 for a justification of analogue selection). This is an important step in providing basic information to managers, so they can monitor and manage the new land development programme in the Bernam in a proper manner.

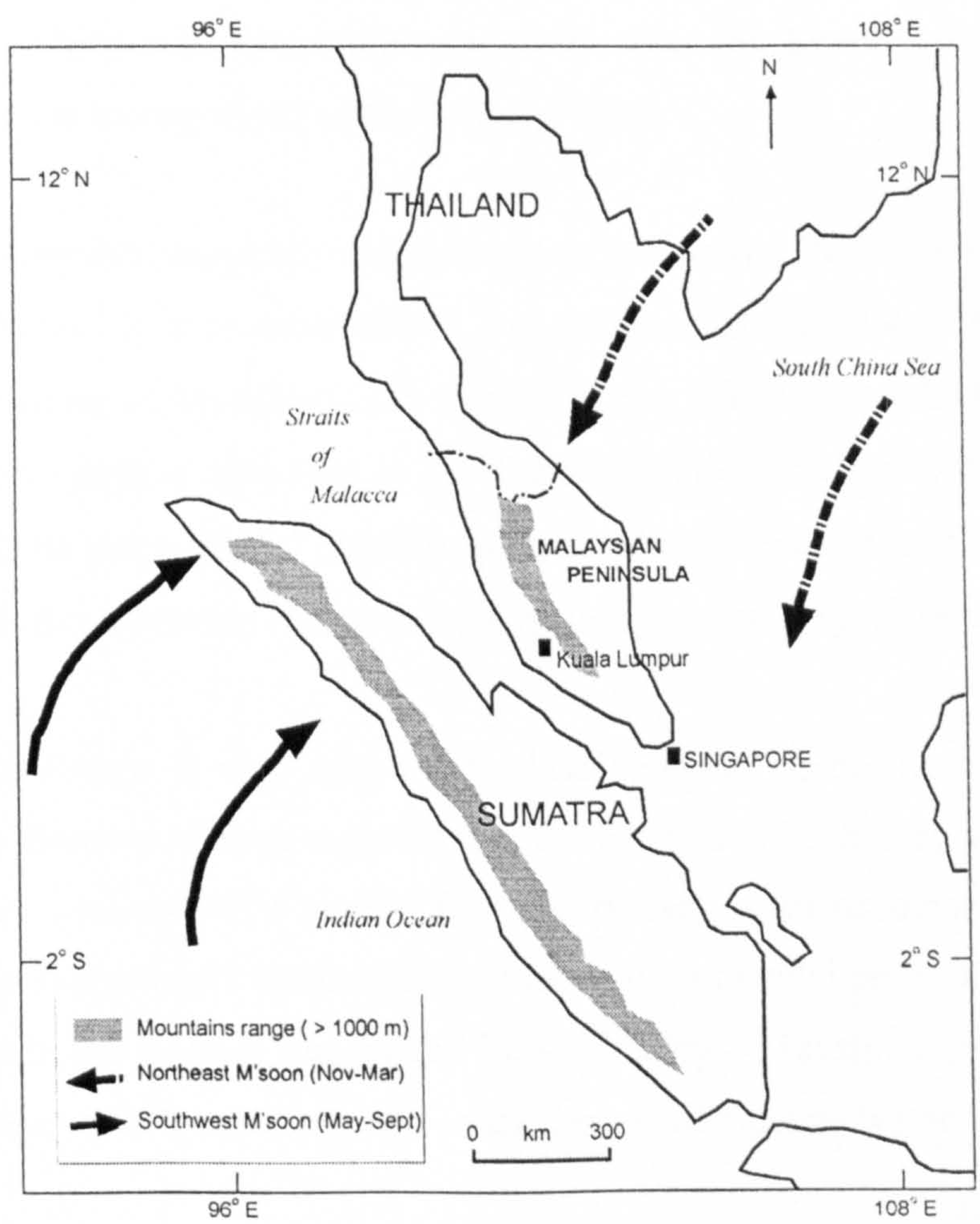


Figure 1.1: Geographical location of Malaysian Peninsula

In these 'analogue' catchments, relations between key environmental factors and development processes can be studied and identified. These can be used to attempt to predict potential impacts of land use change on the hydrology and water quality in the

Bernam Valley and encourage the adoption of sustainable development practices by managers. To achieve this aim, two established catchments on the West Coast of Peninsular Malaysia – the Langat River Basin (Selangor State) and the Linggi River Basin (Negeri Sembilan) - were selected. These two catchments were chosen because each has similarities with the Bernam in terms of climate, geology, river system, and rainfall.

Archived data and physical aspects of the river basins have been explored in order to assess whether they can be used as a basis for the development of transfer functions to predict what might happen in the Bernam Catchment. These would allow recognition of the possible impact of land development scenarios on rainfall-runoff relations and water quality, and they will be related to environmental sustainability issues over a time period since the 1960s. All of this information will allow development of a hydrological framework for river management in the BernamValley.

The Bernam Valley is strategically unique because it involves the interests of two states, Selangor and Perak. It is an unurbanised area, situated at the foot of the Titiwangsa Range (the backbone of Malaysia). The Bernam River will become the main source of water supply for various activities in the Bernam Valley. Hence, protection of this resource should be given careful consideration, so that all kinds of land use change can be planned with the assurance of maintaining quantity and quality of the water resource.

The Titiwangsa Range is very sensitive to development. Therefore, all development projects in the Bernam Valley, especially in the headwaters, must be well planned in order to sustain a clean water supply for various uses, such as domestic, industrial, agricultural and recreational. Otherwise the same environmental problems will occur as have happened in the Kelang, Langat and Linggi Valleys (Mansor, et al., 2000). Rapid land development that ignores environmental issues will cause water problems in the future.

The highland forest is known to be crucial from a tropical hydrological perspective because it serves the headwaters of the water catchments. Tropical forest transpires much water than other vegetation, with more than 1000 mm per year lost to the atmosphere through the evapotranspiration processes (Abdul Rahim and Zulkifli, 2004). The quantity of the water that is delivered to the rivers and to groundwater depends on the extent of protected primary and secondary forest. During wet seasons, forests encourage infiltration and reduce runoff. Conversely, during the dry season, stored water is gradually released from the ground water as base-flow. However, when there is uncontrolled deforestation, urbanization and industrialization without careful landuse planning, this system can be adversely affected (Aylward, 2005; Drigo, 2005; Schweihelm, 2005).

Forests are a vital component in sustaining the water supply (Abdul Rahim and Zulkifli, 1999; Bonell, 2004; Bruijnzeel, *et al.* 2005; Hall, 2005; Murdiyarso, 2005), yet they have been cleared to make way for industrial estates, golf courses and housing estates. For instance, between 1978 and 1994, the Malaysian Government de-gazetted forest reserves of 1.3 million hectares (the same size of Terengganu State – 13 000 km^2) allowing conversion to other land uses. Peninsular Malaysia has 4.7 million hectares of forest reserves, of which 2.8 million hectares are categorized as production forests and the remaining 1.9 million hectares are protected forests. Of the 1.37 million hectares of reserve forests in Peninsular Malaysia classified as water catchment forests, 0.87 million hectares, or 63.5% of the total, are in production forests (Department of Forestry, 1998). In order to minimise the impact of logging activity on water quantity and quality, the government has ensured that loggers comply with the terms and conditions that are described in logging approval licences.

Clear strategies need to be developed to ensure that development does not lead to severe environmental damage. In this context, control of land use development would be an important aspect in deciding the exposure of the Bernam River to pollution. For example, a Geographical Information System (GIS) can be used as an effective tool to help the authorities to prepare the basic information on land use development so that decisions can be rational and objective (Abdul Hadi and Abdul Samad, 2000). In Malaysia, the impact of economic development on the environmental quality of the river basin in general, and on water resources in particular, has not been studied so far in a significant way. Such a study could prevent further environmental deterioration by implementing appropriate policies in the future.

A more environmental friendly approach to river basin management should be immediately put in place in the Bernam Valley in order to avoid threatening the stability of the river ecosystem and water supplies in the Bernam Valley. Therefore, the objective of this study is to provide information about the relations between land use changes and hydrological and water quality response.

1.2 Rationale for research

Rapid development in Malaysia through economic growth of the last few decades has had significant impacts on the environment, including water quality deterioration in urban river basins such as the Klang Valley and Langat Valley near Kuala Lumpur (Ahmad Fariz and Jamaluddin, 2000; Noorazuan, 2000; Ithnin and Sakke, 2001; Jamaluddin, 2001). Many developing countries, especially in Asia, have been intensifying their industrial sectors and food industries and this has placed tremendous stress on water resources (Bruijnzeel, et al. 2005; Murdiyarso, 2005).

In 1999, the world population reached six billion. The growth of population has placed a significant strain on water resources in many countries. For example, in China as a country with a population of more than one billion, it is reported that the water tables under the North China Plain have fallen, reducing available supply by 1.5 million litres per year, due to excessive demands in 2001 (NSTP, 2002). Meanwhile, in India, the pumping of underground water is estimated to be double the rate of aquifer recharge from rainfall (NSTP, 2002). This problem causes water shortages for millions of people. As an example at global level, the United Nations Committee on Natural Resources reported that 80 countries, or 40 percent of the world population, are already experiencing serious water shortages. According to the Malaysian Water Industry Guide 2001, in 1999, the water supply capacity in Malaysia was approximately 10 729 million litres per day, compared to a demand of about 9028 million litres per day. The National Water Resources Study projects that water demand in Malaysia between 2010 and 2050 will rise at twice the rate of population growth (Mohd. Akbar and Rusnah, 2004).

Economic development has also been closely linked with environmental problems in river basins in Malaysia. These problems are associated with multiple factors such as urbanization, diminishing forests and rapid changes in catchment land use and include soil erosion, river sedimentation, floods, and insecurity of water supply. Urban land use change will have impacts on surface runoff and also streamflow (Lazaro,1990). As the land surface is developed for urban use, artificial structures add impervious areas to the watershed, which considerably diminishes the water storage capability. As the area covered by structures becomes greater, the amount of vegetation, natural surface and infiltration will inevitably reduce (Dunne and Leopold, 1978; Douglas, 1983; Hall, 1984; Niemczynowicz, 1999; Paul and Meyer, 2001).

With an average annual rainfall of 3000 mm, Malaysia is rich in water resources. Malaysia has an annual rainfall of 990 billion cubic metres, of which only 360 billion cubic metres (36.4 %) returns to the atmosphere. Surface runoff accounts for another 566 billion cubic metres (57.2 %), while the remaining 64 billion cubic metres (6.4 %) seeps into the soil as groundwater (Department of Drainage and Irrigation (DID), 1998). According to DID, despite abundant runoff, there will be water deficiencies in the regions along the west coast of Peninsular Malaysia unless the government has an appropriate approach to water management. For example, the variation in annual rainfall has a direct influence on the flow and the amount of surface water, threatening water resources where the level of demand is close to the level of supply.

As a consequence, additional problems may arise, for example a shortage of clean water, pollution of water bodies, urban flood disasters and a deterioration in the environment of a river or catchment, as happened in the Klang Valley in 1998, which affected 1.5 million residents for about six-months and cost about RM 55.4 million to provide water rationing (NSTP, 1998). These environmental problems evolve when environmental issues are not properly taken into consideration during the planning of large land development projects for urban and rural areas, infrastructure, and industrialization. More recently, however, authorities such as local governments and the Department of Drainage and Irrigation (DID) have urged that environmental issues be considered at the planning stage and have produced guidelines to help promote more sustainable urban development planning (Chan, 2000; Jamaluddin, 2000). To achieve this approach, coordination and cooperation among relevant agencies involved in water resources needs to be strengthened (Chan, 2000; Dani, 2001). Adequate provision for all types of land development should be made in order to achieve a balance between public interest and the preservation of the natural environment.

The Langat, Linggi and Bernam river basins in Peninsular Malaysia have all experienced environmental problems from deforestation and expansion of agriculture since land development started in the 1970s. It is now believed that, due to the spill-over of development from the Klang Valley to these areas and aggressive local government programmes to locate estate development and labour intensive manufacturing industries, there are likely to be severe environmental consequences as large areas of the natural forest are cleared (Department of Urban and Rural Planning, 1995).

With the rapid increase in urban population (two million people since 1999, according to the Census 2000) and the creation of large urban areas in the Klang and Langat Valleys, the pressure on land resources and space is becoming acute. The urban proportion of the population had increased to 62% in the Census of 2000 from 51% in 1991. States with very high proportions of urban population in the Census of 2000 were Wilayah Persekutuan Kuala Lumpur (100%) and Selangor (87.6%). For that reason, the government has taken various actions to extend the development programme to include areas outside Kuala Lumpur, which are also strategic for development of foreign investment, industry, commerce and business.

Various river basins in Malaysia showed serious deterioration in water quality over a monitoring period of 1986 to 2002 (Department of Environment, Malaysia; see **Table 1.1**). The Malaysian Water Quality Index is based on six parameters: Biological Oxygen Demand, Chemical Oxygen Demand, Dissolved Oxygen, pH, Suspended Sediment Concentration and Ammonia Nitrogen. According to the index, a value 0-59 is classed as polluted, 60-80 as slightly polluted and 81-100 as clean. As indicated in **Table 1.1**, both the number and percentage of slightly polluted and polluted rivers increased after 1990, leaving around 30% of the rivers classified as clean. Proper river basin management is needed in order to minimize the future impact of pollution on water quality due to development projects which are already planned, especially in the Bernam Valley. The extensive deforestation within the catchment area of Malacca's Durian Tunggal Dam headwaters (south of the Klang Valley) in the 1980s is a classic case of major water crisis in Malaysia. The dam which provides a main source of public water supply was dry for about nine months and this forced the Malacca government to acquire a supply from the neighbouring states (NSTP, 1998).

Table 1.1 : Water quality trend in Malaysia: 1986-2002 (from DOE, Malaysia, 2003)

Year (no. of rivers)	River status * No. (%)		
	Clean	Slightly polluted	Polluted
1986 (91 rivers)	49 (54%)	37 (41%)	5 (5%)
1987 (91 rivers)	43 (47%)	45 (50%)	3 (3%)
1988 (91 rivers)	48 (53%)	40 (44%)	3 (3%)
1989 (91 rivers)	45 (50%)	43 (47%)	3 (3%)
1990 (91 rivers)	48 (53%)	35 (39%)	8 (8%)
1991 (87 rivers)	37 (43%)	44 (50%)	6 (7%)
1992 (87 rivers)	25 (29%)	55 (63%)	7 (8%)
1993 (116 rivers)	32 (28%)	73 (63%)	11 (9%)
1994 (116 rivers)	38 (33%)	64 (55%)	14 (12%)
1995 (115 rivers)	48 (42%)	53 (46%)	14 (12%)
1996 (117 rivers)	42 (36%)	62 (53%)	13 (11%)
1997 (117 rivers)	24 (20%)	68 (58%)	25 (22%)
1998 (120 rivers)	33 (28%)	71 (59%)	16 (13%)
1999 (120 rivers)	35 (29%)	72 (60%)	13 (11%)
2000 (120 rivers)	34 (28%)	74 (62%)	12 (10%)
2001 (120 rivers)	33 (27%)	72 (60%)	15 (13%)
2002 (120 rivers)	30 (25%)	68 (57%)	22 (18%)

* Based on Malaysia Water Quality Index (WQI)

Furthermore, the Klang and Langat Valleys experienced a serious shortage of clean water in 1998 due to indiscriminate logging, housing developments in highland areas, diesel contamination originating from a quarry near the water treatment plant and pollutants from more than 100 factories along the river (Jamaluddin, 2000). This problem was made worse with the effects of a prolonged drought (an El Nino phenomenon). The demand for water in the Klang Valley doubled in ten years from about 1200 million litres per day in 1987 to about 2500 million litres per day in 1997. This was an annual growth in consumption of seven percent which has continued so that water demand in year 2002 exceeded 3500 million litres a day.

The poor maintenance of pipes (leakage/burst pipes) has resulted in annual water losses of 50-60% and this will cost about 1.5 billion Ringgit Malaysia for a pipe replacement project. The Government needs to realize the extent of the problem and act quickly by implementing a holistic approach to management, because water demand is expected to rise from the current 2.6 billion cubic metres per annum to 5.8 billion cubic metres in the year 2020 (Department of Public Work, 1998). Typically, Malaysian urban consumers use 200 litres of water a day, while their rural counterparts use a mere quarter of this amount. Therefore, any proposal for new land development in the Bernam catchment should be integrated with appropriate environmental impact assessment in order to make sure the catchment water resources are sufficient for various uses in the near future.

1.3 Research aim and objectives

In this study, the aim is to assess the impacts of land use change (which involves deforestation, changes in agriculture and development of urban areas) on hydrology and water quality in the Bernam river basin. Two developed catchments, Langat and Linggi, are studied as analogues. An examination of the relations between development and hydrology in these two catchments will contribute to an understanding of the prospective consequences of river basin management in the Bernam (**Figure 1.2**).

Thus, the objectives of this research are:

i- To validate archived hydrological data (Langat, Linggi and Bernam).

ii- To assess the morphometric similarity of the analogue catchments and the Bernam.

iii- To assess the impacts of medium-term changes in global atmospheric circulation – particularly those associated with El Nino and La Nina - on rainfall within the study catchments.

iv- To establish key relations between hydrology, water quality and land use change, in the Langat and Linggi by:

a. quantifying type and magnitude of land use changes temporally and spatially and assessing their impact on the hydrology and water quality of the Langat and Linggi Rivers.

b. investigating the association between water quality status and hydrological characteristics.

v- To assess whether the Langat and Linggi are suitable analogues for the Bernam.

vi- To establish hydrological and water quality transfer functions to predict the impact of land development on hydrological variables in Bernam.

1.4 Thesis construction and content

This thesis begins by setting the national picture of development in Chapter One. Chapter two reviews the background literature about land use change and its impact on hydrology in tropical regions. Chapter Three describes the physical characteristic of the study catchments. Chapter Four assesses the data sources and research methodology and Chapter Five discusses the land use history of the study catchments and its relations with hydrological characteristics. Rainfall-runoff relations are discussed in Chapter Six in the context of seasonal monsoonal weather, medium-term changes in rainfall associated with global atmospheric circulation and land-use changes. Suspended sediment, other physical and chemical water quality indicators are discussed in Chapter Seven. Finally, an integration of land use changes, climatology and hydrology within river basins are presented in Chapter Eight.

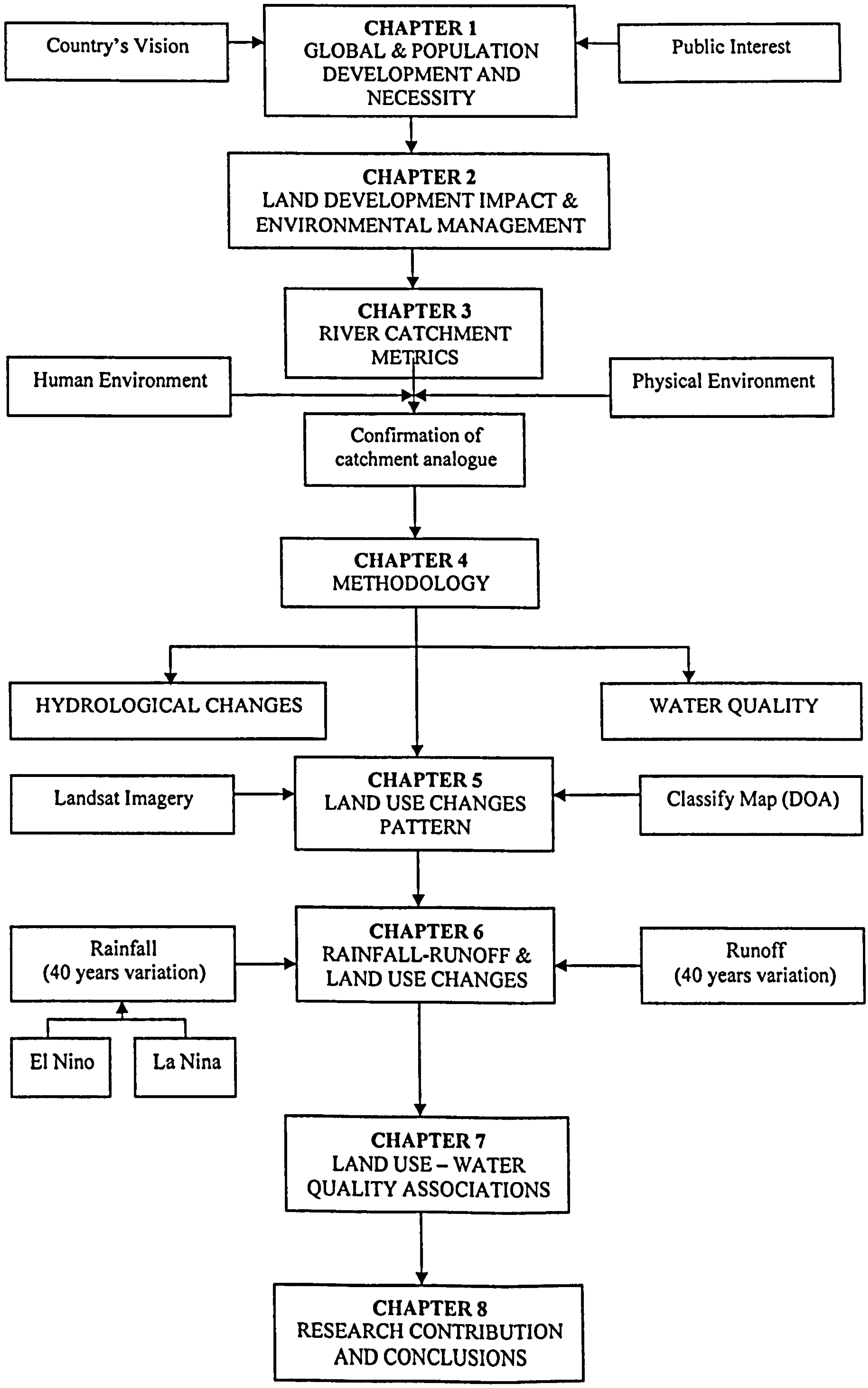


Figure 1.2: General view of research framework

CHAPTER TWO:
IMPACT OF LAND USE CHANGE ON WATER YIELD AND WATER QUALITY IN TROPICAL REGIONS

2.1 Introduction

This chapter reviews existing knowledge of pertinent tropical environmental characteristics, including El Nino and La Nina phenomena as these relate to changes of land use. It also evaluates the impact of land use change, such as forest conversion, agricultural activity, urbanisation and industrialisation, on water quality in small urban and rural catchments. The review provides a back-cloth for the detailed study of key relations between land use changes and their impact on the hydrology and water quality of three study catchments – the Langat, Linggi and the Bernam. It is used to reveal gaps in knowledge about urban and rural catchments within the wet tropical ecosystem.

2.2 Land development and economic growth in tropical countries

In the past few decades, land development in several tropical countries has been influenced by high economic growth, resulting in a significant shift from forest to agriculture, urbanization and industrialization (Calder 1999; Velaquez *et al.*, 2003; Yunus *et al.*, 2004). These changes have produced artificial landscapes in whole or in part (Farina, 2002; Fujihara and Kikuchi, 2005) and have been driven by socio-economic factors. These factors are increasingly identified as having a critical influence on local, regional and global environmental change (Nagendra *et al.*, 2004).

Socio-economic development has a role in providing a better human existence despite increasing population and consequent pressures on resources, including land. In order to accommodate development, land-use will change and this will, in turn, affect hydrologic processes and also have long-term effects on soil. However, socio-economic forces are usually driven by government development policy. Therefore, understanding the links between land development policy and land use change are essential in order to increase effectiveness in managing the land use and minimise the potential impact on environment (Abdullah and Nakagoshi, 2006).

Nowadays, continual rapid change of land use is common in developing tropical countries. It is controlled by the potential value of the land for agricultural, forest, urban, or nature protection uses and is governed by multilevel economic and socio-cultural interactions (Niehoff *et al.* 2002). These countries such as Malaysia, Indonesia, Thailand and Philippines utilize land either for economic development such as agriculture expansion or urbanisation or for daily subsistence through such practices of shifting agriculture (Abdullah and Nakagoshi, 2006). Improper land use development may interfere with ecological processes that determine the functioning of land-cover and this can have drastic effects on different components of the hydrological cycle and on the erosion of soil (Arnell, 1989; Veldkamp and Fresco, 1996).

During the last few decades, tropical Asia and Africa has been affected by intense land use change. The Food and Agriculture Organisation (FAO, 2003) reported that forests in Africa are lost at an estimated rate of more than 50,000 km^{-2} yr^{-1}, the highest rate of any region in the world, largely through commercial exploitation, namely logging and conversion to agriculture. This trend began during the 1980s and still continues. Consequently, high percentages of the moist forests have been largely depleted, e.g. only 22.8% of West Africa's moist forests remain. This is corroborated by Bormann (2005), who conducted studies on land use/land cover changes in central Benin, West Africa, from 1991 to 2000 based on remote sensing data which revealed that the annual expansion of agricultural areas increased from 4.5% to over 15 % in some communes. Meanwhile, the deforestation rate in tropical Asia is about 44 000 km^{-2} $year^{-1}$, and in Malaysia it is around 8100 km^{-2} $year^{-1}$. This type of activity brings severe environmental degradation to natural, semi-natural and artificial ecosystems, such as forests (Endress and Chinea, 2001), riparian zones and urban areas (Yunus *et al.*, 2003).

Many large cities in the developing world which are situated in river basins have experienced environmental and water resource concerns due to rapid land use changes through activities such as logging, agricultural expansion, urbanization and industrialization (Calder, 1999). They face periodically a shortage of water supplies due to the removal of forest cover and its replacement with agricultural activities in headwater catchments. The land use change not only affects water resources but may also have long-term effects on the soil itself due to the overexploitation of vegetative cover for domestic use, overgrazing of pastures and pollution released by industry. Furthermore, the removal of forest cover from a watershed can result in significant hydrological changes, including a decrease in interception of rainfall by the tree canopy (increased net precipitation), and by surface litter, decreased evapotranspiration and increased runoff, which may result in local flash floods (Hamilton and King, 1983; Hamilton and Pearce, 1987).

Over the last several decades, many governments in developing countries in Southeast Asia have initiated road building in rural areas (one of several major land use activities alongside extensive deforestation and changes in agriculture) as a part of their role to provide a better infrastructure, as well as building, quarrying and mining in response to increasing economic development. Tejwani (1993) claimed that these land use activities have ignored environmental factors which caused soil erosion and land degradation on a wide scale. As an example, in mountainous areas of northern Thailand, Bruijnzell and Critchley (1994) claimed that road construction has played a significant role in altering near-surface hydrologic response and in subsequently accelerating soil erosion, which later, has contributed much sediment to the stream systems, including the Chao Phraya River (Ziegler *et al.*, 2002).

Ziegler *et al.* (2002) also described the effect of the expansion of road networks on hydrological processes involving low rates of infiltration, an increase in overland flow generated by unpaved roads that is more frequent and begins earlier during rain events and also contributes to basin stormflow changes. Runoff generated by road surfaces in one sub-watershed is transported into trunk streams, where it contributes accumulatively to watershed hydrological and geomorphological impacts. Ziegler *et al.* (2002) concluded that because of frequent surface flow generation, high connectivity of road sections, and the daily movement of sediment, roads continually disrupt natural watershed systems throughout the course of the rainy season, potentially to a greater degree than agricultural activities in some upland watersheds.

In developing tropical countries, populations and demand for water are growing rapidly, thus an optimization of water resources usage is becoming important (Bonell, 1993). At the same time, demands for industrial wood (pulpwood, saw and veneer logs), fuel wood and charcoal are also strong and this requires the establishment of large areas of fast-growing plantation forests (Evans, 1992; Brown *et al.*, 1997). Coupled with the continued indiscriminate clearing of the tropical forests, which in many areas serve as the traditional supplier of high quality water (Jepma, 1995; Nepstad *et al.*, 1999); the associated deterioration of soil and water quality due to erosion and pollution (Abdul Rahim and Zulkifli, 2000; Chuan, 2003), plus the possibility of gradually less dependable precipitation inputs and an increasing frequency of devastating hurricanes due to changes on the global scale (Wasser and Harger, 1992) all indicate that there is an urgent need to understand the hydrological functioning of tropical forests (Bruijnzeel, 1990, 2002a).

Malaysia has been experiencing extensive land use change associated with government developmental policies. In the 1960s and 1980s, Malaysian economic development was mainly based on the agricultural sector. During this time, approximately 28,000 km^{-2} (13 %) of the forested areas were converted into agricultural land, especially for oil palm and rubber plantations (Department of Forestry, 2000). In the 1980s, there was a major economic transformation to focus on the manufacturing sector. By 1987, this sector became the fastest growing sector and its growth rate exceeded that of the agricultural sector to account for 22.6% of the country's gross domestic product (GDP) (Economic Planning Unit Malaysia, 2004). The progress of this sector has been catalysing other development activities, such as urbanization, building highways, commercial development and other infrastructure. As a result, there has been an increased demand for land, which has involved further removal of permanent forest reserves and state forests. All of these changes have been identified as major causes of environmental degradation (Jamaluddin, 2000).

The increasing pressure of human population on land, forest and water resources has led to misuse and over-exploitation of land and forests. Population concentration in urban areas and the expansion of existing development areas became a global phenomenon particularly after the 1950s. Malaysia, in particular since its independence, has experienced a rapid and intensified urbanisation through a period of high economic growth. This urbanisation brings with it many alterations of nature, including site transformations, such as river channel diversions, changes to the functioning of local ecosystems, pollution, and an alteration in the natural flows of energy, food and materials (Douglas, 1983). Land clearance in headwaters washes sediment downstream, raises the levels of siltation and reduces instantaneous river storage capacity.

It is very clear that with an average annual rainfall of 3000 mm, Malaysia has an abundance of water resources. Water demand in Malaysia estimated at 16 billion m^{-3} in

2002, growing at the rate of 4 % per annum. This is projected to be about 20 billion m^{-3} in 2020. However, if the process of urbanisation keeps increasing without proper environmental assessment, there is a worry that the amount of the annual rainfall received by the river system as the main source of the public water supply (contributing more than 97 %) will decrease by flowing out from the system leading to an inability to fulfil the demand from various sectors. Even now, 25 river basins have been identified as areas experiencing water stress (Jamaluddin, 2001). Therefore, Malaysia will again be expected to face another big water crisis in the near future, just as Selangor, Melaka and Negeri Sembilan States have faced since 1997.

In recent years, the importance of the environmental functions of rivers in urban areas has been increasingly recognised (Chan, 2000). For instance, river water quality tends to deteriorate with the growth of economic activities and urbanisation, whilst the river's self-purification ability is lessened. In particular, increased population density, the expansion of urbanised areas and the creation of a higher building density have become important influences on hydrological processes (Dani, 2001). The increase in population density through urbanisation results in a rise in water demand; this, in turn, gives rise to the need for the development of water resources and increases waterborne pollution through a deterioration in storm water quality.

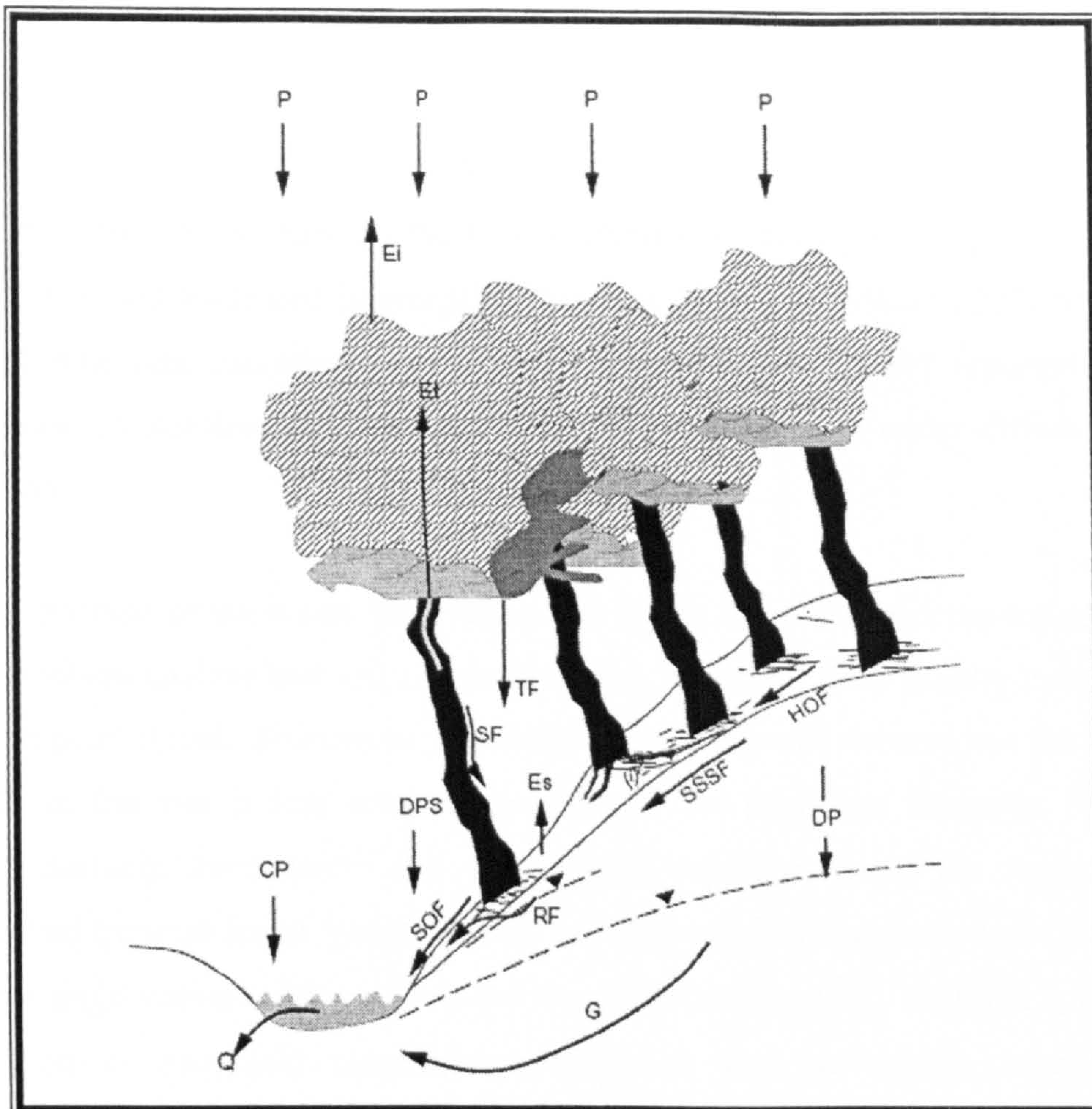
In reality, water resources in the humid tropics are getting more and more depleted in terms of quality with most of the depletion caused by land use and land cover changes (Bruijnzeel, 1990, 1998). The economic losses due to water shortage result mainly from a lack of adjustment in the public policy-making processes regarding the use of resources (Murdiyarso, 2005). Water shortage, in particular, is a growing issue in tropical areas where population pressure and rates of environmental degradation are high. Furthermore, water shortage is increasingly causing political and social tension between upland and lowland communities and between neighbouring districts or countries or other political and administrative units. Therefore, an integrated management plan that involves the various stakeholders is necessary to avoid conflicts (Dubash *et al.*, 2001).

In Malaysia, the impact of inappropriate land development projects located in urban areas has produced challenges for urban managers (local authorities) to make the urban river environment sustainable (Jamaluddin, 2002). For example, such projects have tended to have negative impacts on urban river ecology and, to minimise this, the environmental impacts of land development projects have to be managed properly by the relevant authorities to ensure the sustainability of urban development. Environmental aspects must be considered seriously at the planning stage of large construction projects in environmentally sensitive areas.

2.3 The hydrological cycle in tropical rain forests

This section will describe the hydrological processes operating in a tropical forest, suggesting typical values for components of water flux and storage. A simplified picture of the hydrological cycle of a tropical forest ecosystem is presented in **Figure 2.1.** It is a similar structure as it's occurs in three Malaysia study catchments.

Precipitation occurs in tropical forests in the form of rainfall (P), and also 'fog-drip' (occult precipitation) which normally occurs in coastal mountain regions where orographic lifting of moist ocean air produces adiabatic cooling, condensation and fog (Bruijnzeel, 2002a). The actual precipitation in mountain forests may be higher than in the open because 'fog-drip' may form a considerable part of the total precipitation. For example, fog drip accounted for 10% of the measured precipitation in tropical forest, at 600 m and above, in Puerto Rico (Larsen and Concepcion, 1998), 5 to 20% of "conventional" annual rainfall in Tropical Montane Cloud Forests (Bonell, 2004), about 30% of the annual precipitation in a Douglas Fir forest in Oregon and 100% in the cloud forest of the rainless Atacama desert of Peru (Burgess and Dawson, 2004). Precipitation (P) arrives at the forest floor through three pathways, namely: (i) throughfall, involving the amount of water that reaches the forest floor, typically about 80 % (70-90 %) of above canopy rainfall; (ii) stemflow (SF), which involves a small fraction of water flowing down tree trunks, typically 1-2 %, some of which will evaporate back into the atmosphere, and (iii) crown drip, which refers to water that hits the canopy and is in excess of its interception capacity. Usually, it is not possible to differentiate crown drip and direct throughfall. Therefore, they are generally combined and simply referred as 'throughfall' (TF). From the above processes, the equation for the water balance of a wet canopy can be constructed as Precipitation (P) = Throughfall (TF) + Stemflow (SF) + Rainfall Interception (Ei) (Schellekens, 2000).



P: Precipitation, TF: Throughfall, SF: Stemflow, Ei: Rainfall Interception, Et: Transpiration, Es: Soil Evaporation, CP: Channel precipitation, DPS: Direct precipitation onto saturated areas, HOF: Hortonian Overland Flow, SSSF: Sub Surface Storm Flow, RF: Return Flow, SOF: Saturation Overland Flow, DP: Deep percolation, G: Groundwater flow, Q: Discharge

Figure 2.1: Schematic illustration of the major water fluxes in a lowland tropical rain forest setting (Schellekens, 2000)

Canopy cover intercepts a significant fraction of precipitation on forests where it evaporates without reaching the soil (Klaassen, 2001). The main factors influencing the interception are canopy storage capacity and wet canopy evaporation rate (Loustau *et al.*, 1992). These interception losses are an important component of the hydrological budgets (Whelan and Anderson, 1996) of the terrestrial ecosystems. Interception losses can constitute a considerable net loss to the system (Schellekens *et al.*, 1999). Studies in tropical and subtropical rainforests have shown that the interception losses vary from 6 to 42 % of incident rainfall on an annual basis, indicating interception rates to decrease with forest disturbance intensity (e.g. Asdak *et al.*, 1998; Hutjes *et al.*, 1990; Sinun *et* *al.*, 1992; Scatena, 1990). For instance, the rainfall interception was 11 % in a natural forest and 6 % in a logged forest in a lowland tropical forest in Kalimantan (Asdak *et al.*, 1998). Cantu-Silva and Gonzalez Rodriguez (2001) reported that in pine and oak forests in north-eastern Mexico the total precipitation during the experimental period was 974 mm and estimated interception loss was 19.2%, 13.6% and 23% for the pine, oak and pine–oak canopies, respectively. Llorens *et al.* (1997) reported 15–49 % interception by conifers in a Mediterranean mountainous area under different climatic conditions.

A small fraction of the water that reaches the forest floor will be evaporated back into the atmosphere as litter and soil evaporation (Es), however, Es is usually insignificant in humid tropical forest. 'Hortonian overland flow' (HOF) will occur when the infiltration capacity of the soil is less than the throughfall and stemflow intensity. However, it occurs relatively infrequently due to the high conductivity of the topsoil in most undisturbed tropical forest but may occur on clayey soils (Elsenbeer and Cassel, 1990) or where large volumes of stemflow are concentrated (Herwitz, 1986). It is common in areas such as semi-arid rangelands, compacted soil and paved urban areas. A considerable part of the infiltrated water is taken up by the vegetation and returned to the atmosphere as transpiration. The sum of Et, Es and Ei, is then called evapotranspiration (ET) (Schellekens, 2000).

Water that infiltrates into the soil profile can flow through to the stream in several ways. During storms it can flow laterally as saturated or unsaturated stormflow (SSSF). When the upper soil profile becomes saturated, typically in hillside hollows, concave footslopes or areas with an impeding layer close to the surface (Bonell and Gilmour, 1978), infiltrated water will run off as saturation overland flow (SOF). The contributions of SSSF, HOF and SOF represent the quick-return flow paths of water to the stream network, supplemented by the (usually small) contribution of direct channel precipitation (CP). The remaining soil moisture drains into the stream network by slow-moving throughflow, accounting for a considerable part of the baseflow of streams (Ward and Robinson, 1990). The subdivision of water at the soil surface into the various possible flow types is determined by initial soil water conditions, soil hydraulic properties and micro-topography (Schellekens, 2000).

Reliable estimates of the relative magnitude of the pathways of water to the forest floor in tropical rain forest have been relatively few, despite the broad attention that has been given to this subject (Schellekens, 2000). The most reliable estimates suggest that about 85 % (77– 93 %) of incident precipitation reaches the forest floor as TF, while stemflow (SF) usually accounts for 1–2 %, where small trunks generate more stemflow than large trunks (Bruijnzeel, 1990; Anderson and Spencer, 1991) and interception losses are about 30–50 % under wet maritime tropical conditions (Clements and Colon, 1975; Gilmour, 1975; Read, 1977; Scatena, 1990).

2.4 Tropical rainfall characteristics

In tropical areas (**Figure 2.2**), rainfall is the main factor that determines the seasons. Therefore, the quantity and temporal distribution of rainfall are important criteria to distinguish sub-climatic zones, viz: wet (>1800 mm), wet–dry (700–1800 mm) and dry (<700 mm). The convergence of airflows in the Equatorial Trough is referred to as the Intertropical Convergence Zone (ITCZ). The ITCZ is characterized by the trade winds constitute an important north–south energy and moisture exchange mechanism (as part of the low level branch of the Hadley circulation), which in turn affects tropical wet climates and determines to a large extent of the precipitation distribution in the region (Balek, 1983; Callaghan and Bonell, 2005). Monsoonal circulations also play an important role in determining the warm season precipitation distribution over the eastern tropical Pacific through a large variety of air–sea–land interaction mechanisms (McGregor and Nieuwolt, 1998).

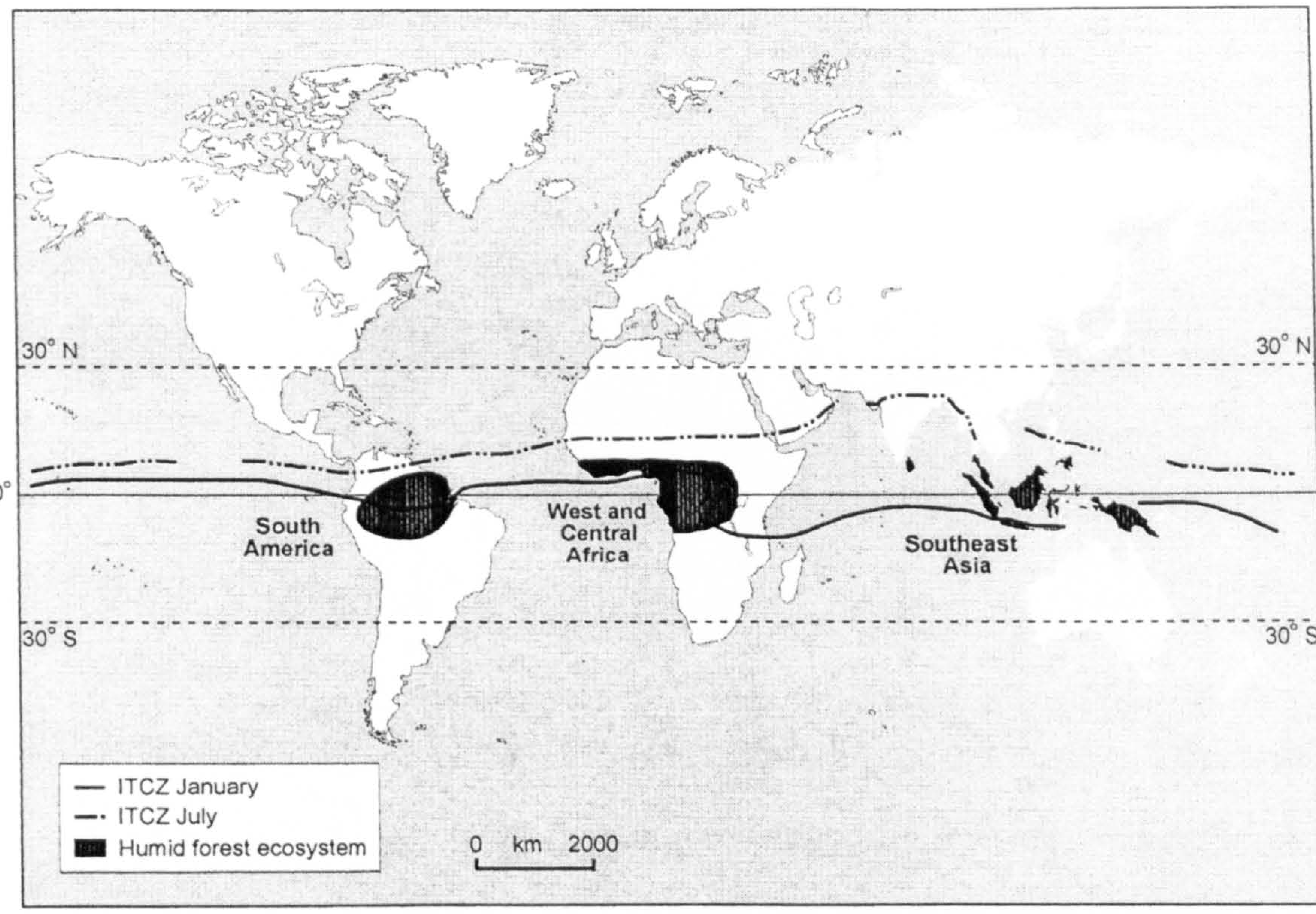


Figure 2.2: Humid equatorial forest ecosystem and the Inter-tropical Convergence Zone

The most variable element of tropical climates is rainfall (McGregor and Nieuwolt, 1998). Wet tropical climates are characterized by temperatures ranging from 24 to 30°C with an annual variation of about 3°C. Most thunderstorms in the tropics are caused by the intense local heating in a warm, moist and unstable atmosphere. The average life span of a convective cell is about half an hour. In humid tropical Asia, the number of thunderstorm days exceeds 30 per year. In southern Thailand, Malaysia and the western part of Indonesia, thunderstorm days exceed 60 per year. These conditions are normally associated with the Indian and South East Asia monsoon trough, which has an active form of towering cumulonimbus clouds, violent turbulence and heavy rainfall (Bonell, 1993).

The summer monsoon is the prime source of rainfall that supports local agricultural and other activities. It is characterized by significant inter-annual and intra-annual fluctuations based on a 30-60 day oscillation of inter-hemispheric energy transfers. The latter are related to higher frequency weather features. For examples, a major feature of the summer monsoon is the fluctuation between active and transition periods of convection (Bonell, 1993). The monsoon trough in South East Asia is highly mobile and its movement determines the spatial distribution of rainfall (Balek, 1983).

In general, total rainfall fluctuations from year to year in tropical lowlands are relatively small compared with monsoonal regions and those areas dominated by orographic conditions. Typical annual rainfall in the wet tropics is close to 2000 mm/year. In some areas, however, it can reach 14.5 x 10^3 mm/year as recorded on Mount Cameroon in West Africa (Hidore and Oliver, 1993) and 10 x 10^3 mm/year in the Choco' forest of Colombia (Latrubesse *et al.*, 2005). Rainfall frequency and intensity in tropical regions are also quite variable. For example, Duitenzorg in Java has 322 days per year with intense and brief thunderstorms, while Rio Branco in Southwestern Brazilian Amazonia has a total rainfall of only ~100 mm spread over three months from June to August (Latrubesse *et al.*, 2005). The spatial and temporal variability of rainfall play a significant part in complicating hydrological processes in humid tropical regions, especially rainfall-runoff relations.

2.5 Evapotranspiration from humid tropical forests

Despite a small number of significant studies undertaken in recent years (e.g. Calder *et al.*, 1986; Shuttleworth *et al.*, 1984; Shuttleworth, 1988), knowledge of many aspects of the hydrology of humid tropical forests remains somewhat uncertain. In particular, there is, as yet, little consensus about the atmospheric and vegetation components of the hydrological cycle in rainforest environments, which together determine the evapotranspiration (ET) from such regions. This represents a major factor in the water balance of these environments and may be critical for the management of forested drainage basins where only around 20-50% of the rainfall ever reaches the rivers (Anderson and Spencer, 1991) and where clearance or conversion of the forest is likely to occur.

The recognition that tropical forests have a significant impact on hydrology has driven a number of studies into tropical forest evapotranspiration (ET) (Bruijnzeel, 1990; Gash *et al.*, 1996). Available estimates of tropical forest ET are based on the catchment water budgets (Bruijnzeel, 1990; Malmer, 1993; Lesack, 1993; Jetten, 1994; Abdul Rahim *et al.*, 1995).

However, according to Ward and Robinson (1990), this method is notoriously prone to errors due to ungauged subterranean transfers of water into or out of the catchment, which produce relatively unreliable estimates of ET unless the catchment is demonstrably watertight. The problem is shown by the contrasting results obtained for various small forested catchments in central Amazonia where reported annual ET ranges from 1120 mm to 1675 mm (Lesack, 1993), despite similar climatic and geological conditions. Similarly, annual estimates of ET for lowland and hill dipterocarp rain forests on granitic substrates in Peninsular Malaysia which receive over 2000 mm of rain annually without a pronounced dry season also vary from about 1000 mm to almost 1800 mm (Abdul Rahim and Baharuddin, 1986).

Many studies such as Dykes (1997), Asdak, et. al. (1998) and Dietz, et. al. (2006) treated ET as comprising two separate components, rainfall interception (Ei) and transpiration or dry canopy evaporation (Et). Ei ranged between 4.5 and 22% of the rainfall incident on the canopy, with an average value of 13%. Annual Et also varied considerably around an average of 1045 mm (range 885- 1285), and was usually either unreliably derived from the difference between estimated ET and Ei, or obtained from water budget calculations for possibly leaky catchments. Evapotranspiration tends to be high under the warm and wet conditions prevailing in the humid tropics and therefore strongly influences the total amount of water available as streamflow (catchment water yield) for a given rainfall regime (Bruijnzeel, 1990). In his review of tropical rainforest water use, (Bruijnzeel, 1990) was not be able to find distinct differences in ET for three major rain forest blocks of West Africa, Amazonia and South-east Asia due to methodological problems.

Bruijnzeel (1990) summarized the literature on evapotranspiration from humid tropical forests with estimates of average annual ET of 1415 mm (range 1310-1500). However, he recognized that values of ET above 1400–1500 mm yr^{-1} were due in part to catchment leakage (groundwater movement) rather than specific climatic conditions favouring high evapotranspiration. Since 1990 there have been several studies that have also obtained high evapotranspiration totals (> 1700 mm yr^{-1}, **Table 2.1**), especially in equatorial areas with high rainfall e.g. Sipitang, East Malaysia, 1835 mm - (Malmer, 1993) and Puerto Rico, 2,180 mm – Schellekens *et al.* (1998). These results seem to confirm the original finding of Richardson (1982) in Jamaica (2000 mm), although her explanation ('high rainfall and breezy conditions') is not necessarily valid for the other sites of high evaporation. For these lowland tropical forests areas, annual totals of ET increase with rainfall, particularly for rainfall exceeding 3500 mm yr^{-1} (Bruijnzeel, 2002a).

Table 2.1: Evapotranspiration components for selected tropical and warm temperate forests. Evaporation values (mm yr^{-1}) rounded off to the nearest 5. Type codes: 1: Coastal and island sites, outer tropics; 2: Continental edge, equatorial; 3: Continental, equatorial; 4: Coastal sites, temperate latitude.

Location	Type	P	ET	Ei	Et	Ei/Et
Queensland, Australia[1]	1	4,035	1,420	1,010	420	2.40
Puerto Rico[2]	1	3,685	2,420	1,790	630	2.84
Sipitang, East Malaysia[3]	2	3,945	1,835	870	965	0.90
Peninsular Malaysia[4]	2	2,775	1,555	640	915	0.70
Guyana[5]	3	2,480	1,485	345	1,135	0.30
Sapulut, East Malaysia[6]	3	2,370	1,440	290	1,150	0.25
South Island, New Zealand[7]	4	2,610	1,100	650	350	1.86
Plynlimon,Wales, U.K.[8]	4	2,035	865	530	335	1.58

(Notes: P = Precipitation; ET = Evapotranspiration; Ei = Rainfall Interception; Et = Evaporation)

Sources: [1]Gilmour (1975); [2]Schellekens (2000); [3]Malmer (1993); [4]Abdul Rahim *et al.*, (1995); [5]Jetten (1994); [6]Kuraji and Paul (1994); [7]Pearce and Rowe (1979); [8]Calder (1990)

Interestingly, for a given rainfall, values of ET observed for forests located on islands in the outer tropics, such as Puerto Rico, tend to be higher than those for forests situated closer to the equator. This is due to the very large variation in intercepted rainfall (range: 220–1790 mm yr^{-1}) whereas the variability in dry canopy evaporation is generally less pronounced (range: 630–1375 mm yr^{-1}), leaving the exceptionally low value derived for Queensland (Gilmour, 1975) which may be related to an overestimation of the stemflow component (Bruijnzeel, 2002b). Detailed knowledge and understanding of ET from tropical forests is a key to a reliable prediction of the effect of rainforest impact on the amount and timing of streamflow (Kumagai, *et al*, 2005). The figures for evapotranspiration and evaporation in tropical regions also give an indication of the importance in the catchment water balance and, hence, the relationship between rainfall and runoff in the catchments under study here.

2.6 Interception and forest structure parameters

The interception process, which mainly depends on the density of vegetation cover, important, especially in a tropical region such as Malaysia, which has large areas of rainforest. Interception by tropical forest is expected to influence the volume of water in drainage systems and also to influence the amount of surface runoff during storm events. However, different types of precipitation and vegetation will also determine the rate of interception. Ward and Robinson (1990) stressed that interception can affect catchment hydrology through its effects on the areal distribution of precipitation reaching the ground surface.

Data on interception loss for vegetation and agricultural crops in tropical countries is very sparse. Observational studies of interception loss fall into several categories. Many researchers have focused on rainfall conditions. For example, in dry atmospheric conditions, interception rates are primarily controlled by rainfall intensity (Llorens *et al.*, 1997). Tsukamoto and Ishigaki (1989) also found that the interception rate increased proportionately with rainfall intensity of less than 7.0 mm^{-h}. However, the relationships between rainfall intensity, duration of rainfall events, and other weather elements are not clear. Researchers have also examined the relationship between wind speed and interception loss. For example, high wind speeds could theoretically orient leaves parallel to the wind and reduce the probability of interception. However, in tropical rainforests with dense canopies, the probability of a raindrop passing through the canopy without contacting a vegetative surface is relatively low even under strong wind conditions (Herwitz and Slye, 1995).

Dingman (1994), defined interception as the process whereby precipitation falls on vegetative surfaces and is re-evaporated. Meanwhile, Teklehaimanot *et al.*, (1991) defined rainfall interception as the process by which plant leaves and stems catch and retain precipitation within the plant canopy and return it to the atmosphere through evaporation or channel it to the ground by stemflow or foliar drip. In addition, individual water droplets are small; they remain suspended in the air and sometimes move through the vegetation and are deposited on the sides of projecting vegetation (Zadroga, 1981 and Harr, 1983). Klaassen *et al.*, (1996) stated that interception is defined as precipitation which is intercepted by vegetation and evaporation before reaching the soil. These various definitions may change the quantity, quality and distribution of precipitation which reaches the soil surface (Wood *et al.*, 1998). However, Bosch and Hewlett (1982) and Calder (1992) both indicate that the general result is higher water losses to the atmosphere from forestland.

Knowledge about interception is essential in studies of catchment water balances (Van Dijk *et al.*, 2001). Most interception studies have been conducted on trees and least on shrubs, grasses, forbs and other herbaceous plants. Observations suggest that interception is large at the beginning of a storm and the area under a plant, such as tree with much foliage, remains dry. Notwithstanding this, Wong, (1991) and Bidin (2001) found that between 13% and 28% of sub-canopy gauges in undisturbed forest in the Danum Valley, East Malaysia caught more rainfall than gauges in the open. This reflects the concentration at drip points but it influences the pattern of soil detachment and erosion on the forest floor.

Interception loss refers to the amount of rainfall intercepted, stored, and subsequently lost by evaporation from the canopy. Interception loss is a significant and sometimes dominant component of evapotranspiration (Schellekens *et al.*, 1999; Price and Carlyle-Moses, 2003) and is much larger for forests, which have larger aerodynamic resistance, than for grasslands (Marin *et al.*, 2000). Over the last four decades, many studies have investigated forests, including tropical rainforests (Sinun *et al.*, 1992; Dykes, 1997; Fujieda *et al.*, 1997; Asdak *et al.*, 1998) and coniferous forests (Johnson, 1990; Loustau *et al.*, 1992; Huber and Iroume, 2001). Tropical rainforests play an important role in regulating regional and global climate, and a massive reduction in forest area could reduce evaporation on a regional scale (Asdak *et al.*, 1998; Marin *et al.*, 2000).

The spatial and temporal variability of rainfall and the stand/canopy structure in a tropical rainforest is large, and this results in a wide range of rainfall interception loss. Interception loss accounts for 10–40% of gross precipitation in various plant communities in the world (Dingman, 1994; 1996; Liu, 1997, Carlyle-Moses *et al.*, 2004; Carlyle-Moses, 2004) and affects water and geochemical balances in forest areas. For instance, in tropical humid and lowland forest communities, the percentage annual canopy interception loss is about 9.2% and 18 % respectively (Asdak *et al.*, 1998; Dietz, *et. al.*, 2006); whilst in Malaysia, lowland forest interception loss is 21 % (Abdul Rahim *et al.*, 1995). Meanwhile, in coniferous forest species (*Pinus* and *Picea*) in the UK and Canada, the interception loss ranges between 21 and 48% (Calder, 1990).

Currently, many researchers are concerned about the environmental effects of forest extraction in tropical countries where rainforests represent major natural and economic resources. Many studies of water relations of forest stands at a local scale such as those of Bosch and Hewlett (1982), Hamilton and King (1984), and Bruijnzeel (1990) have shown that cutting down forest may affect water yield and, at a regional scale, it can reduce evaporation and so precipitation. Calder (1986) and Scatena (1990) showed that interception losses are of major importance in determining the water yield of forested areas relative to yields from other vegetative cover. Previous interception loss studies indicate that improved understanding of the interception loss process for different vegetative covers or management techniques may allow better predictions of the consequences of vegetation changes for water yield (Asdak *et al.*, 1998). Calder *et al.*, (1986), Rao (1987) and Hutjes *et al.*, (1990) have produced sufficient information to explain the complexity of precipitation processes in tropical forest environments. However, despite these significant studies, knowledge of many aspects of the hydrology of humid tropical forest still remains unclear (Dykes, 1997).

Studies by Asdak *et al.*, (1998) in unlogged and logged forest areas of central Kalimantan, Indonesia generally suggest that interception loss in an undisturbed tropical rainforest decreases following logging because logging practices create a discontinuous canopy. The discontinuous canopy affects total interception loss by influencing the canopy's structural properties, i.e. canopy storage capacity, free throughfall coefficient and aerodynamic properties, including the boundary layer conductance. The difficulty with forests with a discontinuous canopy is how much effect the gaps have upon the overall turbulence. In general, as gaps appear in forest canopies, the canopy becomes rougher and turbulence increases, thus increasing the rate of interception loss. At the same time, following logging activities, the total amount of interception loss is reduced as a result of the decrease in canopy storage capacity. The overall effect of logging on the interception loss will be determined by the magnitude of the gaps and the reduction of canopy storage capacity. These relationships have not been investigated very intensively, and therefore more attention should be given to these counteracting relationships in any future evaporation studies in tropical rainforests.

In his experiment (Asdak *et al.*, 1998), the rainfall interception loss for the unlogged forest was 11 % of gross rainfall. This is less than in a similar study carried out in the neighbouring area of Sabah, Northern Borneo and in lowland tropical rainforest in Brunei where interception loss was 17% and 18% of gross rainfall respectively (Sinun *et al.*, 1992; Dykes, 1997), and far less than the interception loss of 21% measured in a region of secondary lowland tropical rainforest in West Java, Indonesia (Calder *et al.*, 1986). In an Amazonian rainforest in Brazil, interception loss was 9% of gross rainfall, whereas in a secondary tropical rainforest in Brazil, it varied from 12 to 20% of gross rainfall (Lloyd *et al.*, 1988). These reported estimates of evaporation of intercepted water in the tropical rainforest environment vary considerably and, therefore, suggest that more rainfall interception studies are necessary.

The capacity of vegetated surfaces to intercept and store water is of great practical importance. It is well documented that the rate of evaporation from a wet canopy is higher than that under dry canopy conditions (Rutter, 1963; Stewart, 1977; Calder, 1977). As such, rainfall interception and its subsequent evaporation constitute a net loss to the system and may assume considerable values under certain conditions (Shuttleworth and Calder, 1977; Schellekens *et al.*, 1998). Conversely, in coastal and montane fog belts, interception of wind-driven fog by forest vegetation or hedgerows may add substantial amounts of moisture to the system (Bruijnzeel, 2002a). Thus, the distinct changes in streamflow observed after forest removal or introduction often reflect the fact that interception losses from tall forests (20-30 m) exceed those associated with lower vegetation, such as grassland or agricultural crops as reported in Panama, Colombia and New Guinea with 20%, 32.7% and 24.6%, respectively (Bosch and Hewlett, 1982; Bruijnzeel, 1990; Calder, 1990; Stednick, 1996, Bonell, 2004).

In conclusion, rainfall interception by vegetation is an essential hydrological process which affects the rate, total depth and spatial distribution of water available for other processes such as evaporation, transpiration and runoff. Generally, interception by forests and individual tree canopies is much greater than for shrubs and other herbaceous plants. Rainfall intercepted by plants is re-evaporated into the atmosphere, and it is normally considered as a loss in the water balance (Gomez *et al.*, 2001).

2.7 General climate characteristic of study catchments

The characteristic features of Malaysia's climate are uniform temperature, high humidity and abundant rainfall (Malaysian Meteorological Services, 2000). They prevail because of the country's maritime exposure. As Malaysia is located in the equatorial region, it is extremely rare to have a full day with completely clear sky, even in periods of severe drought. On the other hand, it is also rare to have an extended period of more than a few days with no sunshine, except during the Northeast Monsoon season.

2.7.1 Air flow and monsoons

Generally, the air flow over the country is light and variable. However, there are periodic changes in air flow patterns of significance to local hydrology (Malaysia Meteorological Services, 2000). Based on these changes, four seasons can be distinguished, namely, the Southwest Monsoon, Northeast Monsoon and two shorter inter-monsoon seasons. The Southwest Monsoon is usually established in the latter half of May or early June and ends in September. The prevailing air flow is generally southwesterly and light, below 7.7 m s^{-1} (15 knots). The Northeast Monsoon usually begins in early November and ends in March. During this season, steady easterly or northeasterly winds of 5.1 to 10.2 m s^{-1} (10 to 20 knots) prevail (Malaysian Meteorological Services, 2000). In this case, the more severely affected areas are the east coast states of Peninsular Malaysia where the wind may reach in excess of 15.4 m s^{-1} (30 knots) during intense surges of cold air from the north (Malaysian Meteorological Services, 2000).

The winds during the two inter-monsoon seasons are generally light and variable. During these seasons, the equatorial trough lies over Malaysia. As Malaysia is mainly a maritime country, the effect of land and sea breezes on the general wind flow pattern is very obvious especially during days with clear skies. On bright sunny afternoons, sea breezes of 5.1 to 7.7 m s^{-1} (10 to 15 knots) very often develop and move several tens of kilometers inland. On clear nights, the reverse process takes place and land breezes with weak strength can also develop over the coastal areas (Malaysia Meteorological Services, 2000).

The Monsoon is caused by land-sea temperature differences due to heating by solar radiation during winter and summer time over continental Asia (Nieuwolt, 1982 and Bonell, 1993). Generally, the Northeast Monsoon brings heavy rainfall, particularly to the east coast states of Peninsular Malaysia and western Sarawak, whereas the Southwest Monsoon is associated with less wet weather.

The Northeast Monsoon is the major contributor of rain in the country (Nieuwolt, 1982). Monsoon weather systems which develop in conjunction with cold air flow from Siberia move southward, producing heavy rains in the east coast states of Peninsular Malaysia often causing severe flooding (typical maximum monthly rainfalls are 600 mm in November in Kelantan and Terengganu and 600 mm in December in Pahang and East Johore; Malaysian Meteorological Services, 2000). During the Northeast Monsoon period, the east coast states of Peninsular Malaysia will experience widespread heavy rain spells, each of two to three days duration. About three to four such spells are expected to occur throughout the monsoon and these cause flood periods. However, the Northeast Monsoon does not have much effect on the rainfall catch on the west coast where all the study catchments are situated, due to the rain shadow effect from the Titiwangsa mountain range. Between the heavy rain seasons, the weather is relatively fair. In November and early December, thunderstorms will frequently be experienced in the afternoon. From mid-January till mid-March the weather is relatively dry, with typical rainfall of 110-160 mm.

The Southwest Monsoon brings less rain. During this season, most states experience minimum monthly rainfalls between 100 - 150 mm. This is attributed to relatively stable atmospheric conditions (Malaysian Meteorological Services, 2000). In particular, the dry condition of Peninsular Malaysia is associated with the rain shadow effect of the Sumatran mountain range. During the inter-monsoon periods, thunderstorms which occur in April and October (transition periods), contribute to the mean monthly rainfall (Desa and Niemczynowicz, 1996).

2.7.2 Rainfall distribution

The seasonal air flow patterns, coupled with the local topographic features, determine the rainfall distribution patterns over the country (Malaysian Meteorological Services, 2000. To describe the rainfall distribution of the country, it is best to refer to the seasons. There are two main types of seasonal variation in rainfall (Malaysian Meteorological Services, 2000): Over the west of the Peninsular (including Langat, Linggi and Bernam) with the exception of the southwest coastal area, the monthly rainfall pattern shows two periods of maximum rainfall separated by two periods of minimum rainfall. The primary maximum generally occurs in September - December (transition between Southwest to Northeast Monsoon) while the secondary maximum generally occurs in March – May (transition between Northeast to Monsoon Southwest).

The average annual areal rainfalls (52 years record) in the Bernam, Langat and Linggi catchments are approximately 2800 mm (ranging from 2100 to 3400 mm), 2400 mm (1900 mm to 2800 mm) and 2200 mm (1700 mm to 2600 mm), respectively. The highest rainfalls occur in the months of April and November with means of 308 mm and 330 mm for Bernam, 260 mm and 288 mm for Langat and 242 mm and 281 mm for Linggi, respectively. Meanwhile, the lowest rainfall occurs in the month of June with means of 163 mm, 136 mm and 131 mm for Bernam, Langat and Linggi, respectively. A trend of gradual increase in rainfall from the coast towards the hilly headwaters prevails in all catchments.

2.7.3 Temperature distribution and relative humidity

Malaysia has a uniform temperature throughout the year. The annual variation is less than 2°C except for the east coast which is often affected by cold surges originating from Siberia during the Northeast Monsoon. However, the daily range of temperature is large, from 5°C to 10°C at coastal stations and from 8°C to 12°C at inland stations (Malaysian Meteorological Services, 2000).

Seasonal and spatial temperature variations are relatively small. In most places, April and May are the months with the highest average monthly temperature and December and January are the months with the lowest. The annual mean minimum temperature for Bernam, Langat and Linggi ranges from 23.7°C to 25.5°C. While, the annual mean maximum temperature ranges from 28.1°C to 35.1°C. Peninsular Malaysia has high humidity. It varies from place to place and month to month depending on the monsoons. The range of mean relative humidity varies from 84% in February to 88% in November.

2.7.4 Sunshine, solar radiation and evaporation

Peninsular Malaysia naturally has potentially abundant sunshine because of its situation close to the equator. However, cloud cover reduces considerably the amount of sunshine and, therefore, solar radiation. On average, Peninsular Malaysia receives about six hours of bright sunshine per day (Malaysian Meteorological Services, 2000).

Cloud cover and temperature are two of the most important factors affecting the rate of evaporation and both are related to each other (Malaysian Meteorological Services, 2000). A cloudy day will mean less sunshine and thus less solar radiation, and in turn, this gives rise to lower temperatures. Evaporation records from the Department of Meteorology show that the cloudy or rainy months are the months with lower evaporation rates, while the dry months are the months with higher rates. For highland areas, such as the Cameron Highlands in Pahang, where the air temperature is considerably lower, the potential evaporation rate is proportionately low at about 2.5 mm per day. Meanwhile, most lowland areas have an average potential evaporation rate of 4 to 5 mm day^{-1} (Malaysian Meteorological Services, 2000). The average daily evaporation rates for stations close to the Bernam, Langat and Linggi catchments are 3.9 mm day^{-1} (1997-2001), 4.8 mm day^{-1} (1972-2002), and 4.0 mm day^{-1}, respectively.

2.7.5 Overview of El Nino and La Nina phenomena

The El Nino phenomenon is a seasonal eastward invasion by the warm South Equatorial ocean current off the Pacific coast of South America that over-rides and displaces the cold Humboult current. During this invasion, atmosphere stability is massively affected, leading to the phenomenon known as El Nino-Southern Oscillation (ENSO) (Kane, 1999). El Nino is a term now used to refer to the more pronounced weather effects associated with the periodically anomalous warm sea surface temperatures and their interaction with the overlying air in the eastern and central Pacific Ocean (Severov *et al.*, 2004). El Nino is an irregular cyclicity of shifts in ocean and atmospheric conditions that affects weather and climate around the globe (Shrestha and Kostaschuk, 2005). Among the effects are increased rainfalls across the southern USA, Ecuador and Peru, which causes destructive flooding, and severe droughts in countries such as Malaysia, Indonesia, Australia, and southern Africa. It can induce conditions that encourage the spread of devastating forest fires, especially in Southeast Asia. A significant reduction in rainfall in the tropical environment will impact on the amount of water in the river system. Several studies such as those of Dettinger et al. (2000) Chiew and McMahon (2002) and Gutierrez and Dracup (2001) have shown significant relations between ENSO events and streamflow at global and local scales.

Meanwhile, according to Kane (1999), an unusually cold ocean temperature in the tropical Pacific has caused the La Nina phenomenon. The shift from El Nino conditions to La Nina and back again takes about four years (Cane, 2005). Understanding this irregular oscillation and its consequences for global and local climate has become important in recent decades as scientists have begun to unravel the complicated relations between ocean and atmosphere that have an impact on water relation within tropical environments. A detailed examination of the influence of El Nino and La Nina on amount of rainfall within the Malaysian study catchments can be found in **Chapter 6** (sub-section 6.2.2 Annual Rainfall).

2.8 The influence of land use change on water yield and water quality

Geist and Lambin (2002) have developed a comprehensive conceptual framework for land use change in the tropics and the factors driving such change, based on the analysis of 152 case studies of tropical forest cover loss. This framework helps in the understanding of the impact of land use on water yield and water quality in the tropics (**Figure 2.3**). They concluded that the loss of tropical forest is determined by different combinations of "proximate" and "underlying" driving forces. So, a universal policy for controlling tropical deforestation will not be effective. They define "proximate" forces as human activities at the local level that have a direct impact on forest cover. Examples of such "proximate" forces are wood extraction, agricultural expansion and infrastructure expansion.

They also stressed that "other factors" have an important role in driving deforestation. Of these, there are pre-disposing environmental factors (e.g. the characteristics of land, including soil quality and topography), biophysical drivers or triggers (e.g. fires, droughts, floods and pest outbreaks) and social triggers (e.g. revolution, social disorder and economic shocks). According to their studies, agricultural expansion was the leading driver associated with all cases of deforestation. Wood extraction was the second most frequent proximate cause of deforestation, followed by infrastructure expansion and other factors. All these factors are interrelated and do not operate in isolation. For instance, in only 4% of the cases did a single factor (agricultural expansion) alone explain the deforestation, while in 30% of the cases two factors were found to be significant (mostly agricultural expansion and wood extraction).

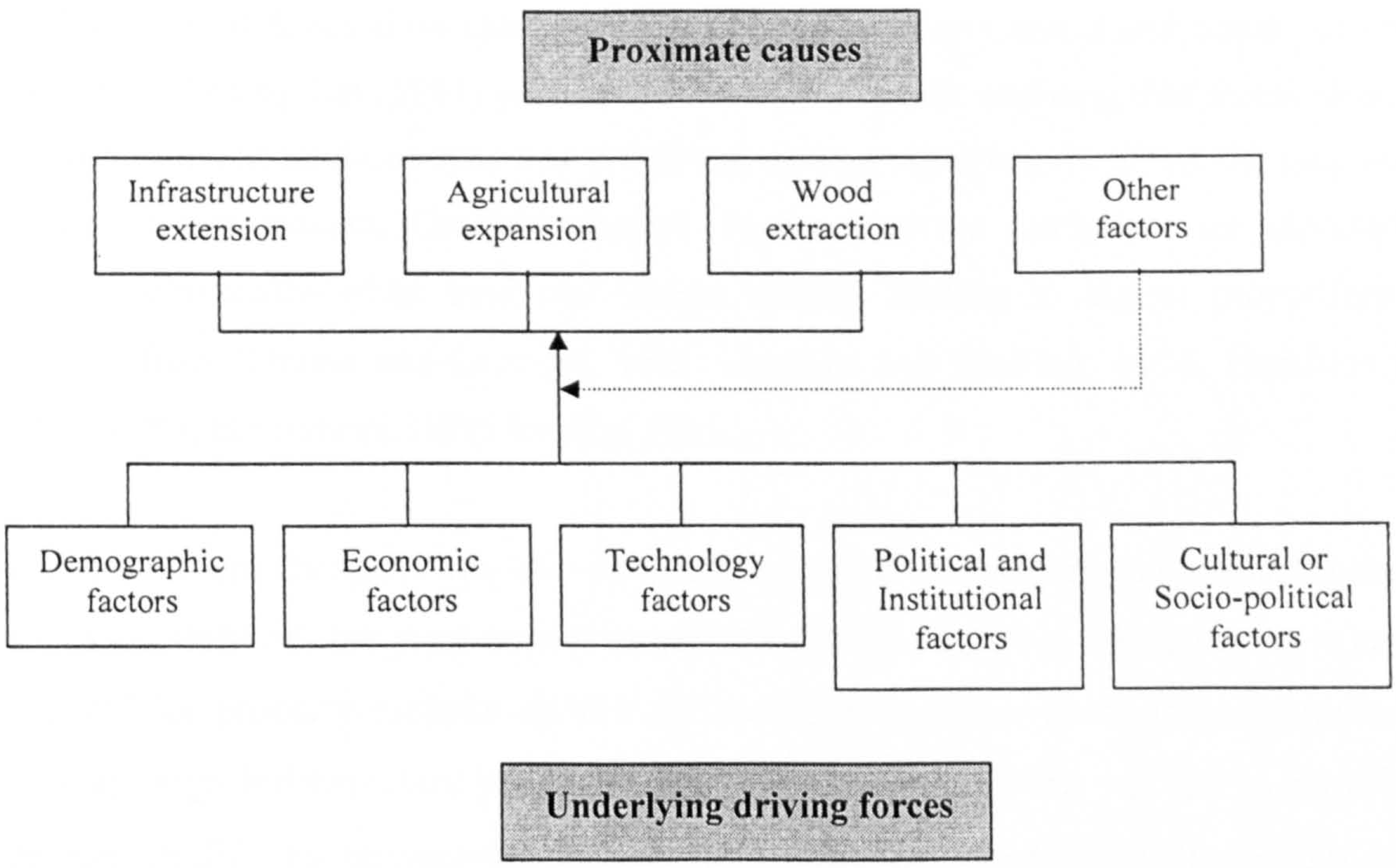


Figure 2.3: Five broad clusters of underlying driving factors supporting the causes of deforestation (Lambin and Geist, 2001)

Meanwhile, Geist and Lambin (2002) define underlying driving factors such as human population dynamics or agricultural policies as a fundamental social process, which strengthens the proximate cause and normally operates at the local level. According to Geist and Lambin (2002), there are five underlying driving factors which support the proximate causes of deforestation: (1) demographic, (2) economic, (3) technological, (4) policy and institutional and (5) cultural. The most frequent underlying driving factors are policy and institutional factors, followed by technological, cultural socio-political, economic and demographic factors. As a conclusion to their studies, Geist and Lambin (2002) stressed that deforestation has been regarded as a one-sided process, whereby little or no attention has been given either to the land-use types that were replacing the forests or to the factors driving that replacement.

As we have known for a long time, land use is one of the key parameters in the hydrologic cycle (Giertz *et al.*, 2005). The impact of land use change on hydrological processes in the tropics was investigated, particularly in terms of rainforest conversion, during the 1980s and 1990s. Most studies such as Abdul Rahim and Baharuddin (1986), Abdul Rahim (1988), Bonell (1993; 1998), Bruijnzeel (1990; 1992), Malmer (1996) and Zulkifli (1989) focused on catchments in tropical Asia or Central and South America. Earlier studies by Lal (1981) presented data from Nigeria, showing that forest clearing, the replacement land-use type and the tillage system significantly affect the magnitude of runoff and erosion. The hydrological responses of the catchment are expected to change drastically when land use change occurs, leading to higher proportions of surface flow (Dunne and Leopold, 1978; Gregory and Walling, 1973; Hamilton and King, 1983; Bruijnzeel, 1990; Ruslan, 1995).

Rapid land use changes such as deforestation, agricultural expansion and urbanisation are associated with the good economic performance of a country, which results in strong demand for property projects as well as the urgent need for quick implementation of various large infrastructure projects. Such alteration in land use has led to significant changes in different components of the water balance of river basins. The magnitudes of such effects are dependent on numerous interacting factors, such as rainfall amount and its distribution, the land use implemented and its intensity, soil properties, terrain characteristics and the management systems implemented (Lal, 1993). Watersheds with large amounts of impervious cover may experience an overall decrease in groundwater recharge and base-flow and an increase in stormflow and flood frequency (Lazaro, 1990). This requires various countermeasures to monitor the urban land development and water resources management, which is strongly affected by climatic and socio-economic conditions as well as institutional planning.

2.9 Hydrological impact of watershed disturbances in tropical regions

Most of the discussion about the impact of land use changes on water yield and water quality in this section comes from experimental catchment studies from various places in the tropical and temperate climate zones. Comparisons are made based on long-term observations by researchers. The experimental studies have been regularly carried out on small catchments where the manipulation of the vegetation over the whole catchment is feasible for experimental purposes (Siriwardena *et. al*, 2006). Zhang *et al.* (1999)

reported that the mean size of experimental catchment is about 1.25 km^{-2}, with 73% from his review being less than 1 km^{-2}. Archer and Newson, (2002) also indicate that normally the catchment size is less than 25 km^{-2}, and frequently less than 1 km^{-2}. From these experiments, considerable changes to catchment runoff due to treatments such as forest conversion to agriculture/pasture or the aforestation of grassed catchments have been reported. All of these studies indicate that the land use change within a watershed will have a significant impact on the water yield and water quality.

There are substantial studies carried out by researchers such as Wilk *et al* (2001) in Northeast Thailand, and Costa *et al* (2003) in south-eastern Amazonia with larger catchments 12,199 km^{-2} and 175,000 km^{-2}, respectively. However, due to non-uniform variations in land uses over the catchment, regeneration with various stages of vegetation and spatial and temporal variation in rainfall, the conclusions of the studies from large catchment data are inconsistent.

2.9.1 Forest and plantation conversion activities

Studies concerning the impact of natural forest conversion on hydrological response have been extensively conducted in both temperate and tropical experimental catchments with the main focus being on runoff and flow regime (Bosch and Hewlett, 1982; Oyebande, 1988; Bruijnzeel, 1990; Bonell with Balek, 1993; Bruijnzeel and Proctor, 1995). Most of these studies have demonstrated increases in streamflow discharge or runoff after complete or partial forest removal in highland areas. In a site with substantial rainfall, a complete removal of forest cover during the first year will increase the streamflow by between 125-800 mm yr^{-1} (Bruijnzeel, 1990; 1996). Since precipitation is the most variable element in tropical climates, both annual and inter-annual variations in mean rainfall should be considered when interpreting the hydrological process-response due to land use change (McGregor and Nieuwolt, 1998).

Forests play a significant role in hydrological processes in the humid tropics as they can intercept a higher amount of rainfall than agricultural crops. The forest floor has an abundance of organic matter and a relatively large proportion of retention pores in the soil profile. Therefore, forest soils have much higher infiltration rates and slightly higher moisture storage capacities than soils under crops or bare ground (Bruijnzeel, 2002a). A conversion of forest to other land use is usually accompanied by an increase in surface runoff and/or streamflow, decreased infiltration due to soil compaction (which would lower the water table), higher peak flows and earlier peaks in stream floods which may lead to greater flood damage downstream (Bruijnzeel, 1990; Calder, 1992; Chang and Lau, 1993).

Tropical deforestation has been an important issue over the past few decades. Commonly, national and international policymakers attribute deforestation to a rapidly growing population of shifting cultivators who are hungry for new land, while another view, often held by environmentalists, blames corporate greed (Lambin and Geist, 2003). Land-cover change has long been viewed as being continuous, but in fact it is a disjointed process, with periods of rapid change and stasis (Lambin and Geist, 2001). An example of stasis is the exceptional economic crisis in 1997 that struck Southeast Asia, with Indonesia and Malaysia among the countries most badly affected. There was a significant decrease in development activity such as urbanization, infrastructure construction and industrialization.

Some of results from the studies are outlined in **Tables 2.2** and **2.3,** meanwhile the major finding from land-use change studies on water relations were summarized by Lal (1983) and Bruijnzeel (1990) as tabulated in **Table 2.4** (cited from Lal, 1993).

Table 2.2: Annual runoff as influenced by deforestation and change in land use

No.	Land use	Country	Year of observation after land use change	Change in annual runoff (% or mm yr^{-1})	References
1.	Selection logging	Malaysia	3rd	+ 44 - 72%	Baharuddin (1988)
2.	Clear-cut logging	Taiwan	3rd	+ 204-448 mm	Hsia (1987)
3.	Plantation crops				
	i) Cocoa	Malaysia	4th	+ 158 %	FRIM (1987)
	ii) Oil Palm	Malaysia	4th	+ 470 %	DID (1989)
	iii) Tea	Kenya	6th	+ 150-300 mm	Blackie (1979)
	iv) Bamboo	Kenya	7th	+ 150-300 mm	Blackie (1979)
	v) *Eucalyptus*	Guyana	3rd	+ 40 mm	Fritsch (1993)
	vi) *Pinus*	Guyana	3rd	+ 210 mm	Fritsch (1993)
4.	Arable land use				
	i) Seasonal crops	Nigeria	3rd	+ 140mm	Lal (1983)

Source: Modified from Bruijnzeel (1990)

Table 2.3: Peak flow and storm flow volume as influenced by change in land use

No.	Land use	Country	Storm Flow Volume (mm yr^{-1} or %)	Peak Flow (%)	References
1.	Clear-cut logging	Taiwan	No significant change	+ 48 %	Hsia (1987)
2.	Plantation to				
	i) Eucalyptus	Guyana	+ 330 - 410 mm	-	Fritsch (1993)
	ii) to Pine	Guyana	+ 385 - 495 mm	-	Fritsch (1993)
	iii) Cocoa	Malaysia	- 26 to 21 %	+ 280 %	FRIM (1987)
	iv) Oil Palm	Malaysia	+ 19 to 37 %	+ 17 -65 %	DID (1989)
3.	Grassland to				
	i) Pasture	Guyana	+ 235 mm	-	Fritsch (1993)
4.	Arable				
	i) Mechanized farming	Nigeria	Increase	Increase	Lal (1983)
6.	Natural forest to Acacia plantation	Malaysia (Sabah)	- 30% 2nd year		Malmer (1993)
6.	Forest fire succession to poor Acacia plantation	Malaysia (Sabah)	+ 35% 1st yr + 83 % 2nd yr + 76 % 3rd yr	+ 68 % 1st yr + 111 % 2nd yr + 58 % 3rd yr	Malmer (1993)
7.	Natural forest to shifting cultivation	Guyana	+ 25 % 2nd yr + 30 % 3rd yr		Fritsch (1993)

* Eucalyptus plantation was established on degraded scrub land

Source: After Bruijnzeel (1990), Malmer 1993 and Fritsch (1993)

Land conversion activity	Impact on water relations
Forest to arable land use (Hamilton and King, 1983)	• Increases the frequency and rate of peak flow • Increases duration and amount of interflow • Increases total annual discharge or runoff • Increases flooding from source area contribution • Raises ground water levels • Decreases the soil water storage in the surface layers
Selective logging (Bosch and Hewlett, 1982)	• Little long-term effect on discharge and runoff rate • Drastic initial increase in water yield including high overland-flow and interflow • Lead to transient change in landscape stability • Causing mass wastage and high sediment load in overland flow
Aforestation of scrubland (Bruijnzeel, 1990)	• Decrease water yield • Decrease peak flow rates and total annual discharge • Decrease interflow volume and rate • Decrease rill-interrill erosion • Decrease landscape stabilize and reduce mass wastage
Forest to crop land and grazed pastures/grasslands (Lal, 1983, 1987; Roose, 1977, Wiersum, 1984)	• Increase sediment erosion • Increase dissolved load in surface runoff and interflow • Accentuate soil compaction and structural degradation • Decrease soil organic matter, species diversity and activity of soil fauna

In terms of watershed functions, the type of land use that replaces forest is more important than the deforestation itself. If the infiltration and water-holding capacity of the soil are reduced, it is likely that dry-season flows will be affected (Lal, 1996). Any land use change or forest disturbance at this time will reduce the current water level and cause water quality deterioration, especially when the concentrations of pollutants in the water body are high (Abdul Rahim and Zulkifli, 1994). As forests have higher evapotranspiration rates than most other land use types, including agro-forestry systems, the balance between reduced evapotranspiration on one hand, and lower infiltration on the other, will determine the final outcome of deforestation and land use change (Calder, 1998; Bruijnzeel, 2004). Deforestation has regularly contributed to large-scale flooding, landslides, sedimentation and water quality deterioration, as the other factors, such as urbanization and the construction of roads (Enters, 1998; Calder, 1998).

Increased occurrences of landslides and flash floods have also been associated with widespread removal of natural forest cover for the purpose of land use transformation in the highlands. In most cases, flood flow increase is actually caused by soil compaction and reduced infiltration, rather than vegetation removal (Balamurugan and Mohd Razali, 1999). There is also evidence suggesting that logging operations, as distinct from deforestation, cause changes in flood peaks, flood volumes and flood frequencies. These changes are due to soil compaction, which decreases infiltration opportunity, causing an increase in overland flow (volume and velocity) and, as a consequence, the flood potential is increased (Toebes and Seng, 1975). Improvement in logging practices along with better harvesting methods which incorporate conservation measures (i.e. retention of buffer strips of forest and properly designed forest roads) will help to reduce these effects. Lal (1983) showed that 6.5 % of rainfall was produced as runoff when a catchment was cleared mechanically (tractors with shear blades). In the Tekam River experimental drainage basins in Peninsular Malaysia, the clearing of the lower 0.97 km^{-2} of a 1.34 km^{-2} basin led to increases in runoff of 85% (110 mm yr^{-1}), 142% (155 mm yr^{-1}) and 97% (137 mm yr^{-1}) from the first to third years respectively. When the remaining 0.37 km^{-2} portion was cleared in year four a 420% increase occurred (Abdul Rahim, 1988). Researchers have different opinions regarding the role of the forests in preventing floods downstream. Abdul Rahim and Zulkifli (1999) claimed that flooding characteristics are definitely affected by the removal of forest cover but only at local level within catchments of less than 500 km^{-2}.

Suspended sediment loads within a river basin mainly depend on climate (i.e. rainfall characteristics), geology (i.e. surfaces rocks), vegetation cover, local topography, soil properties, catchment morphology, drainage network, land use and human activity (Woodward and Foster, 1997; Walling, 1999; Hovius, 1998; Foster and Lees, 1999; Douglas and Guyot, 2005). Rates of erosion measured at a catchment's outlet are termed 'sediment yield'. It will provide useful information about the erosion severity and trends (Lai and Detphanchanh, 2006). Forest canopies, undergrowth and litter layers provide protection for the soil against erosion. Therefore, erosion rates in forested catchments are usually low and associated with natural processes such as channel erosion and natural landslides (Chappell *et al.*, 2005). Removal of protective cover during the conversion of forest or agriculture conversion to other land uses may lead to accelerated erosion and increased sediment yield (Zulkifli *et al.,* 1993). It is commonly assumed that the vegetation cover in tropical forest would largely protect the soil surface from erosion which limits the supply of sediment to a river system. However, as many areas in Southeast Asia (such as Java and Papua New Guinea) are subjected to active tectonics, volcanism, steep slopes and heavy rainfall, they can contribute more than 1000 tonnes km^{-2} yr^{-1} yield to the major rivers (Fletcher, 1996). The extensive deforestation activity in the countries of the region during 1981-1990 (average deforestation rate of 1% per year) also contributed to the increase in soil erosion, therefore increasing the yield in river systems (FAO, 1993).

The implication of land development for sedimentation has been shown in many catchment experiments worldwide (Dykes and Thornes, 2000). Sediment resulting from the erosion of exposed soils is transported by overland flow into the river channels. Alluviation over a long period will eventually lead to a rise in riverbeds, causing a reduction in the carrying capacity of the channel (Ramadasan, *et al.* 1999). Consequently, the ability of river systems to supply water resources are reduced, their efficiency diminished and the costs of maintenance thereby increased. During storm and heavy rainfall events, rivers with critical sedimentation problems often lack the ability to hold and flush out the large amounts of floodwater. This often leads to the overflow of excess water onto the surrounding land, which causes a massive problem for the settlements affected (Ruslan, 2000). However, the downstream effect of development on sediment loads is likely to take a long time to be reflected in a large watershed (Pearce and Watson, 1986).

According to Pearce and Watson (1986) and Purwanto (1999), the production of suspended sediment differs between forest areas depending on their contributing mechanisms; i.e., the degree of disturbance. There is an increase in sediment load entering the river system as a function of land development, especially with urbanisation and the early conversion to agricultural areas in humid tropics and temperate regions as reported by many researchers. This is including catchments in Malaysia, such as 2826 tonnes km^{-2} yr^{-1} in Batangsi (20 km^2 - deforestation), 2476 tonnes km^{-2} yr^{-1} in Chongkak (13 km^2 - deforestation), 1600 tonnes km^{-2} yr^{-1} in Segama Baru (0.6 km^2 - deforestation), 431 tonnes km^{-2} yr^{-1} in Segama Jauh (1.5 km^2 - deforestation), 3100 tonnes km^{-2} yr^{-1} in Relau (12 km^2- agriculture and urban), 1076 tonnes km^{-2} yr^{-1} in Ayamut (1 km^2- agriculture and urban) and 472 tonnes km^{-2} yr^{-1} in Terjun (9 km^2- agriculture and urban), reported by Lai (1992), Lai (1992), Douglas *et al.* (1992), Douglas and Bidin (1994), Sinun (1991), Ruslan (1995), and Ruslan (1995), respectively. Meanwhile, Douglas (1975) reported that a catchment, with 23% of its area possessing urban surfaces, in Dumaresq (84 km^2), Australia recorded 3829 tonnes km^{-2}yr^{-1}, whilst an urbanizing suburban area of Tokyo (0.5 km^2) recorded 25414 tonnes km^{-2} yr^{-1} (Kinosita and Yamazaki, 1974), and a 100% disturbed area in Tahiti (0.1 km^2) recorded 7300 tonnes km^{-2} yr^{-1} (Wotling *et al.*, 2000). In a developed catchment in Bradford, UK (58 km^2), Old, et al. (2006) reported that the specific sediment yield at the upstream station was 80 tonnes yr^{-1} km^{-2}, while it was 40 tonnes km^{-2} yr^{-1} at the downstream station. These values are comparable to the value of > 100 tonnes km^{-2} yr^{-1} suggested by Walling and Webb (1996) for a small- and intermediate-sized catchment. Foster *et al.* (2002) also suggest a similar range where the agricultural land drains contribute more than 50% of the sediment yield within small (1.5km^2) UK catchment. Sediment yield decrease in a downstream direction in UK rivers is related to the interception process by the sewer system. Conversion from natural forest to rubber and palm oil plantations is common in Southeast Asia. It has been reported that the level of sediment yield will decrease to a natural condition when groundcover vegetation is re-established (Fletcher, 1996).

It can be clearly seen that for a small-sized catchment, the suspended sediment yield is significantly higher than a larger catchment, as a part of the sediment was deposited during transportation downstream. Catchments possessing relatively small mountain-headwater areas and relatively large lowland areas, such as the African Congo (3820 x 10^3 km^{-2}), record comparatively low sediment yields of below 100 tonnes km^{-2} yr^{-1}. Meanwhile, in catchments where elevation exceeding 1000 m is combined with high rainfall (averaging at least 3000 mm yr^{-1}), such as in Papua New Guinea and Taiwan, the yield will exceed 1000 tonnes km^{-2} yr^{-1} (Douglas and Guyot, 2005). In small, undeveloped, tropical rainforest catchments in Malaysia, such as Telom (77 km^2), Mupor (22 km^2), Gombak (140 km^2), Kalangan (3 km^2), Lawing (5 km^2), and Segama S5 (1 km^2), the yields are 53, 41, 97, 15, 54, and 312 tonnes km^{-2} yr^{-1}, respectively (Shallow, 1956; Leigh, 1982; Douglas, 1975; Sinun *et al.*, 1992; Lai, 1992; Ruslan, 1995; Douglas *et al.*, 1992; **Figure 2.4**). However, the forested catchments of Ok Ningi (4.6 km^2) and Ok Tedi (420 km^2) of Papua New Guinea recorded yield at 10 746 and 7857 tonnes km^{-2} yr^{-1}, respectively, as a function of higher relief and rainfall (Pickup *et* al., 1981). The sediment loads recorded at downstream locations reflect the amount of erosion and deposition process within river catchment. As the catchment size increases, the depositional process increases relatively (Hovius, 1998). This inverse relation between sediment yield and drainage basin area has been reported by many researchers, such as Walling and Webb (1981), Milliman and Meade (1983), Foster and Lees (1999) and Restrepo and Kjerfve (2004). However, Trimble (1981) and Dunne (1979) stated that the extensive storage of sediment in some tropical and sub-tropical catchments is not feasible for catchments smaller than 2000 km^2.

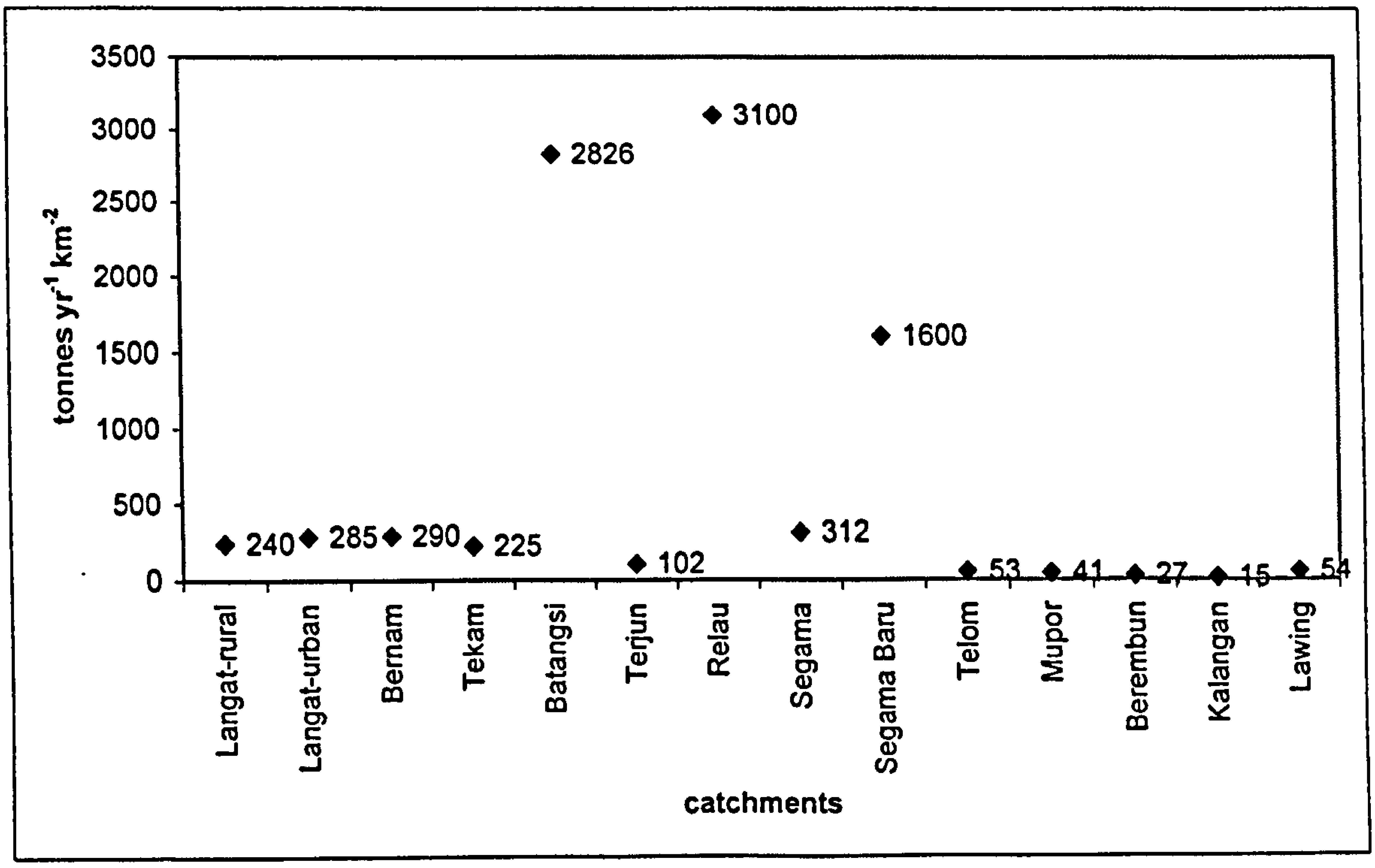


Figure 2.4: Distribution of sediment yield within Malaysian's catchment

2.9.2 Urban development

Urban hydrology has an increasing role to play in the sustainability of human societies because the growth of urban areas brings significant changes in the physical properties of the land surface (Sanders, 1986; Niemczynowicz, 1999). Various infrastructure developments in urban areas bring an additional need for flow monitoring. In fact, any construction of urban, water-related infrastructure must be well planned and based on good knowledge in order to understand the expected effects of these structures on water flows in order to avoid/reduce damage to the man-made constructions.

The study of the relationship between water resources and urbanization is not new and has focused on the impact of land use change on streamflow discharge, runoff volume, peak runoff, channel dimensions and stormwater quality (Tang *et.al.*, 2005; White and Greer, 2006). Urban hydrology may be referred to as the study of hydrological processes both within and outside the urban environment that are affected by urbanization. The particular aspects of urbanization that have most obvious influence on hydrological processes are the increase in population density and the increase in building density within the urban area (Hall, 1984). Hall has described the consequences of such changes as shown below (**Figure 2.5**).

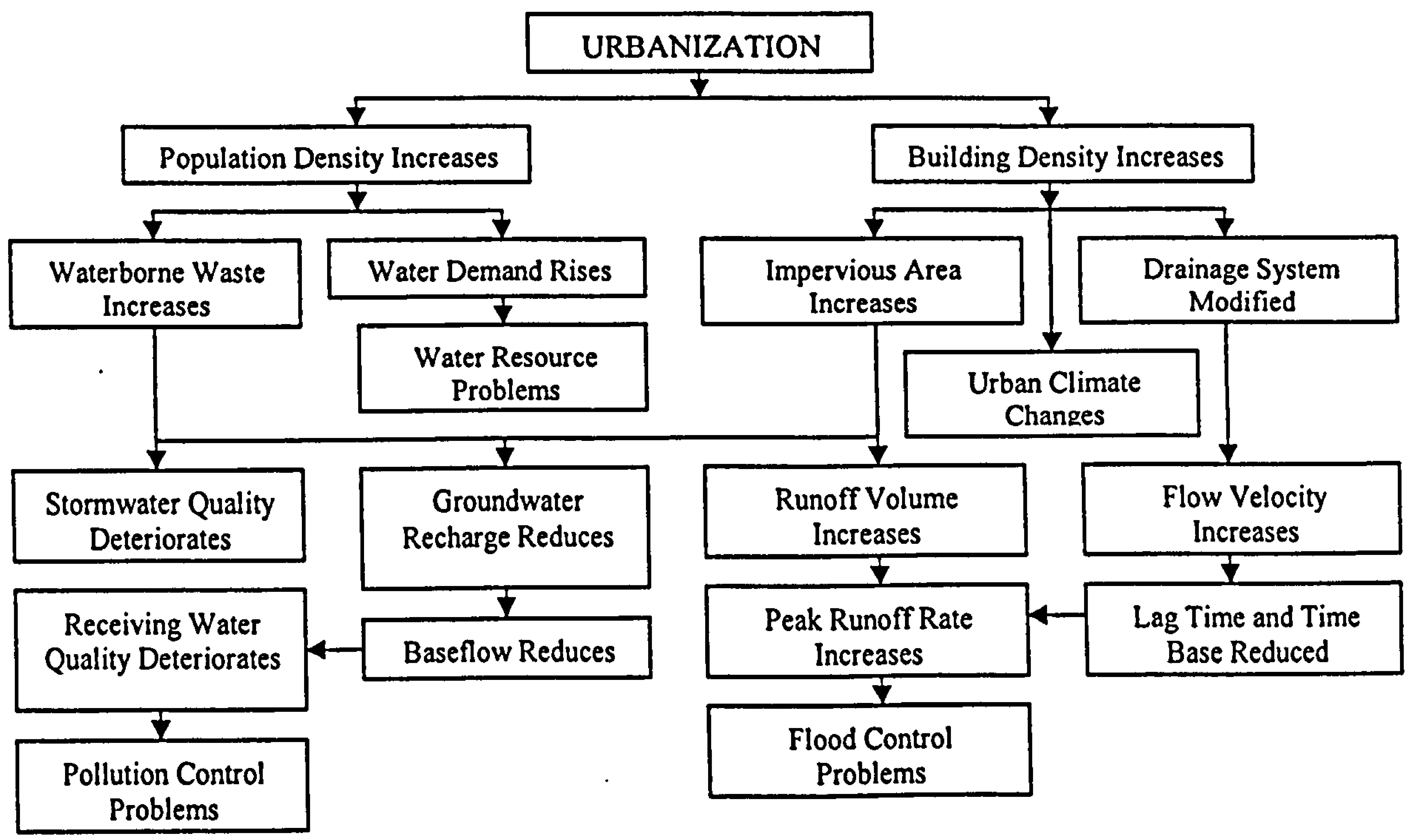


Figure 2.5: The effects of urbanisation on hydrological processes (Hall, 1984)

It is clear that urbanization processes within a watershed create a new hydrological environment by replacing the natural surfaces (changes of land cover) such as forest and soil with artificial surfaces such as asphalt. These changes tend to increase the area of impervious surfaces (Paul and Meyer, 2001), decreases infiltration of precipitation and increases runoff in proportion to the cover (type, extent, porosity etc) of the impervious surface (Dunne and Leopold, 1978; Douglas, 1983; Hall, 1984; Gordon *et al.*, 1992; Leopold, 1994; Arnold and Gibbons, 1996). This statement was support by White and Greer (2006) who investigated the effects of watershed urbanization on the streamflow characteristics of Los Penasquitos Creek, in coastal southern California. They found that the runoff increases between 200 to 500% when impervious surface cover exceeds 10% of the watershed (Arnold and Gibbons, 1996; Paul and Meyer, 2001). The total runoff increased by an average of 4% per year as urbanization increased from 9% to 37%, representing an increase of over 200% from 1973 to 2000. In this study, the impervious cover has been occupied by small-lot residential, industrial, and commercial land uses, which represent 40–95% of urbanization areas. In addition, Mykura (1989) found that a built up business centre and industrial area with 90% and 80% impervious surfaces, respectively, have 0.90 and 0.80 runoff coefficients compared to residential areas. When natural land is altered by human activities, rainfall that used to be absorbed into the ground now must be collected by storm-sewers that convey the runoff into local streams. These streams may not have the capacity to handle the artificially inflated amounts of runoff. Reduced infiltration of precipitation to groundwater aquifers may reduce groundwater recharge and stream base-flow (Hollis, 1975; Packman, 1979; Paul and Meyer, 2001). Reductions in base-flow can cause a decline in water quality as pollutants become more concentrated and degrade riparian habitats as water levels decrease (Chan, 1997).

Urbanization also increases storm runoff, peak discharges and flood magnitudes and decreases lag time and time to peak (Dunne and Leopold, 1978; Hall, 1984; Ithnin, 1992; Niemczynowicz, 1999). Increases in flood magnitudes are greater for floods with shorter recurrence intervals than those with long recurrence intervals (Hirsch *et al.*, 1990). This statement was corroborated by White and Greer (2006) who also reported that for return intervals of >5 years, flood magnitude was always highest during 1988–2000 the period of high (more than 25%) urbanization and lowest during 1965–1972 the period of low urbanization (less than 15%) urbanization and intermediate during 1973–1987, the period with moderate urbanization (15-25%). For example, the estimated 1-in-2-year flood was 6.41 m^{-3} s^{-1} during the period 1965–1972, 20.86 m^{-3} s^{-1} during the period 1973–1987, and 35.67 m^{-3} s^{-1} during the period 1988–2000. Due to increased urbanization, they have estimated that the floods return intervals of 1.5–3 years, have increased from 350% to over 700%, however, the influence of urbanization on flood magnitude appeared to diminish with increasing return intervals. Tetzlaff *et a.* (2005) in their study at small developed catchment in Schwarzbach, Germany, also suggests an increase in flow acceleration in urban impacted catchment between 78% (54 km^{-2}) and 250% (1.8 km^{-2}), where the physical catchment characteristics, e.g. mean slope and mean elevation causes a high value in flow acceleration.

A study by Old *et al.* (2006) in the steep and heavily urbanised catchment of Bradford Beck (58 km^{-2}), West Yorkshire also strengthened the previous statement about the increase of peak discharge due to urbanisation. They found that the flow regime is 'flashy' especially from Middlebrook gauging station downstream, which reflects the area's highly urban nature where more than 35% of the annual flow significantly occurs in the short time of 10% of the year. Specifically, the outlet gauging station (Shipley Weir) recorded 12.3% of annual flow in just 1% of the year, compared to the 9% occurring at Middlebrook. The extreme response of flow to rainfall at sites in the urbanised part of the catchment is typical where the urbanised part of the catchment was effective in enhancing the proportion of annual flow due to changes in land cover. For example, a study of small urban watercourses in north London by Mullis *et al.* (1996) observed that there were high correlations between precipitation volumes and total storm discharge (0.91) and the duration of storm flow (0.93) due to urbanization.

However, the runoff yield for the urbanised part of the catchment was only 260 mm yr^{-1}, which is significantly lower than expected due to its being intercepted by the combined sewer system prior to reaching the outlet at Shipley Weir. Meanwhile, the suspended sediment yield (wet year) recorded at Shipley Weir is 40 tonnes km^{-2} yr^{-1}, which is half of the 80 tonnes km^{-2} yr^{-1} yield at the Middlebrook station. This value is comparable with the suggested value of > 100 tonnes km^{-2} yr^{-1} for small and intermediate stations in upland areas and the typical value for United Kingdom rivers of 50 tonnes km^{-2} yr^{-1} described by Walling and Webb (1987). Sediment yield decreases in a downstream direction in United Kingdom rivers, as explained by Old *et al.* (2006) as a function of the sewer system, which intercepts the sediment before it reaches the outlet. Therefore, the understanding of the spatial and temporal variations in flow and the transport of suspended sediment is important in order to achieve the effectiveness of river monitoring and management.

As much of the urban areas are covered by artificial surfaces, there is an increase in level of heavy metals contaminants to receiving waters as typical, non-point source pollution (Macdonald *et al.*, 1997). Urban impervious surfaces such as highways, roads, streets and parking lots were recognized as the major metal contributing areas, where heavy metal emissions from urban transportation are deposited onto these surfaces and transported to receiving waters through surface runoff (Sartor *et al.*, 1974; Morrison *et* *al.*, 1984). It was found that in the highly urbanized watershed of Vancouver, Canada, the flow increased over the storm event, and similar concentration trends were observed for total zinc and the total suspended sediment in the stormwater (Yuan *et al*, 2001). However, the amount of heavy metal released into the water body are dependent on rainfall volume, rainfall intensity, catchment size and slope, and the antecedent dry period length since the last rain (Sonzogni *et al.*, 1980; Macdonald *et al.*, 1997). Yuan *et al*, (2001) also suggested that the road pollutant wash-off was generally assumed to be a function of the amount of pollutants on the road surface at the time of the storm, and the rainfall intensity. This particular factor shows the importance of the availability of vegetation cover within an urban catchment to intercept the rainfall, therefore, the amount of pollutant entering the river system could be minimized. The increasing urban population also contributes to the higher domestic waste release to the river especially after rainfall events. The increment can also be caused by overflow septic system drainage and leaky water or sewage pipes (Hirsch *et al.*, 1990; Konrad and Booth, 2002; Greer and Stow, 2003).

As corroboration, Ren *et al.* (2003) examined the rate of urbanization and the changing pattern of land use in Huangpu River; Shanghai, between 1947 and 1996 over a period of eight census years based on historical records as well as collected samples. The analysis revealed that an increase in urban area from 111.8 km^{-2} in 1947 to 269.9 km^{-2} in 1996 has corresponded to the rapid degradation of water quality (physical and chemical parameters) where the classification index increased from two (slightly polluted) to the maximum of four (very polluted). These figures were recorded at the outlet station. This is in contrast to the period of slow urban growth in the period 1964-1979 when the water quality classification only recorded at level one (clean). There is also a positive correlation between the proportion of urban land-use (such as residential and industrial buildings) and worsening water quality classification with r^2 values of 0.92 and 0.89 respectively. It appears that land use is an important contributor and explaining factor regarding water quality in Shanghai. Therefore, the management of land with respect to its development and use needs to be addressed in any attempt to mitigate the further degradation of water quality along the river.

2.9.3 Agriculture activity

Giertz *et al.* (2005) have conducted a study in a small catchment (Aguima catchment, 30 km^2) in central Benin to analyse the effects of changes in agricultural land use on the hydrologic processes and soil properties. The following effects have been identified:

i. Increase of surface runoff and soil erosion.
ii. Reduction of macroporosity and therefore reduction of saturated hydraulic conductivity as well as the infiltration rate.
iii. Reduction of soil thickness on slopes and therefore reduction of water storage capacity.
iv. Reduction of evapotranspiration and soil water withdrawal and therefore higher soil moisture.

All above mentioned effects cause higher discharge volumes in catchments with agricultural land use. Bruijnzeel (1990) already reported that the discharge volume after land conversion in the humid tropics is significantly higher and could be to up to 800 mm/yr on top of annual yield after removal of more than 33% of forest cover. This was confirmed by comparing the discharge volume of two sub-catchments of the Aguima catchment (Benin, West Africa) with different land uses (upper Aguima catchment: mainly savannah and forest, upper Niaou: mainly agricultural land). In the relatively dry year of 2001, the annual runoff was over 120 mm^{-a} higher in the catchment with agricultural land use than in the catchment with natural vegetation for which a total value of only 23 mm^{-a} was observed. For the wetter year of 2002, the difference is about 74 mm yr^{-1}, which is still 68% higher for land under agriculture than under natural vegetation.

Due to the lower infiltration capacity, the formation of infiltration excess overland flow was more frequent on cultivated than on forested areas at the beginning of the rainy season. On cultivated plots, the annual surface runoff amount was up to 4 times higher than on savannah plots. The maximum runoff amount was detected on cotton fields with 229 mm^{-a} for the year 2002, which is 20% of the annual precipitation. However, the results from the field subjected to hillslopes processes show that the slope length plays a significant role in the amount of overland flow where the surface runoff decreases with increasing slope length due to re-infiltration of surface runoff downhill (Van de Giesen *et al.*, 2000). In the middle of the rainy season (September) the difference of runoff amount between the upper Aguima and the upper Niaou catchments is lower due to the soil being nearly saturated. Therefore saturated overland flow occurs in both catchments. The maximum runoff coefficient for upper Aguima and upper Niaou is 0.21 and 0.25, respectively. These results corroborate with the data from a Nigerian catchment, where a runoff coefficient of 0.25 was obtained by Campling *et al*, (2002).

Studies of the impact of different types of vegetation on runoff and water yield in a sub-humid subtropical climate in Dehradun, India, have been conducted by Narain *et al*, (1998). Over the years, average runoff from cultivated fallow was 38% of the season's rainfall which reduced to 28% under maize, 21% under maize and *leucaena* and 13% under maize and eucalyptus. Narain *et al.* also reported that observed runoff losses from cultivated fallow and maize correspond well with the earlier studies conducted in the region. Bhardwaj *et al.* (1985) reported about 30-35% runoff under maize and 40-50% from fallow land on a 4% slope. Yearly differences are ascribed to variations in the amount and distribution of the rainfall. Wiersum (1985) suggested that runoff reduction under the trees is attributable to the increased interception and infiltration capacity. In an earlier study at Dehradun, eucalyptus canopy intercepted about 12% of rainfall. A reduction in water yield up to about 16% in the first 10 years' rotation of Eucalyptus is also reported from natural grassland in the Nilgiri hills of south India (Samraj *et al.*, 1988). Although these types of vegetation are quite different to rainforest and agricultural crops in Malaysia (rubber, palm oil and cocoa trees), the information about the runoff losses and consumption of water provides a general indication in order to understand the responses in the study catchments.

2.10 Experimental catchment studies in Malaysia

To study the effect of forest conversion on water yield, hydrologists commonly used the experimental catchment approach. In this case, the paired catchment method with manageable sizes of watershed ranges from 10 to 20 km^{-2} or less than 25 km^{-2} is widely used in many countries, including Malaysia (Hewlett, 1982; Abdul Rahim and Zulkifli 2000), in which to apply 'treatment' uniformly. However, the study of small headwater catchments usually subjected to leakage problem (groundwater contribution from neighbouring areas), which could affect the accuracy of the experiment (Bruijnzeel, 1990).

The early experimental catchments in Malaysia in the 1970's, focused on the impacts of forest conversion to commercial crops such as rubber, cocoa and oil palm plantations which took from one to two years. There was no calibration period (Douglas, 1978; Leigh 1978 and Peh 1978). This could limit the findings concerning the impact on hydrology. However, in 1977, DID initiated a proper experimental catchment study at Tekam River, Pahang, in order to measure the impact of forest conversion to cocoa and oil palm trees on hydrological characteristics such as runoff, base-flow, peak flow and sediment yield. This was followed by the Berembun experimental catchments at Berembun Hill Forest Reserve, Negeri Sembilan, in 1979, under the auspices of the Forest Reserve Institute, Malaysia (FRIM) (Abdul Rahim, 1989). This study was focussed on hydrological characteristics, water quality and sediment yield over a period of about 10 years. In a further development, FRIM established another experimental catchment at Tarek Hill Forest Reserve, Selangor, in 1990 for assessing the hydrological impacts of forest plantation establishment (Saifuddin *et al.* 1991).

Other studies have tended to focus on such factors as nutrient losses from forested catchment (Zulkifli *et al*, 2006), surface erosion and sediment delivery in headwater catchment (Lai and Detphachanh, 2006; Sidle *et al*, 2004; Chappell *et al*, 2004; Ruslan, 2000; Lai *et al*, 1999; Douglas and Bidin, 1994; Douglas *et al*, 1992; Lai, 1992), the sediment budget of a reservoir catchment (Ruslan and Malina, 2003), the impact of land use change on ecosystem health and the focus of general environmental impact (waste, noise, air pollution and water quality) due to urbanisation in river basins (e.g. Jamaluddin, 1999; Mansor *et al.*, 2000; Yaakob, 2000; Azizan and Hanim, 2001; Ithnin and Sakke, 2001). However,.there are few studies that document both urbanisation and agricultural activity within a catchment. With this limitation, the information from other tropical river basins is important in order to understand the processes and responses in the study catchments of Langat, Linggi and Bernam.

The literature on tropical catchments reviewed in this study reveals that land use change has an impact on water yield and water quality. However, conclusions have been drawn to date only from work in very small catchments that have been carefully chosen for experimental monitoring. There is a need to explore moderate-sized catchments, since these represent the scale at which multifarious land-use changes arise in response to economic development. It is also a scale at which water resources become important for growing populations. This is where this research attempts to fill gaps in existing knowledge.

2.11 Summary

This chapter has reviewed the literature on physical characteristics of the wet tropical environment, together with an assessment of land development under pressures of economic growth. Information on components of the water-balance within tropical rain forests has been described in detail. A review of our current understanding of the impact of land use change in tropical catchments reveals that work has, so far, been carried out largely on very small basins where land-use and land-use change are not complex. This leaves an important knowledge gap of practical concern to planners i.e. what can be expected of rainfall-runoff in larger catchments subjected to the range of land-use changes commonly found in areas where pressures are exerted by economic development. The next chapter describes the detailed characteristics of the Langat, Linggi and Bernam catchments and assesses the suitability of the developed Langat and Linggi catchments as analogues of the future hydrological response of the Bernam, which is scheduled for major commercial development.

CHAPTER THREE:
PHYSICAL CHARACTERISTICS OF THE STUDY CATCHMENTS

3.1 Introduction

This chapter describes the general physical background of the selected study areas and the techniques used to characterise catchment morphometry. The objective of this chapter is to assess the morphometric similarity of the analogue catchments and the Bernam. Morphometric information is a convenient way of quantifying the similarities between the Langat and Linggi and the Bernam catchments in that a good deal of information can be obtained from published maps and verified using satellite imagery (**Figure 3.1**). The objective is only partially achieved because parameterization has involved simple measures of the drainage net and catchment size and the archived hydrological data contain a number of flaws that limit their usage. Nevertheless, the morphometrics provide a backcloth for assessing the hydrological performance of each drainage basin and a basis for understanding inter-basinal comparisons.

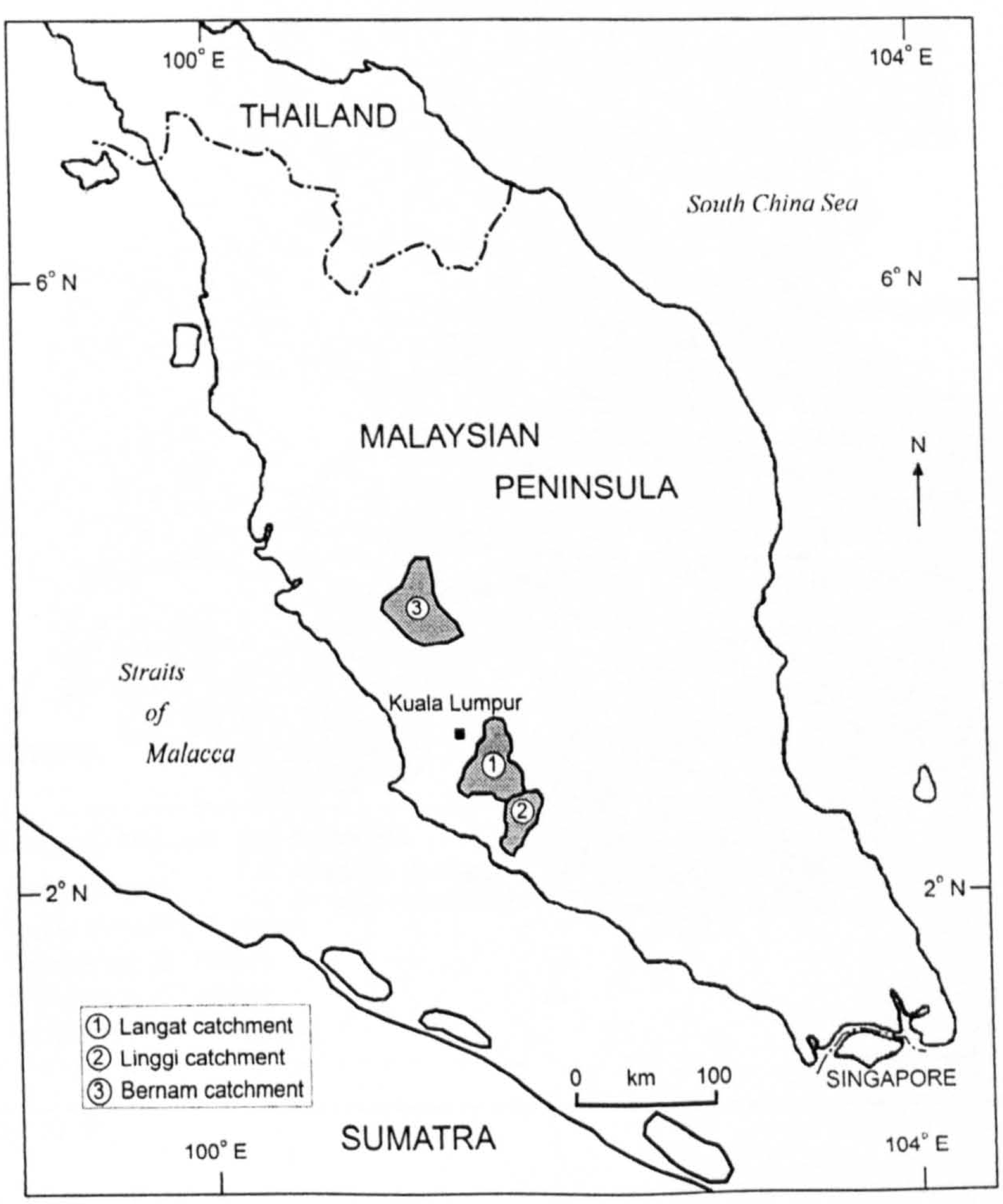


Figure 3.1: Location of study catchments in Peninsular Malaysia

3.2 Physical characteristics of study catchments

3.2.1 Langat catchment

The Langat River Basin is focussed on the outlet gauging point at Longitude 101° 45'E and Latitude 02° 52'N on the West Coast of Peninsular Malaysia (**Figure 3.2**).

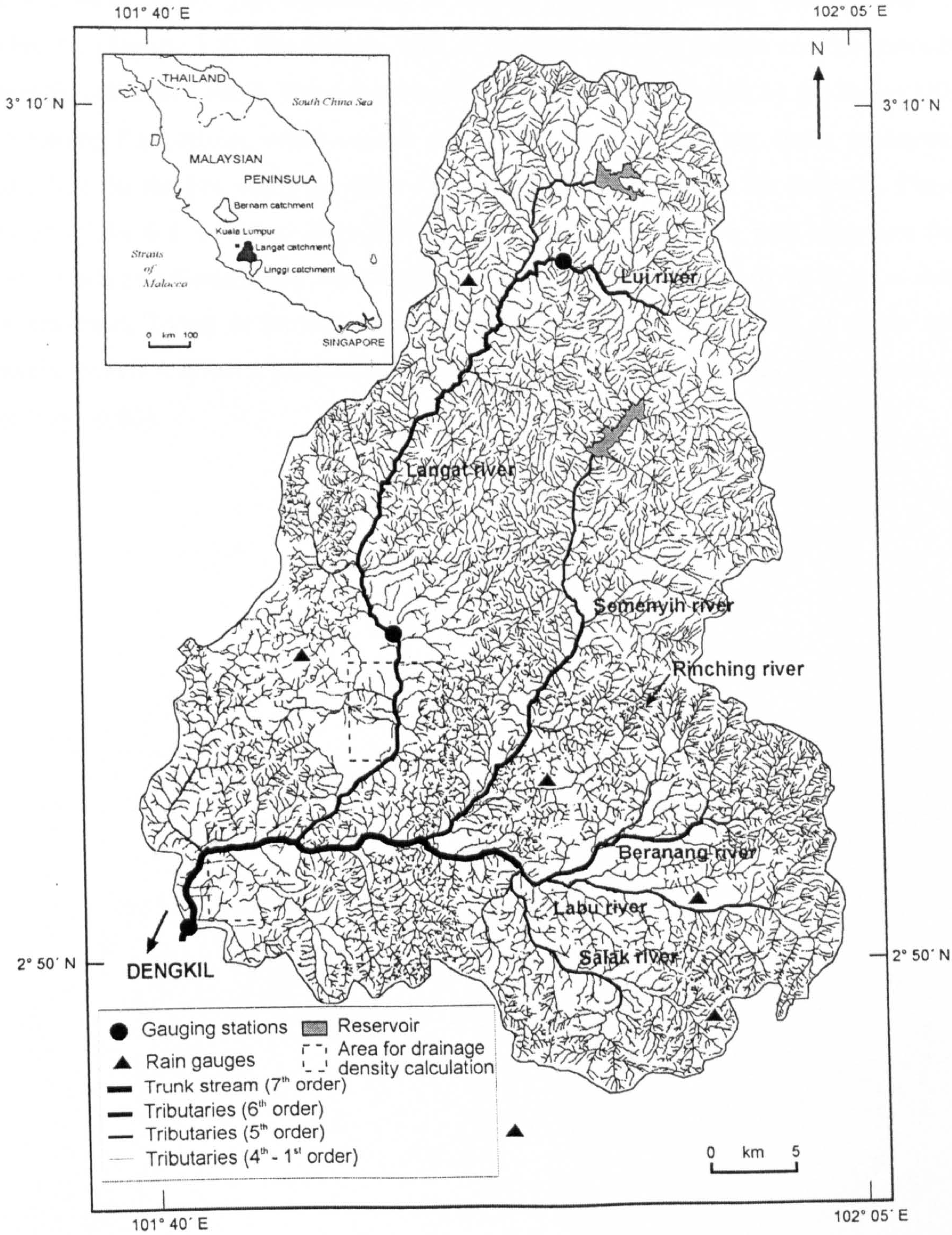


Figure 3.2: Drainage networks of the Langat Catchment

3.2.1.1 Geology

The base rock material in the Main Range is a batholith, a granitic magma mass that was intruded into the anticlinal folds of the peninsula during the late Triassic-early Jurassic period (Tjia, 1988). Based on radiometric dating of granite samples in southern Thailand and parts of the peninsula, the Main Range is mainly Triassic or older (Lai and Detphachanh, 2006). The explanation of related geological periods can be found in **Table 3.1 (Figure 3.3)**. The country rock of the headwaters is granite and this extends under the hill near Cheras. The majority of the hill areas are underlain by the Kenny Hill and Kajang Formations, which consist of metamorphosed sandstone, shale, mudstone, and schist. In the low flatlands, thick Quaternary sediments cover the bedrock. These consist of the 0.5 to 5.5 m thick Beruas Formation crowned by a peat layer and the clayey Gula and Kempadang Formations that increases in thickness to 40 to 50 m near the sea-coast. Lying underneath is the Simpang Formation consisting of sands and gravels, which reaches a thickness of about 40 m in the low flatlands (Department of Geology, 2000).

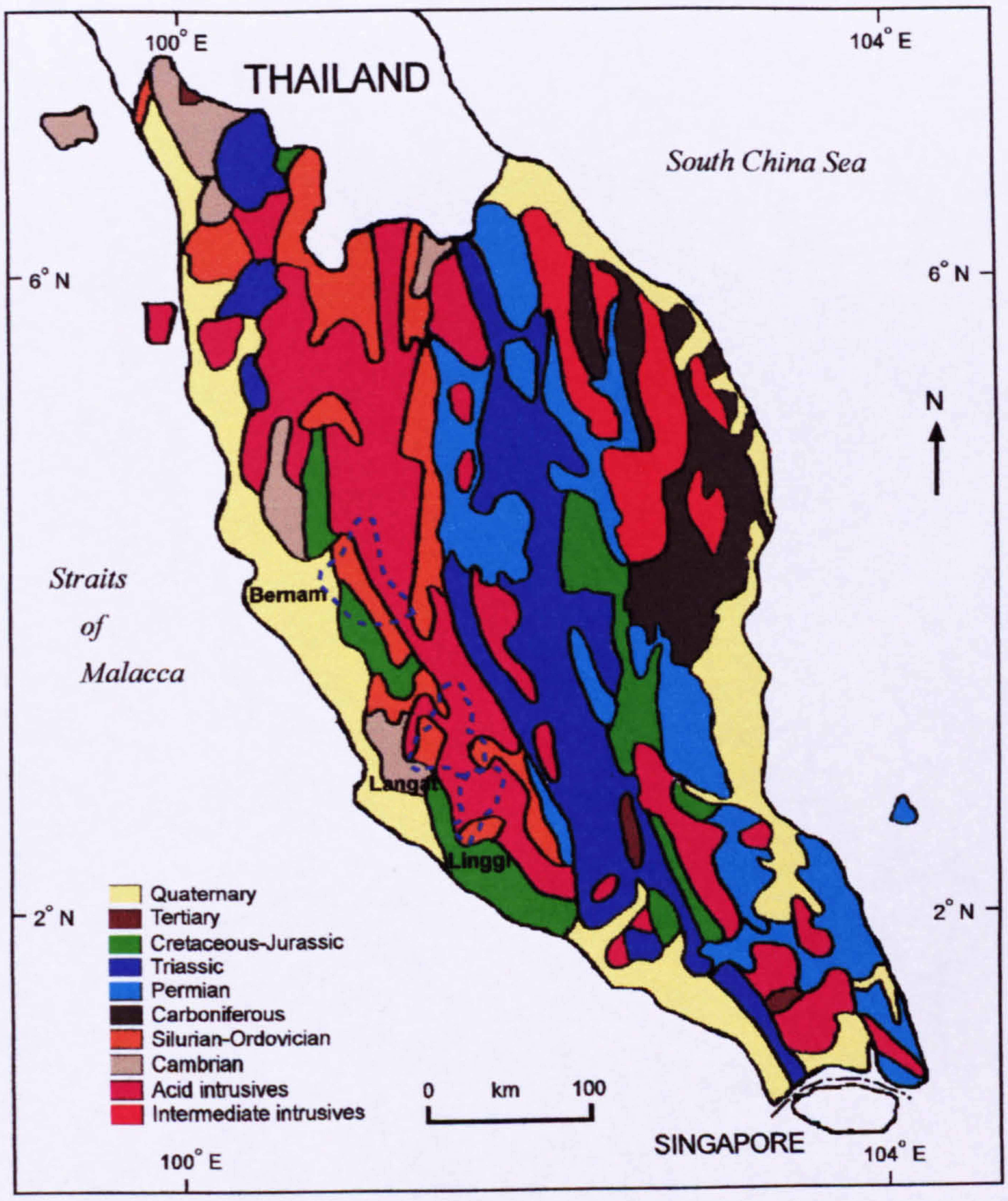


Figure 3.3: Geological map of Peninsular Malaysia

Table 3.1: Geological period of Peninsular Malaysia (Department of Geology, 2000)

Geological period	Description
Quaternary	Marine and continental deposits: clay, silt, sand, peat with minor gravel. Basalt of Early Pleistocene age in the Kuantan area.
Tertiary	Isolated continental basin deposits of Late Tertiary age: shale, sandstone, conglomerate and minor coal seams. Volcanic in the Segamat area.
Cretaceous-Jurassic	Continental deposits of thick, cross – bedded sandstone with subordinate conglomerate and shale/mudstone. Volcanics are locally present.
Triassic	Interbedded sandstone, siltstone and shale; widespread

	volcanics, mainly tuffs of rhyolitic to dacitic composition in central peninsula. Limestone prominent in lower part of succession. Conglomerate and chert locally prominent.
Permian	Phyllite, slate and shale with subordinate sandstone and schist. Prominent development of limestone throughout the succession. Volcanics, rhyolitic to andesitic in composition, widespread.
Carboniferous	Phyllite, slate, shale and sandstone: argillaceous rocks are commonly carbonaceous. Locally prominent development of limestone. Volcanics of acid to intermediate composition locally present.
Silurian-Ordovician	Schist, phyllite, slate and limestone minor intercalations of sandstone and volcanics.
Cambrian	Sandstone/metasandstone with subordinate siltstone, shale and minor conglomerate.

Generally, the soils (**Figure 3.4**) can be divided into two groups: (a) the soils formed on a wide range of rock types in the interior hills and mountain, and (b) the soils of the coastal alluvial plains (Department of Agriculture, 1999). The sedentary soils are developed on igneous, sedimentary and metamorphic rocks, and are strongly weathered with mostly kaolinitic clay minerals. The overriding influence of parent material under the hot and humid climate is indicated by the high proportion of resistant minerals left *in situ*. The sedentary soils fall under the classification orders of Nitosols, Acrisols, and Ferralsols (Ultisols, Oxisols). The coastal alluvial soils fall into the categories Gleysols, Cambisols, Podzols (Entisols, Inceptisols, Spodosols) and can be grouped into four main types: (1) predominantly fine-textured clay and clay loam; (2) peat and organic soils; (3) acid sulphate soils; and (4) sandy soils (bris soils). The peat, acid sulphate and 'bris' soils are problem soils and are difficult to manage for both crops and pasture (Department of Agriculture, 1999).

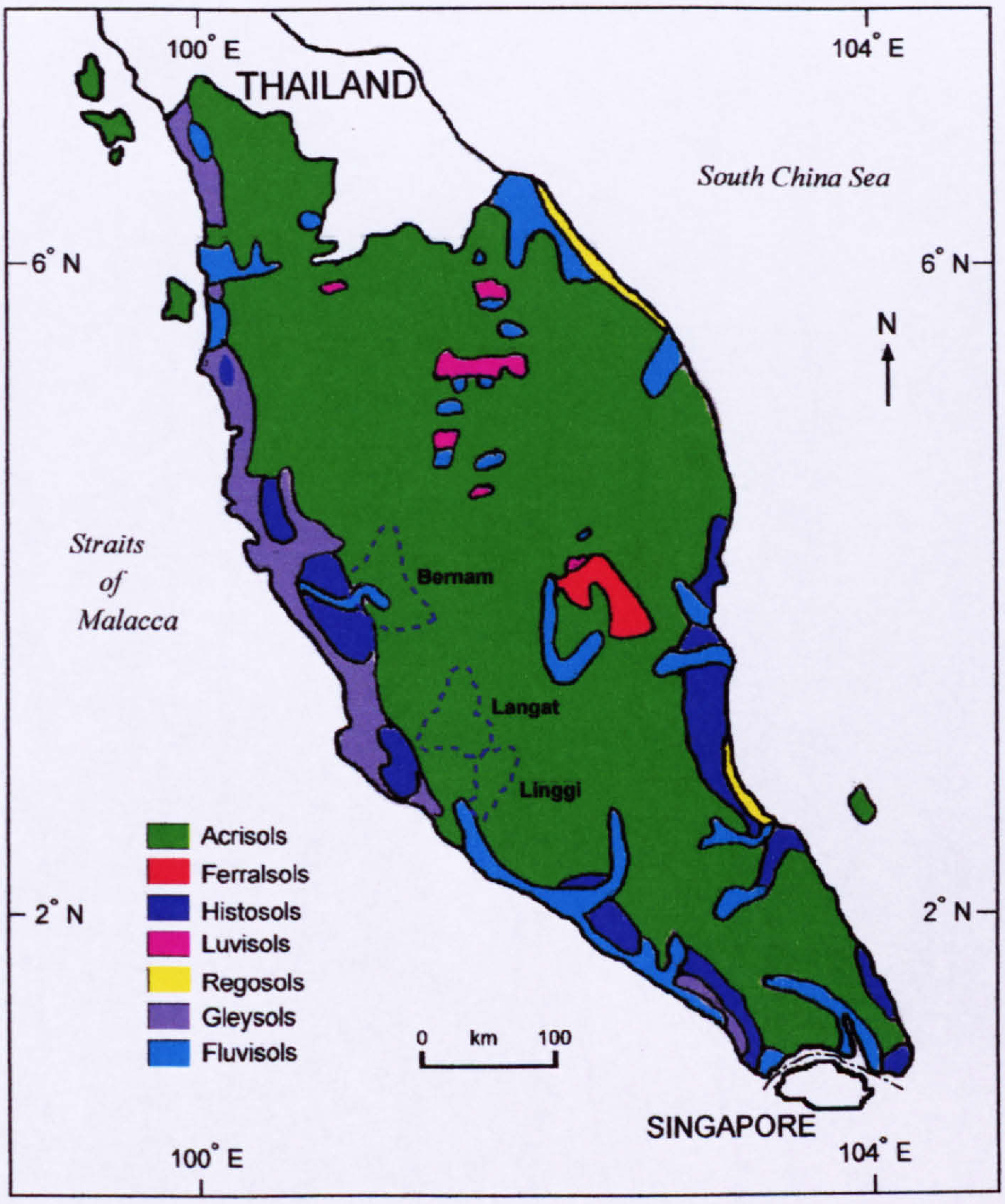


Figure 3.4: Soils map of Peninsular Malaysia

The area with the following soil types are prone to erosion: (a) alluvial soils (Telemong-Akob, local name); (b) the soil series developed from sediments (Serdang-Munchong-Bungor, local name) found in areas of settlement; and (c) the soil series (Churam, local name) found in headwater sub-catchments (Department of Agriculture, 1999). In the Langat catchment, the alluvial Telemong-Akob Sedimentary and Hillsoil are sensitive to erosion especially when exposed to heavy rainfall.

3.2.1.2 Topography and river system

The Langat Basin can be broadly divided into three topographic areas: namely, mountain, hills and flat lowlands. Groundwater recharge areas lie in the mountainous and hill areas and an aquifer distributes water widely to the flat lowlands. The Langat River and its left bank tributary, the Semenyih River, rise on the western slopes of the central Malaysian mountain ridge. Both rivers flow southwestward in their mountainous headwaters. They gradually change direction, passing through in the hill areas near Kajang and Bangi to flow west towards to Straits of Malacca. The Langat River is joined by the Semenyih River in the flat lowlands near Dengkil. The other sixth order tributaries are the Lui and Beranang rivers. There are two reservoirs, the Langat Reservoir and Semenyih Reservoir, located in the upstream section of Langat and Semenyih catchments, respectively. The Langat Reservoir, built in 1981, has a catchment area of 54 km^{-2} while the Semenyih Reservoir, built in 1982 with the purpose of supplying domestic and industrial water, has a catchment area of 41 km^{-2}. The Langat Reservoir is also used to generate a power supply of moderate capacity for the population within the Langat Valley. The total catchment area upstream of Dengkil is 1257 km^{-2}.

Point sources of pollution within the Langat are located not only in the urban and industrial areas but also in the rubber and palm oil estates situated along the Langat main trunk and its tributaries, particularly the Semenyih and Rinching Rivers. The Langat catchment has been developed since late 1980s, but this has occurred mainly along the lower reaches of the trunk stream and is less evident upstream. As development increases, potential point sources of pollution are expected in two areas – the Semenyih and Rinching River catchments.

3.2.2 Linggi catchment

The Linggi River Basin is focussed on the outlet gauging point at Longitude 101° 85' E and Latitude 02° 32' N, and is adjacent to the Langat River Basin (**Figure 3.5**).

3.2.2.1 Geology

The geology and soils are similar to that of the Langat (**Figure 3.3**). Country rock in the mountain headwaters is granite. The hill areas consist of metamorphosed sandstone, shale, mudstone, and schist. In the low flatlands, thick Quaternary sediments lie over bedrock (Department of Geology, 2000). The Telemong-Akob soil series occurs in this area. This soil is well drained and has developed through extensive weathering and leaching under high temperatures and intense rainfall (Department of Agriculture, 1999). Thus, the soil is generally low in fertility.

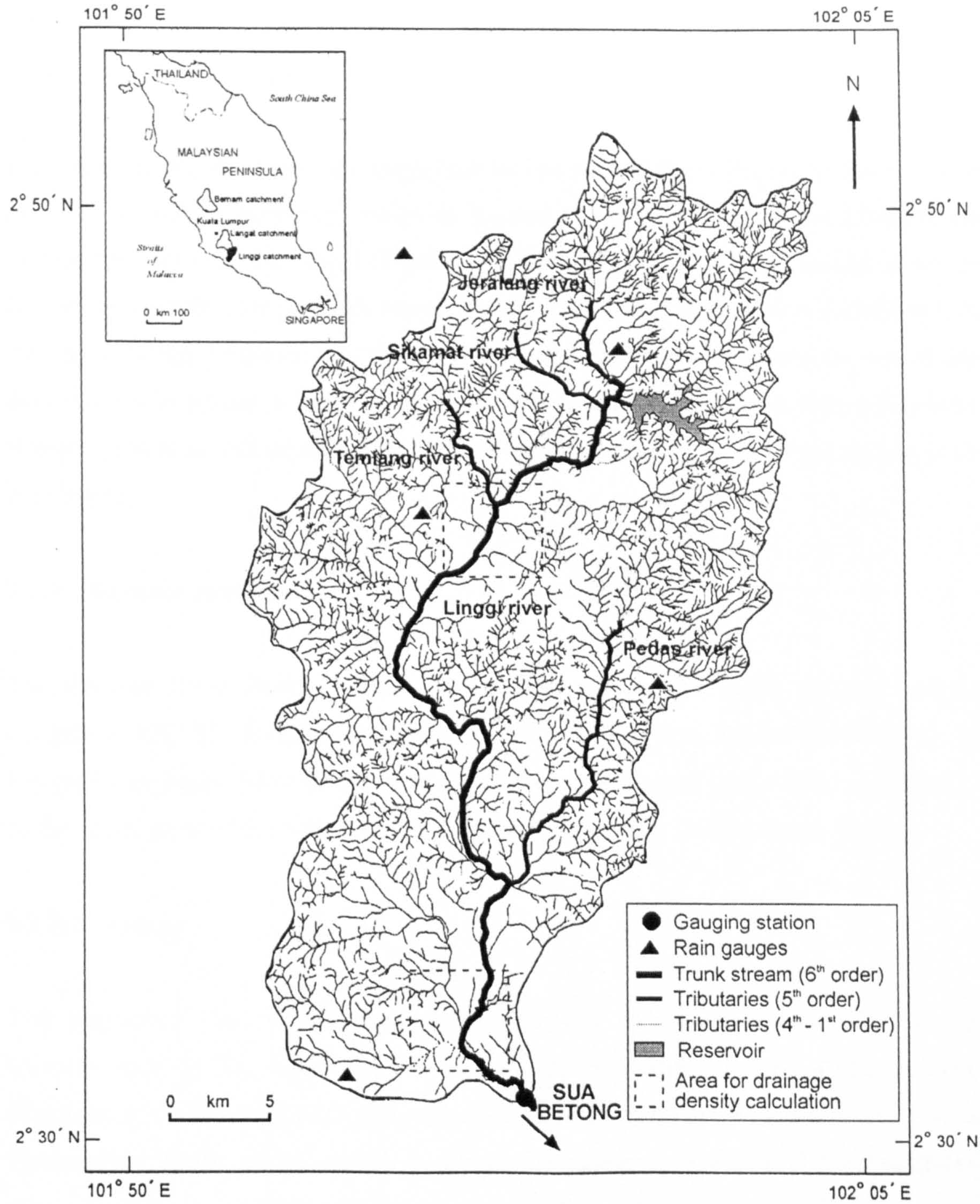


Figure 3.5: Drainage network of the Linggi Catchment

3.2.2.2 Topography and river system

As with the other basins, the Linggi can be broadly divided into three zones: namely, mountainous headwaters, hill areas and flat lowlands. The Linggi River and its right bank tributary, the Jeralang and Temiang rivers, originate on the western slopes of the central mountain ridge of the Malaysian Peninsula and the combined stream flows into the Straits of Malacca. The other main fifth order tributary is the Pedas River. The Linggi catchment has one reservoir, namely the Terip Reservoir, built in 1985 with a catchment area of 40 km^{-2} for domestic water supply. The total catchment area of the Linggi Basin at the gauging station is 528 km^{-2}.

Point sources of pollution in the Linggi catchment are mainly in the urban and industrial areas of Seremban township, which is located at the junctions of the Sikamat and Temiang Rivers with the Linggi (**Figure 3.5**). The rubber and palm oil estates which are situated along side of main trunk stream and major tributaries have also contributed. As the size of Linggi catchment is considerably smaller than the Langat and the rate of land development is greater, a larger proportion of the lower catchment has been subjected to change. This area will undoubtedly contribute more pollution to the river system in the near future.

3.2.3 Bernam catchment

The Bernam River Basin (**Figure 3.6**) is focussed on the outlet gauging point at Longitude 101° 35' E and Latitude 03° 70' N, about 70 km North-Northwest of the Langat River Basin. Most of the watershed lowland is planted with rubber and palm oil. In the upper parts of the watershed the dominant vegetation is dipterocarp forest.

3.2.3.1 Geology

The catchment lies on unfaulted metamorphosed sedimentary rock (**Figure 3.3**). Country rock in the headwaters is the granite that forms much of the mountain backbone of the Peninsula and this extends to form the hilly areas near Behrang Ulu and Proton City. Some of the upland areas are underlain by metamorphosed sandstone, shale, mudstone and schist. Some exposures of quartz mica, mica schist and quartz schist are present along the stream valley. In the low flatlands, thick Quaternary sediments fill the valleys and lie unconformably on the bedrock. These deposits consist of clay, silt, sand and peat with minor layers of gravel (Department of Geology, 2000). The soils of this area are principally the Telemong-Akob series (**Figure 3.4**). All soils are well drained. Textural classes lie between loam and clay, with moderate to average soil moisture holding capacity. Due to the well drained soils, little overland flow can be expected from most rainstorms.

3.2.3.2 Topography and river system

The topography of the watershed is hilly to mountainous country rising to heights of 2500 m in the north-east corner. The Bernam Basin can be broadly divided into three topographic areas, namely: mountain (more than 1000 m above sea level); hills (100-1000 m above sea level), and flat lowlands (below 100 m above sea level). As in the Langat, groundwater recharge areas lie in the upstream mountainous and hill areas and the water is redistributed laterally under the flat lowlands. The Bernam River originates on the western slope of the central mountain ridge of the Peninsula. It flows southwestward to be joined by its major tributary - the Slim River (sixth order) from the north, followed by the Ingki River (fifth order), the Sungkai River (fifth order), Behrang River (sixth order), Soeharto River (fifth order) and the Trolak River (fifth order), after which of enters the flat land near Soeharto Village and flows westward to the Straits of Malacca. The catchment area of the Bernam River Basin is 1123 km^{-2}.

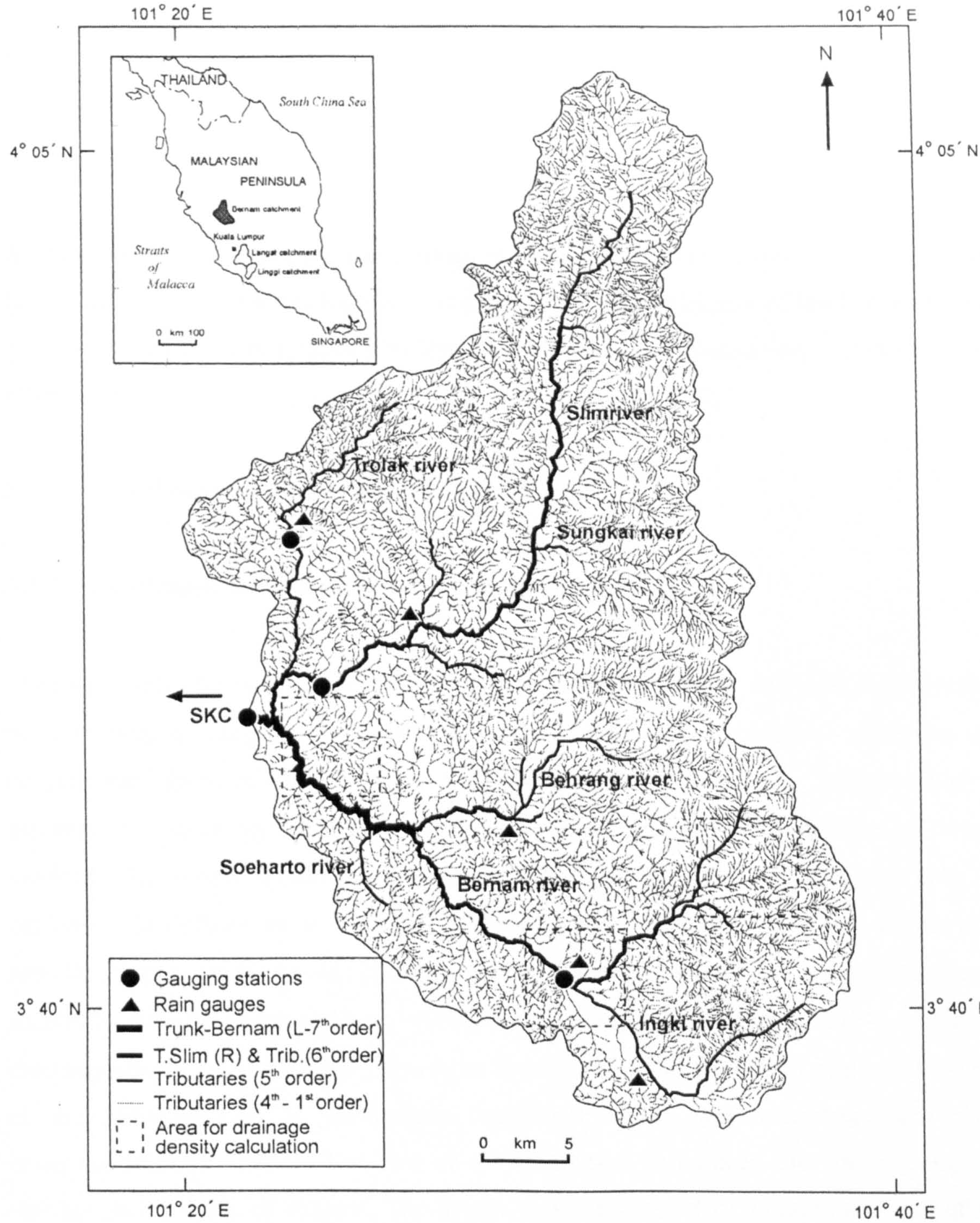


Figure 3.6: Drainage network of the Bernam Catchment

The town of Tanjung Malim is situated in the upper part of the catchment at the foot of the Titiwangsa Range, on which Proton City is built and other settlement areas and the villages of Behrang Ulu and Slim are situated.

Because the Bernam catchment has yet to be developed, the potential point sources of pollution are expected to be in the new industrial areas located at Behrang (the middle reaches of the Bernam; **Figure 3.6**). The main industrial project that has been launched is a national car plant (Proton) at Proton City, accompanied by a number of other factories supplying car components. This development process is matched by construction of housing estates and these are also expected to contribute domestic pollution to the river system.

All three catchments have similar geology and soils. This is important if the Langat and Linggi are to be used as analogues to understand the future impact of land development on hydrology and water quality in the Bernam due to deforestation, agriculture and urbanization.

3.3 Morphometry of the study catchments

3.3.1 Catchment delimitation and drainage network

Drainage area (A) is an important catchment characteristic in hydrological research because, within a single morphoclimatic regime, it reflects the volume of water that can be generated from rainfall (Gregory and Walling, 1973). Normally, rainfall depth is assumed to occur uniformly over the watershed; therefore, the volume of water available for runoff would be the product of rainfall depth and drainage area. A catchment is defined as an area that includes all the surface area which drains to a specific location on the stream (Dingman, 1994). The catchment area has been used as a substitute for discharge (Kirkby, 1993; Montgomery and Dietrich, 1994). A linear discharge-basin area relationship has been found to be valid for humid regions (Leopold et. al., 1964) and to be particularly significant for smaller catchments and short networks (Kirkby, 1993). The size of the catchment influences the water yield, the number and the size of streams. The length, shape and relief of a catchment will affect the water and sediment yield (Gregory and Walling, 1973). Catchment areas can be identified for a particular area, for example above a gauging station or study site. The area is delimited by a topographic divide (theoretical line) which passes through the highest point between a stream and its neighbours (Gordon et al., 1992).

In this study, Malaysian topographical 1:50 000 scale maps with a contour interval of 50 metres produced in 1992 and based upon information from aerial photographs dating from 1984 as well as a field survey in 1987, have been used in order to derive parameters of the catchment morphometry (catchment area, drainage density, stream order, length, perimeter, bifurcation ratio and shape). Contour crenulation was adopted for drainage network delineation (Gregory and Walling, 1973; Goudie, 1990) which in this case was based upon blue lines on topographic maps. However, this approach has some disadvantages, due to the fact that not all of streams appear on maps, especially in urban, agriculture and limestone areas. In these cases, there are a few tributaries which are not connected to the trunk stream because no blue lines appear on the map. To solve this problem, lines were drawn to connect these tributaries to the main stream. In order to get a precise stream network tracing, supplementary information including contour crenulations, latest field surveys and latest aerial photographs should be used. Studies by Eyles (1966) (*cf* Ayoade, 1988) in Malaysia showed that the use of map evidence alone could lead to errors because it gives a different value of drainage density compared to aerial photographs in a granite area (Gregory and Walling, 1973). Errors normally arise when assuming that an area on a topographic map is the real drainage area. This happens frequently in landscapes with low relief and porous soils or areas underlain by limestone where water flow patterns may not follow land surface contours.

Catchment boundaries have been drawn through the ridge tops of highlands areas (which appear on topographic maps as dotted lines). A problem arose in areas with little relief especially in flat downstream areas where the boundaries cannot be drawn precisely. After each catchment was delimited, the area of each and those of sub-catchments were measured by Digital Planimeter. It is important to state here that the catchment areas were determined by the outlet gauging stations downstream.

A summary of the morphometrics for Bernam, Langat and Linggi is presented in **Table 3.2** below, meanwhile the details of measurement are shown in **Appendix 1.** The drainage areas of Langat and Bernam are comparable, being 1257 km^{-2} and 1123 km^{-2} respectively. However, the Linggi catchment is smaller, with an area of 528 km^{-2}. Even with the smaller size compared to Bernam, it still could be used as an analogue catchment. This is because, the Linggi catchment which is adjacent to Langat, could provide additional information for rainfall-runoff response due to urbanization within smaller systems and could also be compared to the sub-catchments of Langat and Bernam with similar sixth order stream. The trunk streams, seventh order, in Langat and Bernam are 52 km and 41 km long, respectively, while the Linggi trunk stream is of sixth order and is 39 km long. The main tributaries which form sub-catchments established for Langat and Linggi are at sixth order and fifth order, respectively. In

Bernam, there are two major tributaries with sixth order and fifth order. The Langat sub-catchments are the Lui, Semenyih, Rinching and Labu, while, the Jeralang, Temiang and Pedas are the sub-catchments of the Linggi. The Bernam sub-catchments are Slim, Trolak, Sungkai, Behrang and Ingki. These tributaries/sub-catchments will play a significant role in understanding the complexity of the rainfall-runoff within and between catchments.

Table 3.2: Summary of morphometric properties of the three study catchments

Characteristics	**Catchment**		
	Langat	**Linggi**	**Bernam**
Total area (A) (km^{-2})	1257	528	1123 502 (B) 621 (S)
Drainage basin perimeter (P) (km)	186	127	175 96 (L) 129 (R)
Drainage density ($km\ km^{-2}$)	4.2	4.1	4.6
Stream order (Strahler, 1957)	7	6	7 7 (L) 6 (R)
Bifurcation ratio (Average)	4.2	4.9	4.3 3.8 (L) 5.0 (R)
Total length of trunk stream, L (km)	52	39	41 32 (L) 41 (R)
Shape of catchment			
o Form Factor (F) (Horton, 1932)	0.45	0.40	0.68 0.38-L; 0.48-R
o Circularity Ratio (C_M) (Miller, 1953)	0.45	0.40	0.45 0.68-L; 0.46-R
o Elongation Ratio (E) (Schumm, 1956)	0.76	0.66	0.93 0.78-L; 0.70-R

Notes: B – Bernam; S – Slim

The discharge recorded at the gauging stations in Langat and Linggi catchments are subject to the flow regulation (water release) from the Langat and Semenyih reservoirs and Terip reservoir which have been built in the headwaters. The monthly time series analysis of the discharge data is expected to show the flow fluctuation due to this influence during the dry season (to fulfil a demand for water treatment plant downstream) and also during the rainy season.

The Bernam catchment is drained by two main rivers, which are the Bernam river itself and the Slim river, a major right bank tributary which is 32 km in length. The sub-catchment area of Slim river is more than half of the total catchment with an area of 611 km^{-2} which will be reflected in the total discharge recorded at the outlet. The Slim river joins the Bernam, which flows from south-westwards of the catchment for about 2 km before reaching the gauging station at SKC. Interpreting a hydrograph for rainfall-runoff relation will be very complicated especially when the rainfall event did not occur at the same time in both sub-catchments. Rainfall spottiness due to convective storms, which commonly occur in the area, plays a significant factor in the distribution of catchment rainfall. The lack of availability of rain gauges for the highland areas (above 1000 m) also makes the analysis more complicated.

In an attempt to understand this complexity, Slim discharge data (where available) recorded at the Slim gauging station, about 5 km upstream of SKC, will be analysed. The data for Slim station have been subtracted from SKC data in order to obtain the discharge flowing from the trunk (Bernam). It is hoped that this step give some indication of which part of the catchment contributes more discharge recorded at SKC station. It is expected that the discharge from the left trunk (Bernam) will reach the gauging station at SKC first since it is more circular than Slim – a circularity ratio of 0.68 and 0.46, respectively. However, despite this, the elongation ratios for both are quite similar, the Bernam has a value of 0.78 and Slim a value of 0.70, suggesting a similar gathering time.

3.3.2 Drainage density (D_d)

Horton (1932, 1945) defined drainage density (D_d) as the total length of the stream channels per unit area (km km^{-2}). $D_d = L_T/A$, where L_T is the total length of the channel within an area, A. Drainage density represents the amount of channel required to drain a unit of catchment area (Gordon et al., 1992; Lin and Oguchi, 2004). Drainage density provides a hydrologist with a useful numerical measure of landscape dissection and runoff potential. Basins with a low drainage density normally lie in a landscape with well-vegetated hillslopes which promote infiltration where the potential for runoff is small, while a high drainage density indicates a highly dissected landscape or landscape of low relief such as a coastal plain or an arid region (Berger and Entekhabi, 2001).

A higher drainage density will maximise the opportunity for water and suspended sediment to reach the stream network (Reid and Frostick, 1987). Gregory and Walling (1973) stated that drainage density is the most valuable index of drainage basin form and processes operating along a watercourse. It is important in determining the time of travel of flood water. It is also often seen as a key indicator of the differences in velocity and residence time of water on hillslopes and in the stream channel (Berger and Entekhabi, 2001). Closer investigations of the processes responsible for drainage density variation have revealed that a number of factors collectively influence stream density. These factors include local climate, topography, soil infiltration capacity, vegetation cover, and geology. It may also reflect the influence of humans (Tucker and Bras, 1998).

Accurate measurement of drainage density is important, especially in hydrological studies, but in reality it is difficult to establish, particularly in large basins (Tucker and Bras, 1998). The estimation of a basin's drainage density requires delineation of the stream network (Berger and Entekhabi, 2001). In this study, calculation of drainage density is not based on every single stream within the catchment area due to time. To measure a drainage density value for the Langat, Linggi and Bernam catchments, a systematic sampling method has been used, while recognising that the locality of the first order streams is biased towards the headwaters where we might expect the highest stream density within the catchment (Ng, 2005). By sampling three locations (headwater, mid-catchment which in this study, coincide with urban area and outlet area) of 25 km^{-2} each (see **Figure 3.3, 3.5** and **3.6**) and establishing the total length of stream within the areas manually using a digital opisometer, a reasonable estimate of the average of three readings of drainage density has been obtained. In this case, the drainage density values for the headwater areas for all catchments are reasonably high compared with the mid catchments and downstream, where the areas are already developed with urban surfaces or settlement.

Horton (1932) suggested that the value of drainage density for steep impervious areas in regions of high precipitation ranges is between 0.93-1.24 km km^{-2}, and is almost zero in permeable areas with high infiltration rates. Langbein (1947) suggested a range of values 0.55-2.09 km km^{-2} in humid regions, with an average of 1.03 km km^{-2} (Gregory and Walling, 1973). In Langat and Linggi, the drainage densities (averages) are similar at 4.2 km km^{-2} and 4.1 km km^{-2}, respectively. However, for the Bernam, the drainage density is slightly higher at 4.6 km km^{-2}. This is quite high compared with the values mentioned above, but not as high the Koobi Fora semi arid drainage basin in Kenya where the drainage density is 90 km km^{-2} for a catchment of 7 km^{-2} (Reid and Frostick, 1987). The high value of drainage density in semi-arid areas is normally due to surface runoff from intense thunderstorms that erodes sparsely vegetated slopes (Gordon et al., 1992).

The range of value of 4.1 to 4.6 km km^{-2}, derived for Langat, Linggi and Bernam, is similar to that of an undeveloped small catchment in Penang (the Terjun Catchment), studied by Ruslan (1995) which is 4.0 km km^{-2}. Meanwhile, in a catchment which is already developed (the Relau Catchment), also studied by Ruslan (1995), the drainage density is only 2.7 km km^{-2}. Other studies by Lai and Detphachanh (2006) and Zulkifli et al, (2006) in two small experimental headwater catchments, namely Pangsun and Tarek Hill which neighbour Langat and Bernam, have a slightly higher drainage density with 4.9 km km^{-2} and 5.1 km km^{-2}, respectively. As a comparison, these values are similar to values recorded by Langat, Linggi and Langat headwaters with 4.9 km km^{-2}, 4.8 km km^{-2} and 5.4 km km^{-2}, respectively.

3.3.3 Stream order and bifurcation ratio

According to Strahler (1964), stream order allows classification of a stream on the principle that the order of the trunk stream has some relationship with the size of the contributing area, channel dimensions and stream discharge (Horton, 1932; Strahler, 1957; Shreve, 1957 and Scheidegger, 1965). Stream order provides an index of the amount of flow which can be produced by a particular network (Gregory and Walling, 1973 and Gordon et al., 1992).

In this study, Strahler's method has been chosen because it is widely used by hydrologists. A disadvantage of Strahler's method is that a large number of minor tributaries may join a larger order stream, adding substantially to its discharge but not to its stream order (Gordon et al., 1992).

The bifurcation ratio was introduced by Horton (1932) and is defined as the number of stream segments of a given order divided by the number of stream segments of the next highest order. Bifurcation ratios normally range between 2 and 5 and tend to be larger for more elongated basins (Beaumont, 1975). Strahler (1964) stated that the range is between 3.5 and 5 in watersheds where geologic structure is not a dominant factor. In this study, all catchments values for the bifurcation ratio fall within that range, with 4.2, 4.1 and 4.6 for Langat, Linggi and Bernam respectively. The ratio for Bernam is slightly higher as it is more elongated than Langat and Linggi with an elongation ratio of 0.93.

Figure 3.7 shows the similarity of stream order between the Langat and Bernam catchments with seventh order which reflect the similarity in terms of geological structure and type of rocks. Basically, the figure demonstrates that a geometric relationship (Horton's law of stream length) exists between the numbers of stream segments in successive stream orders (Gordon et al., 1992). Most of the length of the main trunk for both catchments stands at sixth order before being joined by sixth order tributaries just before the outlet to form a seventh order stream (see **Figure 3.2** and **3.6**).

In Langat, the two main tributaries of sixth order (Semenyih and Beranang rivers) form a seventh order river before joining the Langat trunk. Therefore, it is expected that the contribution of river discharge is much higher from the tributaries which flow from the left hand side of the catchment. The same occurs in the Bernam, where the main Bernam trunk of sixth order is joined by the Behrang tributary to form a seventh order river before being met by the Slim tributary just before outlet. These relations add further justification for using Langat as an analogue for Bernam. Meanwhile, the Linggi catchment which is half the size of Langat and Bernam only have sixth order river. Despite this, the Linggi catchment can be compared to other sixth order tributaries in

Langat and in Bernam, especially for the Slim sub-catchment. Therefore, an analogue indicator of process-response due to land use change does not depend only on Langat.

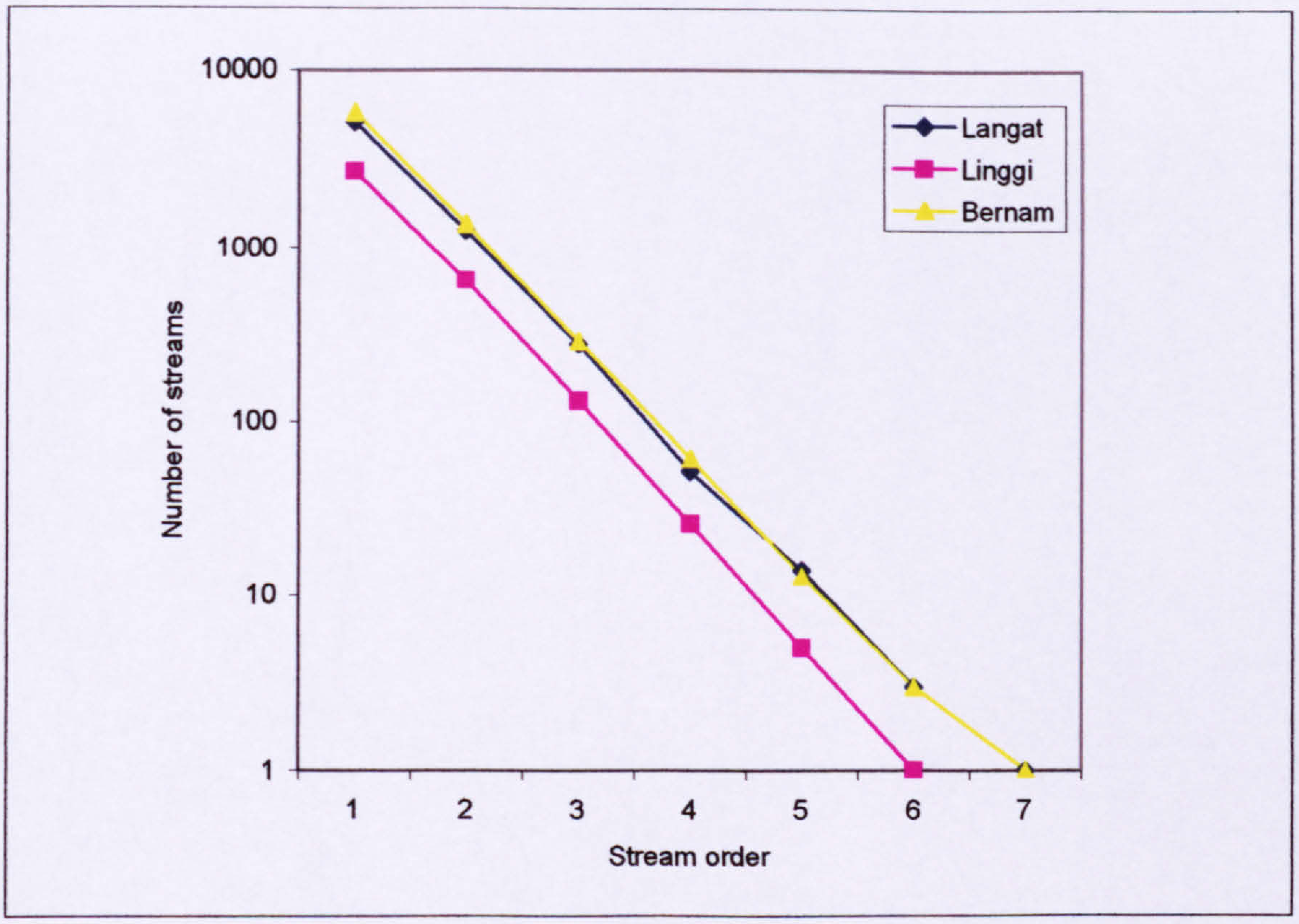


Figure 3.7: Strahler stream order: Langat, Linggi and Bernam catchments

As expected, the Langat and Linggi are generally similar in stream order to the Bernam, but, there are a few dissimilarities between sub-catchments. There are reasons for this: (1) it may be due to slight differences in geological structure and type of rock, (2) it could be that a stream network on the topographical map is not fully representative due to irreducible error, and (3) it may be that the river network has been "lost" due to land use change and urbanisation especially in the middle and downstream parts of the catchment.

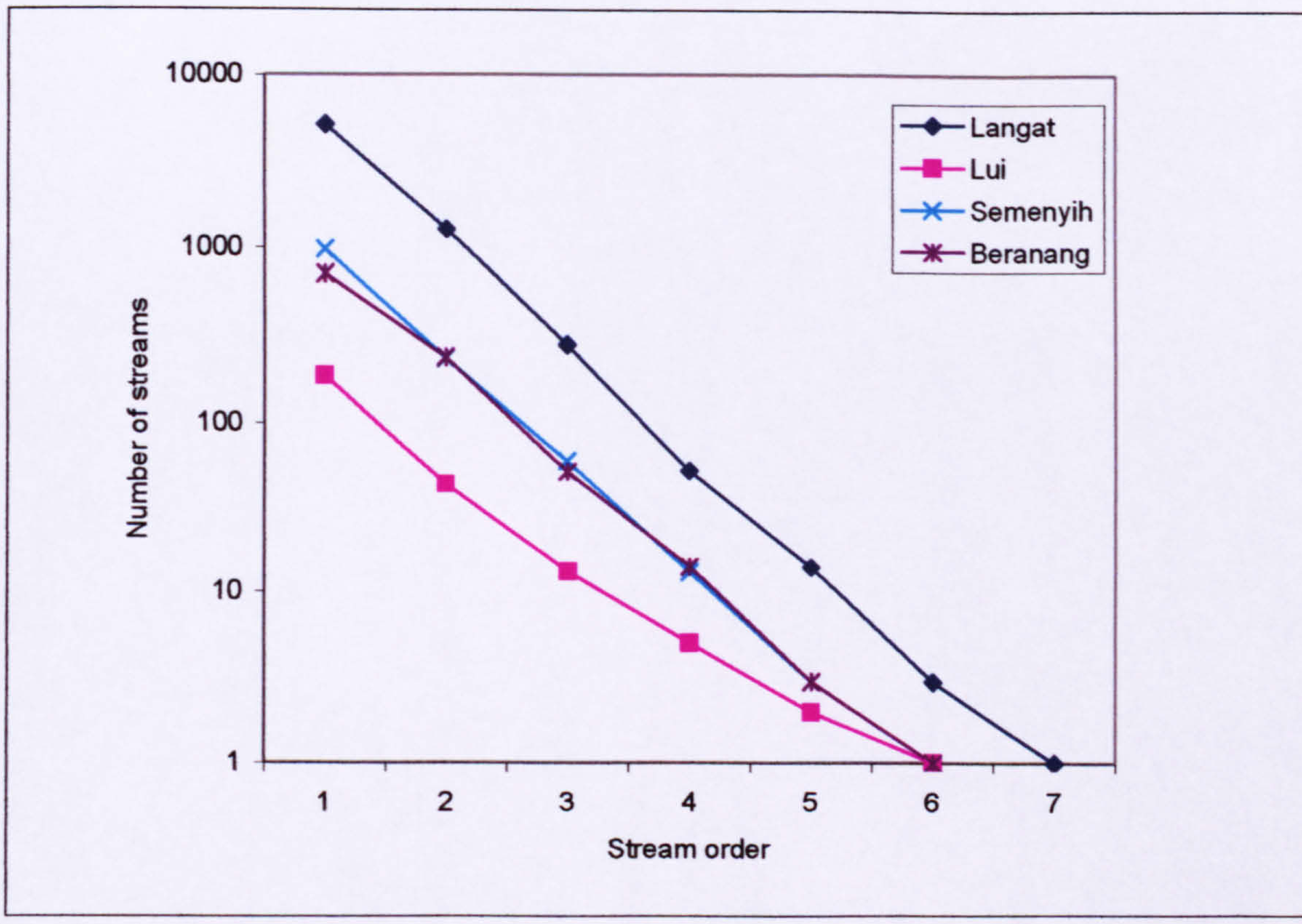


Figure 3.8: Langat stream order: trunk stream and sub-catchments

Figure 3.8 demonstrates that, for the Langat, all three main sub-catchments have sixth order of rivers. For the Langat trunk, the slope at fourth order is slightly different (can also be seen in **Figure 3.7** when comparing to Bernam) which may be due to the "loss" of river network due to urbanisation, mining processes and also the establishment of reservoirs. There are some areas in which an arbitrary line has been drawn in order to connect the two branches of third order rivers to form an fourth order. However, for the area with a lot of 'missing' networks, there is no junction with a same or higher order tributary. The Beranang and Semenyih tributaries are also of fifth order which could be because most of the lower part of the tributary is situated in an urban area. The Lui tributary has a peculiar relation which is not geometrical; here the number of first and second order streams is larger than expected. The manual calculation from the tracing network map shows no error. There is the possibility that the lithology of the Lui sub-catchment, is high in alluvium, has caused a larger lower order network in this area.

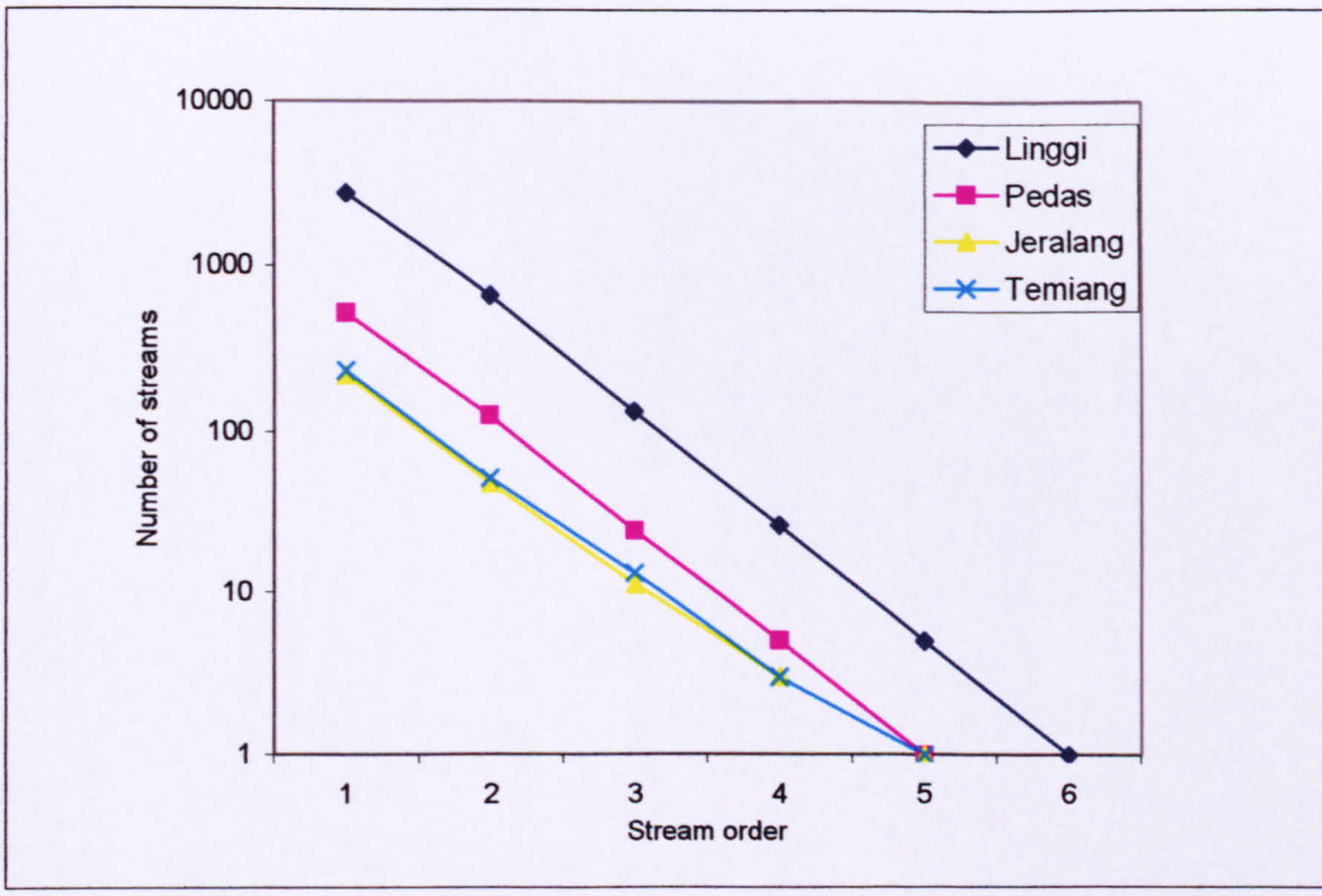


Figure 3.9: Linggi stream order: trunk stream and sub-catchments

Figure 3.9 shows a similar geometrical relation between stream order for the Linggi trunk and three major sub-catchments. The sub-catchments of the Jeralang and Temiang Rivers are situated upstream and are slightly different in terms of first to fourth order compared with the Pedas which has a slightly bigger and more elongated basin. The loss of lower order network for the Linggi trunk and other tributaries is likely to have been caused by mining activities, which occur in a few places upstream and also downstream, as well as the establishment of a reservoir.

Figure 3.10 demonstrates the stream order relation for the Bernam catchment and its major sub-catchments. The main tributaries which have been highlighted in this section are the Bernam trunk which consists of the Behrang tributary, which is a sixth order river, and the Slim tributary (right hand bank) which consists of the Trolak tributary, which is a fifth order river. Both tributaries have a similar geometrical relation for all orders and plot parallel with the main Bernam trunk. The Bernam (sixth order) is joined by the Behrang tributary to form seventh order and moves downstream to meet the Slim tributary just before the outlet. It is expected that the runoff hydrograph recorded at SKC station will have a double peak. The Bernam catchment also has mining activities downstream which are expected to affect the number of lower order streams joining the main stream.

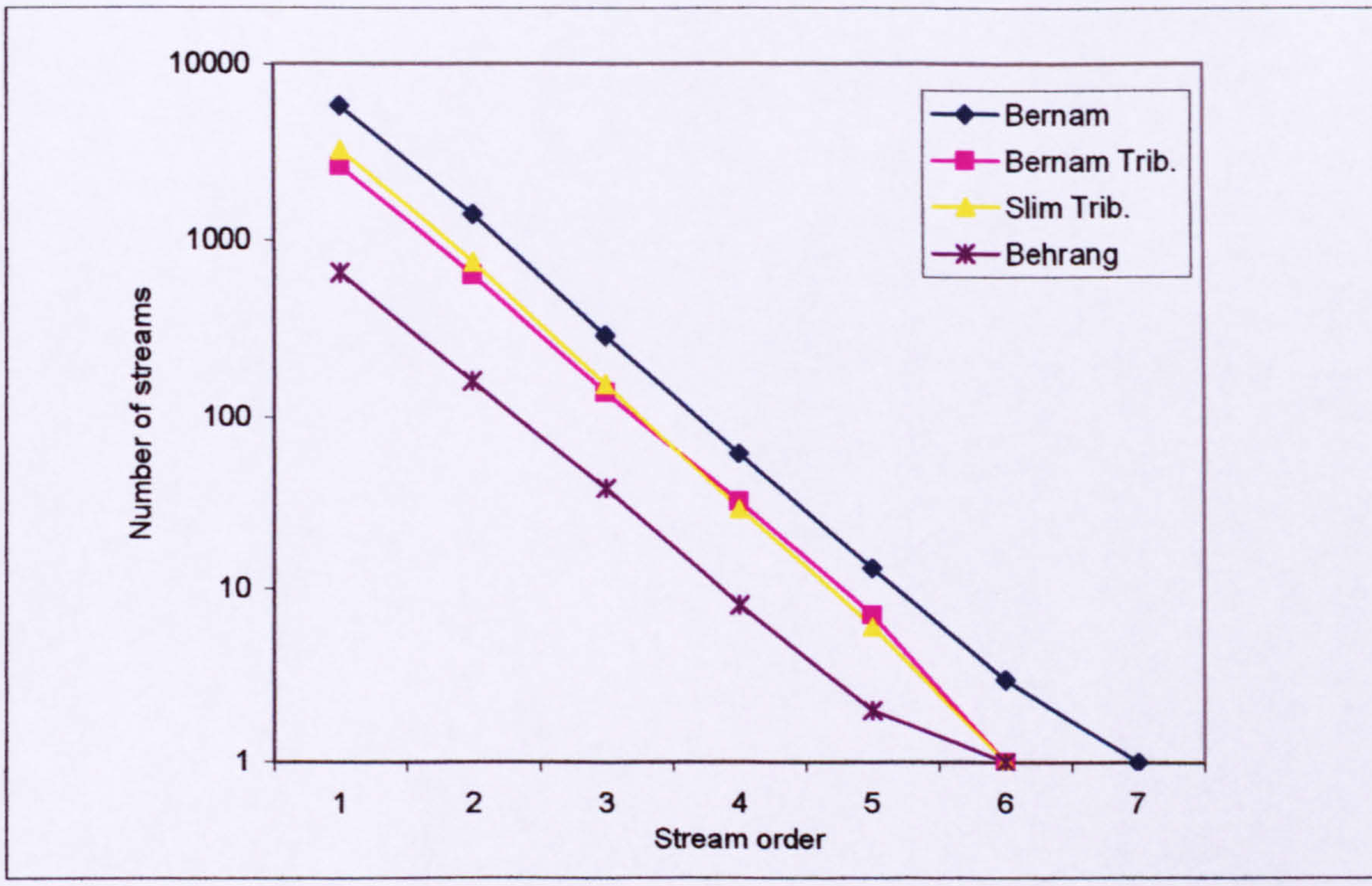


Figure 3.10: Bernam stream order: trunk stream and sub-catchments

3.3.4 Catchment length and perimeter

The catchment length (L) was obtained by measuring a straight-line that roughly follows the main channel from the upstream catchment boundary to the downstream gauge or outlet. This parameter is important in explaining the travel time of water through the drainage network and the availability of sediment for transport in a drainage system (Gordon et al., 1992). Drainage area and length are measures of the watershed size that can be used to reflect different aspects of the catchment's hydrological response to rainfall. The drainage area is used to indicate the potential for rainfall to provide a volume of water; meanwhile the length is usually used in measuring the travel time of water through a watershed.

The total length of trunk for Langat, Linggi and Bernam is 52 km, 39 km and 41 km, respectively. There is a problem with the Bernam since there are two main trunks flowing from different directions; these two sub-catchments, namely the Bernam and Slim were measured separately in order to get the length and measure the travel time of water. The length of the left tributary (Bernam- seventh order) is 32 km; the Slim tributary (sixth order) is 41 km. Therefore, the runoff hydrograph measured at SKC outlet station is expected to record a larger volume of water within a shorter time mainly from the Bernam which has a larger order, a smaller drainage area and is more circular rather than the Slim tributary. The factor of rainfall spottiness and the effect of fog-precipitation especially for the Slim tributary, which has more than half of its area situated in uplands (of the Main Range) will contribute to a different peak of runoff hydrograph and make it more difficult to understand the response.

The perimeter of the Langat and Bernam catchments are similar at 186 km and 175 km. The perimeter of the Linggi catchment is smaller at 127 km, but this is similar to the Slim tributary in the Bernam which is 129 km.

3.3.5 Catchment form

Catchment form can reflect the way that water is delivered to the outlet (Gregory and Walling, 1973). Several simple methods have been derived to express the catchment form: (1) Form Factor (F) of Horton (1932) defined as drainage area divided by basin length; (2) Basin Circularity (C) of Miller (1953) defined as the ratio of the area of basin and the area of a circle with the same perimeter; and (3) Basin Elongation of Schumm (1956), defined as a diameter of circle with same area as the basin divided by the basin length.

Generally, a circular watershed will result in runoff from various parts of the catchment reaching the outlet at the same time and this will lead to greater quick-flow (Qp) and a smaller hydrograph time-base. A more elongated basin will contribute runoff to the trunk stream over greater time, and therefore produce smaller flood peaks. However, this is a simplistic process-response model. Other factors such as the direction of storm travel, land cover/use, soil characteristics and surface roughness may mask some of the effects of basin shape.

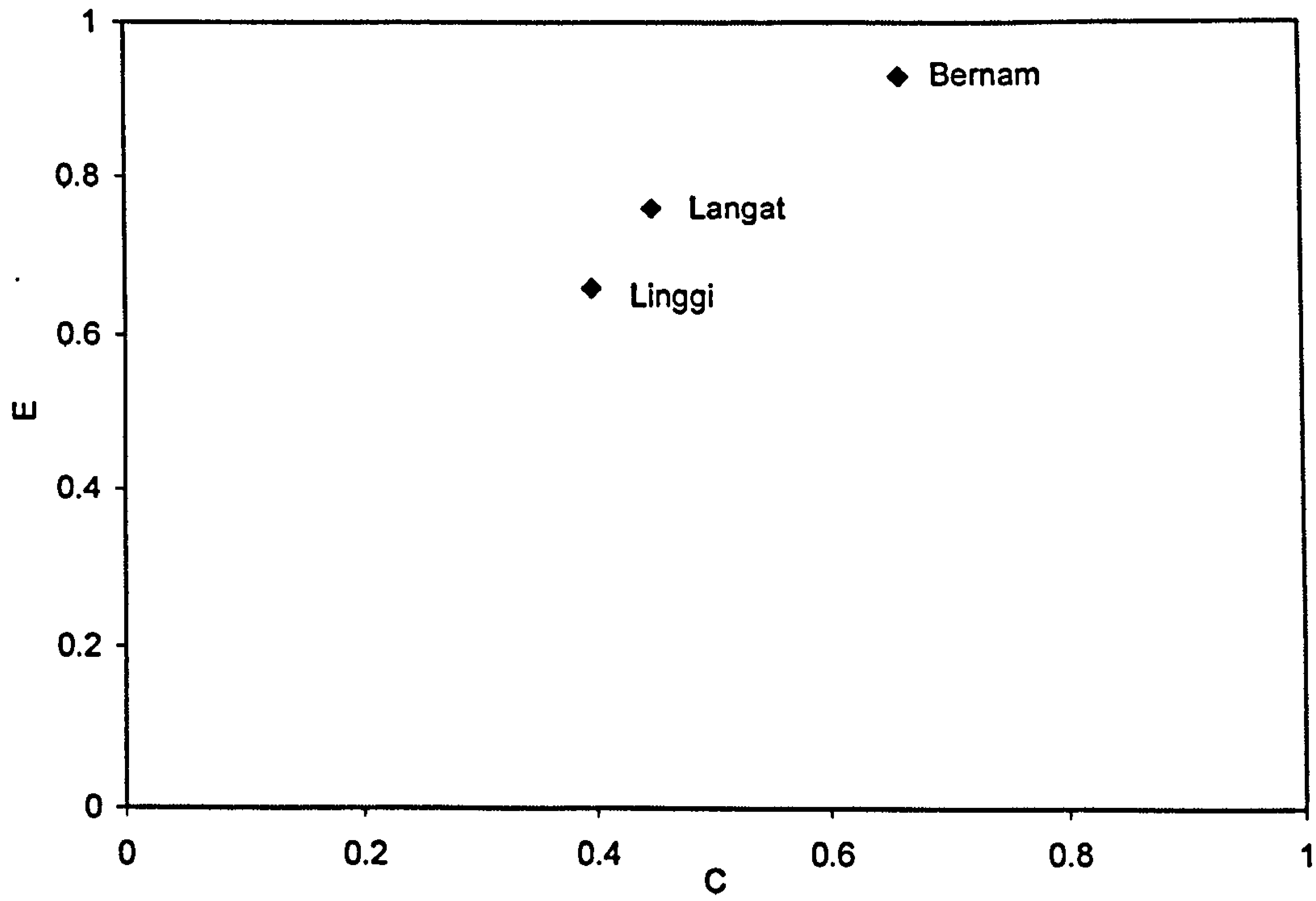


Figure 3.11: Relationship between basin Elongation (E) and Circularity (C)

As the circularity is greater, the Bernam catchment (**Figure 3.11**) should produce a quicker and more peaked hydrograph response. However, there are two main sub-basins drained, respectively, by the Slim tributary (right) and the Bernam itself. These have a slightly different length. For this reason, it might be expected to exhibit a doubled peaked hydrograph. The time of water travel for the Slim tributary is expected to be shorter because its shape is more elongated and less circular compared with the Bernam (**Figure 3.12**). The Langat catchment is elongated when compared with Linggi, but the travel time of water will be different because of the different sizes of these drainage areas. In addition, the two main tributaries, Semenyih and Beranang, of sixth order, could contribute much more water discharge compared with the Langat trunk itself. The Langat and Semenyih reservoirs also play a significant role in regulating flow discharge. All these factors complicate an understanding of the runoff hydrograph recorded at Dengkil station. This complication will be discussed in the next chapter.

Figure 3.12, shows the co-variation of elongation and circularity for the main sub-catchments. This highlights the fact that the Lui catchment in Langat is more circular and the Tg. Malim catchment in Bernam more elongated. Thus it is expected that the travel time of water for Lui is much quicker compared with Tg. Malim in Bernam.

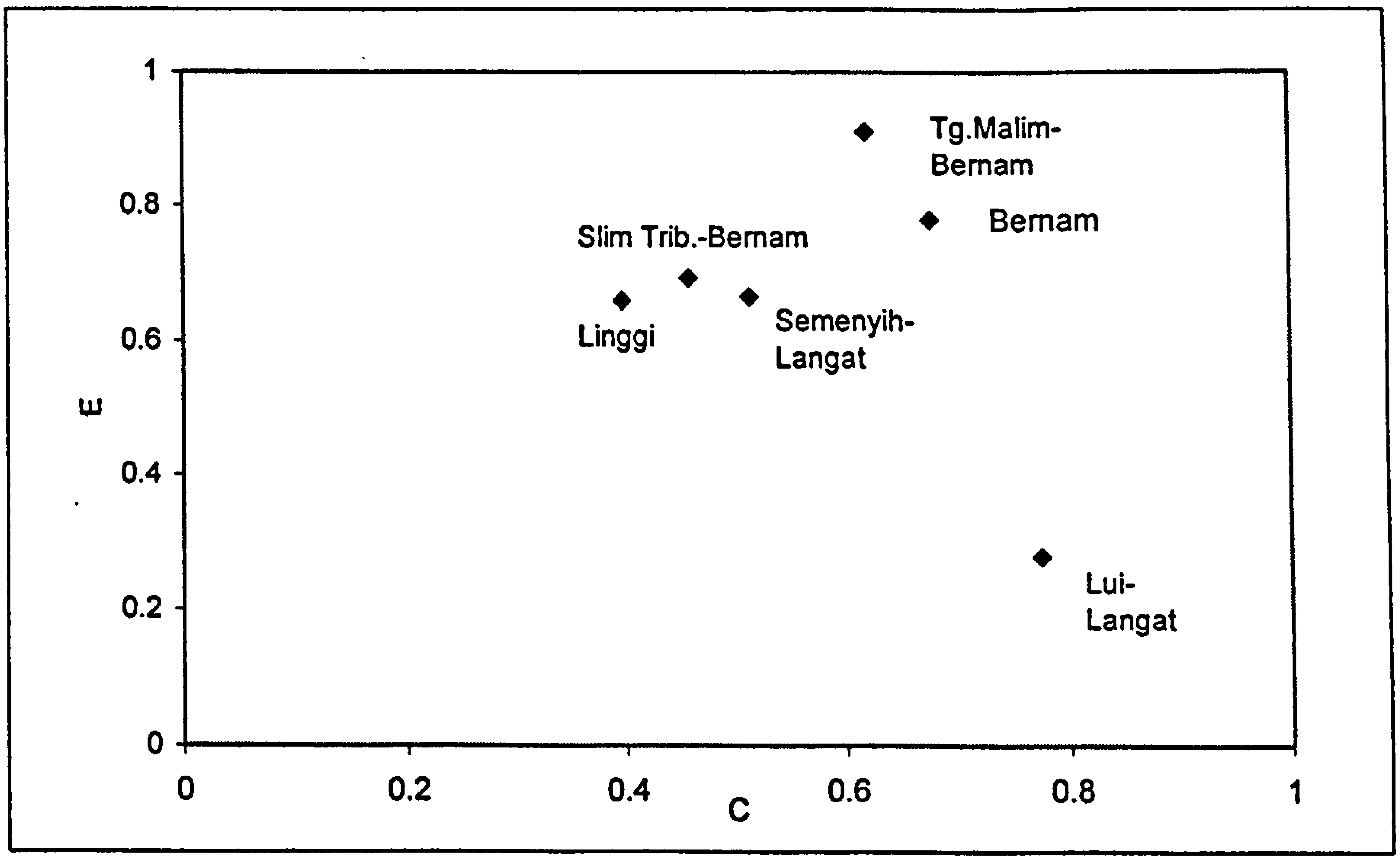


Figure 3.12: Main sub-catchments (6th order) relationship between basin Elongation (E) and Circularity (C)

3.4 Rationale of analogue catchment selection - the Langat and Linggi rivers

The selection of rivers as analogue catchments for the Bernam in this study is based on three main factors;

i. The Langat and Linggi catchments have been subjected to a rapid land use change since 1980 which has provided a major contribution for the economic growth and development of Kuala Lumpur. Since the Bernam catchment has been chosen as a new area for economic growth to support the Kuala Lumpur city centre (Eighth Malaysian Plan, 2000), there is a need to understand the effect of land use changes on water yield and water quality in these catchments in order to predict the future impacts in Bernam.

ii. Both catchments are situated on the west coast of Peninsular Malaysia which overall have similarities in rainfall, geology, soil and morphometric properties such as catchment size, drainage density, stream order and shape of catchment.

iii. Both catchment have been subjected to a variety of research carried out by many government agencies, especially DID and DOE since 1980, therefore, the availability of hydrological, water quality and land use historical datasets arguably met the research requirement, but with the need for some justifications and reservations.

The west coast of Peninsular Malaysia, which mainly focuses on Kuala Lumpur and neighbouring areas, has been the most developed area since Malaysian independence. There are a few other catchments, such as the Kinta catchment (Perak) and Juru catchment (Penang), about 140 km and 250 km north of Kuala Lumpur, respectively, which have also been subjected to rapid development, but they were quite far from Kuala Lumpur and dissimilar in terms of physical factors and morphometry. The catchments of the east coast could not be considered since the rainfall regime is quite different because of the Northeast Monsoon which brings a lot of rain to the area. Therefore, the selection of the Langat and Linggi catchments is expected to provide a useful analogue for the Bernam through the analysis of land use change impact on rainfall-runoff, sediment yield and also water quality. It is hoped that this information will help to establish transfer functions for Bernam in order to predict the future possible impact of land use changes on water yield and water quality.

3.5 Summary

This chapter provides basic information about the geology, topography and morphometry of the study sites (Langat, Linggi and Bernam catchments). It also highlights the potential of the selected urbanised Langat and Linggi catchments as anologues for predicting changes that may take place in the largely undeveloped Bernam catchment. The morphometric study provides information that is useful in understanding the relation between rainfall-runoff in response to changes (actual and planned) in land use. However, not all of the morphometric information is used subsequently in discussion due to the limitations of the hydrological data. Chapter Four elaborates on an assessment of the archived hydrological data in the context of analysing the effects of land use change on water yield and water quality.

CHAPTER FOUR:
DATA SOURCES AND RESEARCH METHODOLOGY

4.1 Introduction

To achieve the aims and objectives of the study, archived hydrological, water quality and land use data for the years 1960 to 2002 were analysed. All of these data sets were obtained from various Malaysian government agencies. This chapter describes and evaluates the sources and background of the datasets, including the data collection procedures adopted by each agency; the methods used in the computation of areal rainfall, runoff and sediment yield; land use satellite imagery processing; and water quality analysis. This chapter will provide data quality assurance thorough a number of validation processes; this is the first objective of the study. The validation process reveals that there are many limitations on the use of the dataset due to missing data or data that contains errors or inaccuracies. This has reduced the amount of data available for rainfall-runoff analysis, in some cases leading to a removal of catchments from the analyses and producing significant gaps in time-series. The various statistical techniques used for data screening, validation and analysis are also set out.

4.2 Archived data sources

In a study that relates changes in water management and runoff to changes in land use, there are needs for data covering a long period of time, if possible, several decades, especially in tropical areas that are subject to climatic variability (Manley and Askew, 1993). Since the studies involve two developed catchments, Langat and Linggi, which are expected to act as an analogue in providing information about potential changes in water yield and water chemistry in the undeveloped Bernam catchment, it is important to understand hydrological relationships before, during and after land use changes have occurred.

It has been suggested that a 40-60 year record is required in order to acquire some level of confidence in hydrological analyses (Bonell and Balek, 1993). But, for tropical regions like Malaysia, which have become independent states only in the last four decades, records of such length are rare due to lack of instrumentation, expertise, budget and environmental limitations. Despite these difficulties, hydrological records of 40 to

50 years length have been acquired and have been through data screening as a validation process.

4.2.1 Hydrological data

Hydrological and water quality data - namely rainfall, river discharge, suspended sediment discharge (SSQ) and suspended sediment concentration (SSC) – form the main basis of this research. These data have been selected in order to recognise key catchment relationships in the rainfall-runoff process, sediment transport and hydrochemistry affected by land use change. The source of these historical data was the Department of Irrigation (DID), Malaysia. In terms of quality assurance, it is understood that DID has followed its departmental guidelines, manuals and hydrological procedures of operation and that these closely follow those of the World Meteorological Organisation (WMO) for standardization of observation and instrumentation, technical regulations and guidance on practice. Therefore, the data quality control implemented by DID should be acceptable. Most of the data stored in Notepad format by DID and are later transferred to MS Excel worksheets in order to provide a time-series database. The data checklists of the selected gauging stations are given in **Appendix 2.**

4.2.1.1 Rainfall

The rainfall data were obtained from the Department of Irrigation (DID), Malaysia. DID is the only government agency which supplies data for the whole of the main Malaysian drainage basins free of charge. They have established many monitoring stations since 1930, especially for rainfall, and provide the long historical record required by this study. There are a few private agencies and research institutes like universities, which conduct research relating to hydrology, but they do not have complete information/data records extending over long periods of time. The Meteorological Office also has a historical data archive, but it does not have many stations, unlike DID, and record length is often very limited.

Rainfall is expressed as the depth of standing water that would accumulate on a level surface per unit time. The exposure of a rain gauge, such as its height above ground level, shape, diameter of orifice, material, surroundings (trees, building etc), human error (instrument reading and keying in of data) and even the method of installation, can vary widely. Each of these factors, in addition to the prevailing climatic conditions (two monsoons seasons) and local storm movement direction, will affect the actual and reported catch of a rain gauge. Certain of these factors have been found to affect the raw rainfall data obtained from DID and need to be considered in order to get best estimates of rainfall. For example, two different rain gauges situated close to each other in the Bernam catchment (200 meters apart) did not give the same values of rainfall catch even during the same thunderstorms. Based on observation during the field visit, all of the rain gauges are properly installed by DID and there is no shading effect from nearest trees. In addition, problems such as the short duration of available data, missing records, lack of record homogeneity and accuracy of point rainfall conversion to areal estimate should also be considered. Therefore, all of the data had to undergo thorough checking using deductive, analytical time-series analysis.

In1984 DID maintained a total of 1050 rainfall stations in the whole of Malaysia. The DID standard rain gauge has a 203 mm (8 in) diameter orifice which stands at 1.37 m (4 ft 6 in) above ground level and is fitted with a standard windshield; since 1973 recording has been measured by means of a tipping bucket (0.5 mm/tip). Before that, DID used a 127 mm (5 in) diameter orifice as recommended by the World Meteorological Organisation (WMO). To understand if a change of equipment has affected the record, a double mass curve analysis has been applied.

DID has stressed that a study of the effect of exposure on rainfall catch by certain type of rain gauge under different tropical climate conditions (as experienced in east and west coast of Peninsular Malaysia) is essential in order to get a best representative value for all rainfall events. From the study of the performance of the 203 mm (8 in) gauge compared to 127 mm (5 in) gauge in terms of windshield effectiveness and gauge height from the ground, it has been found that the 203 mm (8 in) performs reasonably well (Desa and Niemczynowicz, 1996). Therefore, this gauge has been use by DID since July 1973 as a very high standard gauge to record the rainfall data in Malaysia. Gregory and Walling, (1973), had stressed that a rain gauge should have certain requirements such as prevention of out-splash and minimisation of evaporative loss from the collection vessel to ensure the quality of data collection. Rain gauge design could also influence the measurement results because of differences of specification between manufacturers.

In terms of locations of the rain gauges that have been used in this study for all three catchments, most of them have been situated in palm tree estates since 1930 and had been managed by the estate manager/estate personnel before DID fully took them over in the 1970s. How good the management by estate personnel was (in terms of knowledge, equipment, site management etc) is not questionable since most of them were British or trained by the British government and so would arguably follow the standards set at that time. But an inter-station correlation between DID and the nearest Meteorological Office gauges provide some indicator of the level of confidence in the quality of the database. Although the DID has monitored and managed all of the rain gauges since the 1970s, there are still missing values in the historical records. To deal with this problem, historical records from the Meteorological Office have been used for interpolation where required.

All rainfall data were obtained as daily point rainfall (mm) recorded at 09.00 hours. Since rainfall is unevenly distributed over the catchment, with rainfall depth decreasing with distance from a storm centre, a large variation can occur over relatively short distances. To overcome this problem, in part, catchment rainfall has been calculated from point rainfall using the Thiessen Polygon method (Thiessen, 1911). There are other common methods normally used to calculate areal rainfall such as Arithmetic Average, the Isohyetal Method, the Least-Square Surface Method, Inverse-Distance Interpolation, Optimal Interpolation/Kriging (Ayoade, 1988; Dingman, 1994 and Wanielista *et al.*, 1997), etc, but since the topography of the study catchments in this research is not flat, the number of rain gauges is very limited and the gauges are non-uniformly distributed over the catchment, the Thiessen Polygon method is the more appropriate and commonly used method for the analysis (Dingman, 1994).

Despite Dingman's (1994) caution that the Thiessen Polygon and Arithmetic Average methods are not suitable for handling data where topography is important unless the area has lots of gauges well distributed over the region, Thiessen Polygon is an interpolation method that assumes the values of unsampled locations are equal to the value of the nearest sampled point/rain gauge. It defines the individual regions of influence around each of a set of points such that any area within a particular polygon is nearer to that polygon's point (rain gauge) than to any other point, and, therefore, has the same value of rain (Goovaerts, 2000). A difficulty with this approach is that the measures are assumed to be more homogenous within units (polygons) and to change only at the boundaries. Since there is only one observation per polygon no within-area variation can be estimated (Tabious and Salas, 1985). This limitation will not have a significant impact on this study, since the purpose of the analysis is only to produce an areal estimate for every catchment, which will be used later in the catchment rainfall-runoff analysis.

Thiessen Polygons have been used to provide a best estimate of areal rainfall from point rainfall for the Langat, Linggi and Bernam catchments for the period from 1960 until 2002. This length of period has been chosen for the study coverage since most of the hydrological records are available from the country's data provider. However, the number of rain gauges available is very limited. Several rain gauges with long records have been used for all of the catchments. Hitherto, all of the available records have been through a thorough verification process. This used time-series analysis to visualise and inspect any systematic pattern for month, season and yearly datasets to check any inconsistency and also reliability. Due to this, a few gauges with long periods of incomplete data were left out (**Table 4.1**).

Table 4.1: All catchments: List of rain gauge used and left out for areal rainfall calculation

Catchment	Gauges used/year of record	Gauges left out/year of record
Langat	Ampang (1947-1995) Rinching (1948-1994) West Country (1949-1994) Lenggeng (1948-2000) Setul (1950-2002) Labu (1948-2002)	Peres (1993-2003)* Lui (1970-2003)* TNB (1946-2003)* Sedgeley (1930-2000)* Semenyih (1993-2003)* 6 kaki (1970-2003)* DID Kajang (1975-2003)*
Linggi	Setul (1950-2002) Pantai (1971-2002) Seremban (1951-2002) Per. Tinggi (1947-2002) Sua Betong (1948-2002)	Astana (1959-2003)* Mambau (1947-1987)* DID Sikamat (1971-2003)*
Bernam	Trolak (1948-2002) Bedford (1948-2002) Behrang (1948-1994) Hospital (1948-1994) Gumut (1948-2002)	Escort (1930-1996)* Ketoyong (1947-2003)* DID Tg. Malim (1996-2003)*

Note: * = contains missing values for more than half of the monthly or/and yearly record length.

Inevitably, the locations of gauges are not optimal for areal analysis, especially in Bernam where all of the rain gauges are situated in the lowland areas which cover about 70 % of the catchment. In fact, all the gauges selected still include a few months or/and years with missing values (**Table 4.2**). These records need to be treated (filled in) prior to the areal calculation. Therefore, an inter-station correlation and double mass curve analyses have been performed between DID gauges and the nearest Meteorological Office gauges located within catchments to get a transfer function for annual data only. These procedure(s) allowed for the process of filling in missing values for certain rain gauges for short periods where required. The reference gauges from the Meteorological Office have been used since they are arguably acceptable in terms of quality control. However, the Meteorological Office gauges only give yearly data and the number of stations is limited. Therefore, the DID gauges which have daily, monthly and yearly data have been retained as the main source for the study. The length of the records used in this analysis varies since it is only based on the complete annual data for both gauges; hence in, some cases, outliers were removed.

Table 4.2: All catchment rain gauges: Periods which involve the process of filling in missing values using a transfer function from inter-station correlation to form a database for study from 1960-2002

Catchment	Rain gauge/periods of record	Year of fill in data from 1960	Transfer function gauge
Langat	Ampang (1947-1995)	1967-69, 75* & 1996-2002**	Met.Off. TNB vs Ampang
	Rinching (1948-1994)	1964, 69, 75, 77, 96* & 1997-2002**	Met.Off. Bangi vs Rinching
	West Country (1949-1994)	1995-2002**	Met.Off. Bangi vs West Country
	Lenggeng (1948-2000)	1963-65, 75-77, 84-85, 2000* & 2001-02**	Met.Off. Bangi vs Lenggeng
	Setul (1950-2002)	1970-71, 74-76 & 1986*	Met.Off. Seremban vs Setul
	Labu (1948-2002)	1985-88 & 2000*	Met.Off. Seremban vs Labu
Linggi	Setul (1950-2002)	1970-71, 74-76 & 1986*	Met.Off. vs Setul
	Pantai (1971-2002)	1960-69**, 70-73, 78-79 & 1982*	Met.Off. vs Pantai
	Met. Off. Seremban (1951-2002)	All completed	-
	Per. Tinggi (1947-2002)	1966, 73, 78, 82, 95 & 1998-2001*	Met.Off. vs Per.Tinggi
	Sua Betong (1948-2002)	1962, 67-68, 76-80 & 1991-97*	Met.Off. vs Sua Betong
Bernam	Trolak (1948-2002)	1961-62, 72 & 1986-88*	Met.Off. T.Malim vs Trolak
	Bedford (1948-2002)	1961-62, 69, 72, 80-81, 86 & 1995*	Met.Off. T.Malim vs Bedford
	Behrang (1948-1994)	1960**, 87, 91*, 1994-2002**	Met.Off. Behrang vs Behrang
	Hospital (1948-1994)	1962*, 1995-2002**	Met.Off. T.Malim & DID vs Hospital
	Gumut (1948-2002)	1960-62, 77, 99 & 2001*	Met.Off. T.Malim vs Gumut

Note: * month missing; ** year missing

The transfer function output from inter-station correlation analyses for all catchments **(Table 4.3 and Figures 4.1, 4.2 and 4.3)** shows a very high correlation between Meteorological Office and DID gauges. It has been shown by the slope that the regression coefficient values for several gauges fall between 92 – 99 % for all catchments at a level of significance of 0.01. These highly correlated values reflect the very close distance between gauges where the average separations for Langat, Linggi and Bernam are 5, 4 and 3 km, respectively. These distances could minimise the effect of rainfall spottiness from convective storms. However, there are cases in each catchment where the slope values fall to around 84%, with lower significance for certain gauges, even where the distance between gauges is relatively small (about 3 km). This shows that in the complex tropical system, rainfall spottiness has a significant influence on the rainfall catch within the catchment. In these cases, the transfer function has still been used, since they represent the only option available after going through rigorous data assessment. It is expected that the effect from this less good data will not have a large impact on the areal rainfall since it is only used to fill in several missing years at related point gauges which represent a small portion of the weighted areal rainfall for the whole catchment. These transfer functions were used to fill in the missing annual data for related gauges. For all of the catchments, the length of data that has been treated is between 13 – 37 % of the total record length (43 years). This is large, but with closely correlated transfer functions, it is hoped that point rainfall can stand as an acceptable data surrogate in the areal rainfall calculation **(Table 4.4)**. The correlation values for Langat range from 0.52 to 0.79 with an average distance between gauges of about; 16 km, 0.51 to 0.89 for Linggi with a distance of 22 km; and 0.52 to 0.75 for Bernam with a distance of 18 km.

Table 4.3: Statistical summary for established transfer function from inter-station correlation analyses of annual rainfall

Catchment	Rain gauge	Distance (km)	Period	N	R	R^2	Sig. level	Slope*	Standard error
Langat	MO Bangi - West Country	1	1985-1994	10	0.8988	0.8079	0.01	0.9741	111.14
	MO Seremban - Setul	2.7	1985-1997	13	0.8877	0.7880	0.01	0.8460	111.64
	MO Seremban - Labu	3.4	1951-1985	35	0.4334	0.1878	0.01	0.9970	297.17
	MO Reservoir - DID Ampang	4.8	1982-1995	14	0.4601	0.2117	0.1	1.0156	267.36
	MO Bangi - Rinching	6.9	1985-1995	11	0.8250	0.6806	0.01	0.9991	171.95
	MO Semenyih - Lenggeng	11.3	1988-2000	13	0.6340	0.4019	0.05	0.9646	329.02
Linggi	MO Seremban - Pantai	2.6	1983-2002	20	0.7212	0.5201	0.01	0.9499	217.36
	MO Seremban - Setul	2.7	1985-1997	13	0.8877	0.7880	0.01	0.8460	111.64
	MO Seremban - Per. Tinggi	2.9	1983-1993	11	0.7984	0.6374	0.01	1.0097	221.97
	MO Seremban - Sua Betong	5.7	1979-1990	12	0.3017	0.0910	n.s	0.9988	351.14
Bernam	MO T.Malim - Hospital	0.2	1951-1994	44	0.9850	0.9703	0.01	0.9909	62.55
	MO Behrang - Behrang	1.2	1974-1993	18	0.2387	0.0570	n.s	1.0950	507.36
	MO T.Malim - Gumut	2	1951-1995	45	0.4464	0.1993	0.01	1.0603	359.27
	MO Trolak - Trolak	2.9	1975-2001	27	0.3635	0.1321	0.1	0.9216	271.52
	MO Trolak - Bedford	6.5	1975-2002	28	0.7261	0.5272	0.01	0.8254	266.70

Note: * All regression forced through zero (assumed same rainfall event occurs at both gauges); n.s = not significant

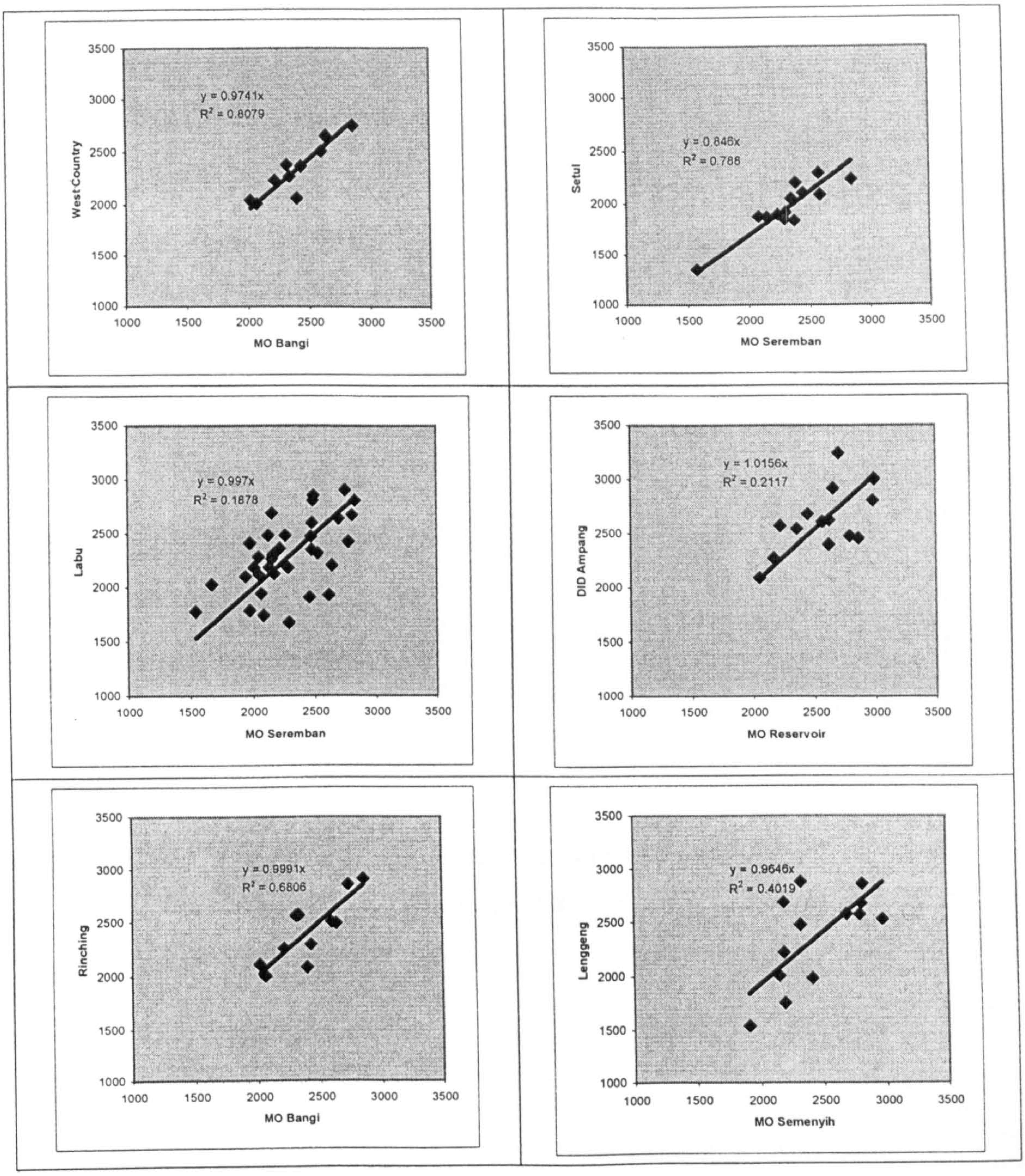


Figure 4.1: Langat catchment: Inter-station correlation for annual rainfall transfer function

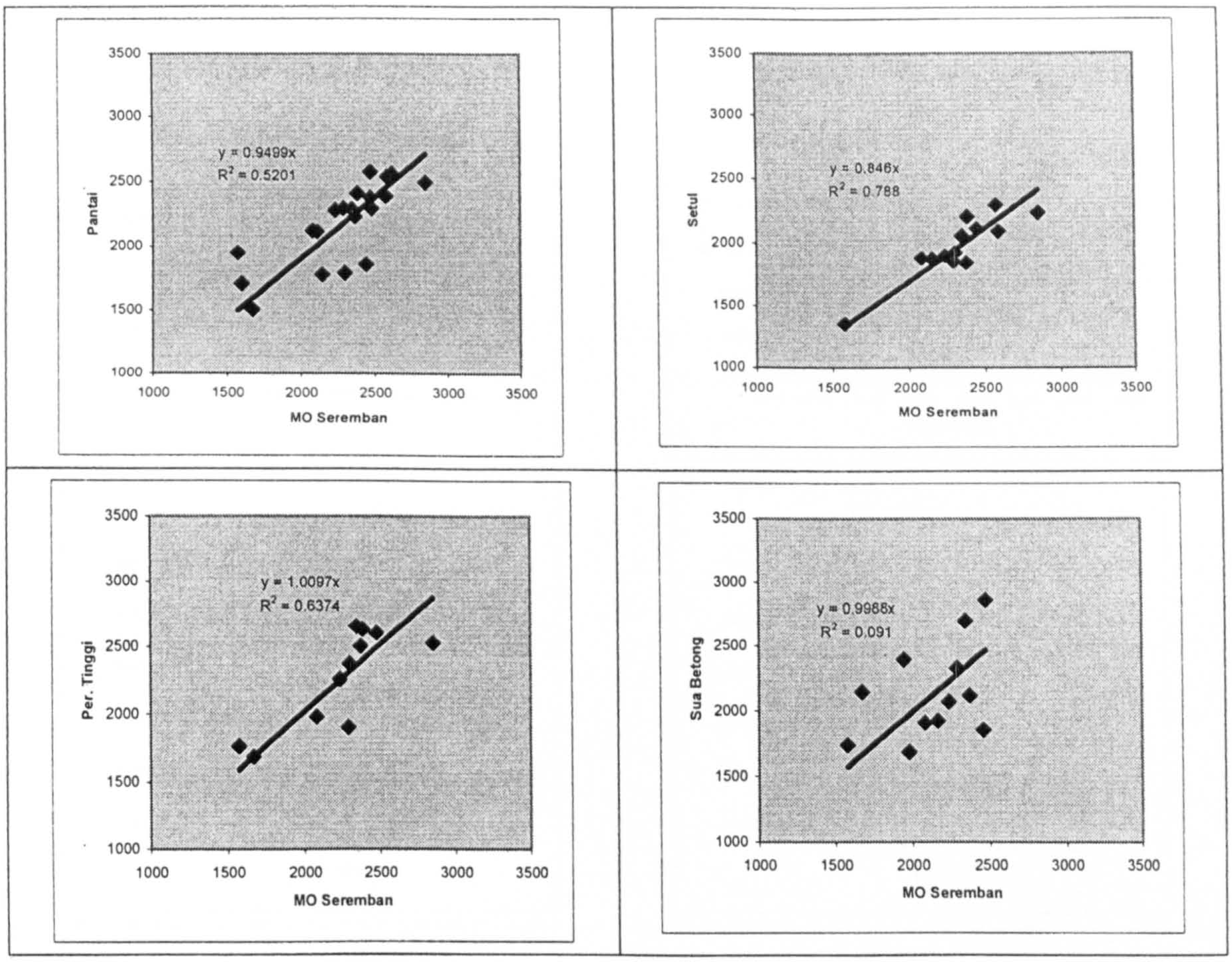


Figure 4.2: Linggi catchment: Inter-station correlation for annual rainfall transfer function

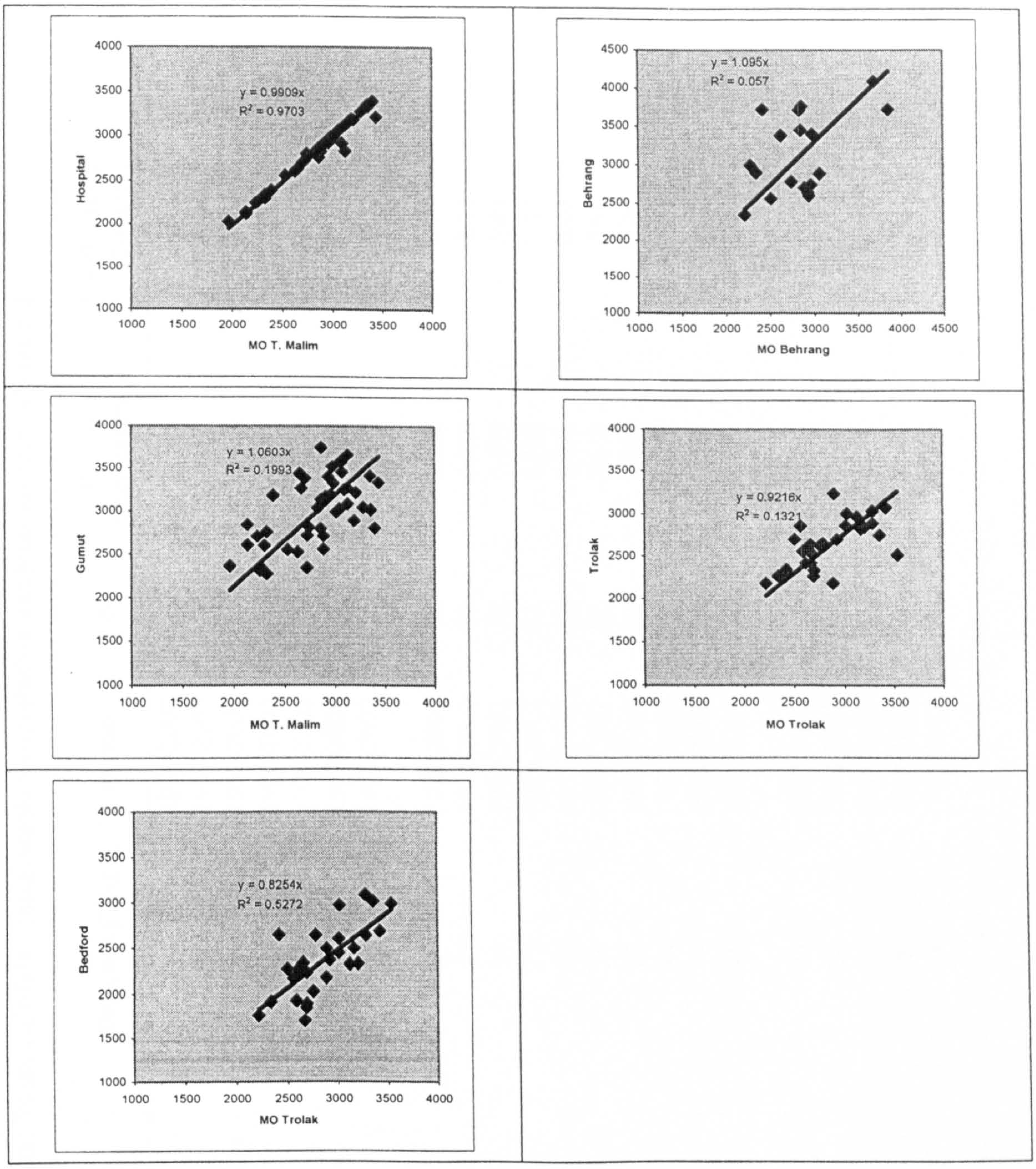


Figure 4.3: Bernam catchment: Inter-station correlation for annual rainfall transfer function

Table 4.4: All catchments: Point rainfall - inter-station correlation analyses for annual rainfall

Catchment	Rain gauge	Distance (km)	Period	N	Pearson Correlation, r	Significant level (2-tailed)
Langat	West Country - Rinching	16	1950-2002	53	0.797	0.01
	Labu - Setul	14	1950-2002	53	0.684	0.01
	DID Ampang – West Country	22	1950-2002	53	0.598	0.01
	Lenggeng – West Country	28	1950-2002	53	0.533	0.01
	Lenggeng - Rinching	9	1950-2002	53	0.520	0.01
	Rinching - Setul	17	1950-2002	53	0.519	0.01
	Lengeng -Setul	8	1950-2002	53	0.489	0.01
Linggi	Pantai – Per. Tinggi	19	1951-2002	52	0.890	0.01
	Seremban – Per. Tinggi	13	1951-2002	52	0.820	0.01
	Sua Betong – Per. Tinggi	24	1951-2002	52	0.739	0.01
	Seremban - Pantai	12	1951-2002	52	0.705	0.01
	Pantai – Sua Betong	38	1951-2002	52	0.621	0.01
	Seremban – Sua Betong	28	1951-2002	52	0.619	0.01
	Setul – Per. Tinggi	24	1951-2002	52	0.603	0.01
	Seremban – Setul	14	1951-2002	52	0.559	0.01
	Setul - Pantai	11	1951-2002	52	0.556	0.01
	Setul – Sua Betong	40	1951-2002	52	0.512	0.01
Bernam	Hospital - Bedford	22	1948-2002	55	0.745	0.01
	Hospital - Trolak	28	1948-2002	55	0.680	0.01
	Hospital - Gumut	7	1948-2002	55	0.677	0.01
	Trolak - Bedford	8	1948-2002	55	0.661	0.01
	Gumut - Bedford	28	1948-2002	55	0.521	0.01

Table 4.5: Point rain gauge and weighted area use in an areal rainfall estimation using the Thiessen Polygon method

No.	Rain gauge/polygon	Area (km^2)	Weighted area
	Langat catchment (1950-2002, 53 years):		
1.	Ampang	402	0.32
2.	Rinching	278	0.22
3.	West Country	274	0.22
4.	Lenggeng	141	0.11
5.	Setul	78	0.06
6.	Labu	85	0.07
		1257	**1**
	Linggi catchment (1951-2002, 52 years):		
1.	Setul	24	0.05
2.	Pantai	1234	0.25
3.	Seremban	145	0.28
4.	Per. Tinggi	126	0.24
5.	Sua Betong	100	0.19
		529	**1**
	Bernam catchment (1948-2002, 55 years):		
1.	Trolak	200	0.18
2.	Bedford	403	0.36
3.	Behrang	220	0.20
4.	Hospital	188	0.17
5.	Gumut	111	0.10
		1123	**1**
	Bernam catchment:		
1.	Trolak		
	Lowland	115	0.11
	Upland	84	0.08
2.	Bedford		
	Lowland	173	0.16
	Upland	230	0.21
3.	Behrang		
	Lowland	184	0.17
	Upland	37	0.03
4.	Hospital		
	Lowland	115	0.10
	Upland	74	0.07
5.	Gumut		
	Lowland	82	0.07
	Upland	29	0.03
	Lowland	669 (60%)	1
	Upland	454 (40%)	

The creation of Thiessen Polygons for Langat and Linggi (**Table 4.5**) catchments is reasonable and fulfils a basic principle of the method. The perpendicular lines bisect the adjoining (triangulation) lines evenly and form a polygon highly representative of the areal estimation for the whole catchment (**Figures 4.4 - 4.6**). However, for the Langat catchment, there is no gauge available with a full length of records for the upland areas. Therefore, the headwater areas in Langat and Semenyih are based on rainfall recorded at the lowland station of Ampang (DID). This gauge has a very strong correlation, $R^2 = 0.84$, $p = 0.01$, with the upland gauge belonging to the Meteorological Office at Langat Reservoir, with a distance of about 4.8 km between them, but the annual records are only available for 14 years. Therefore, the upland areas are expected not to affect significantly the amount of rainfall received by this particular polygon. The figures for the Linggi headwaters are based on Pantai rainfall data.

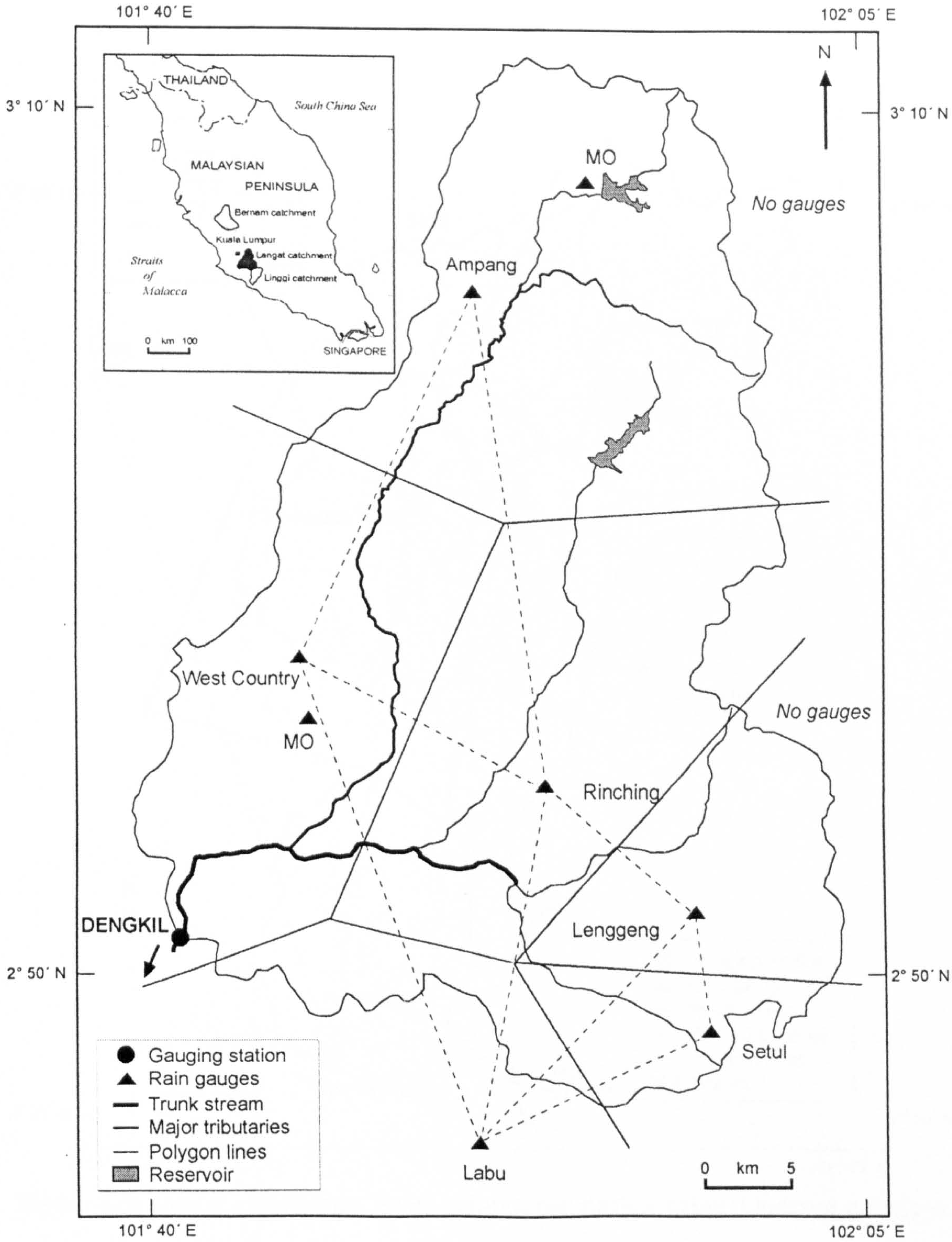


Figure 4.4: Langat catchment: Areal rainfall estimation using Thiessen polygons

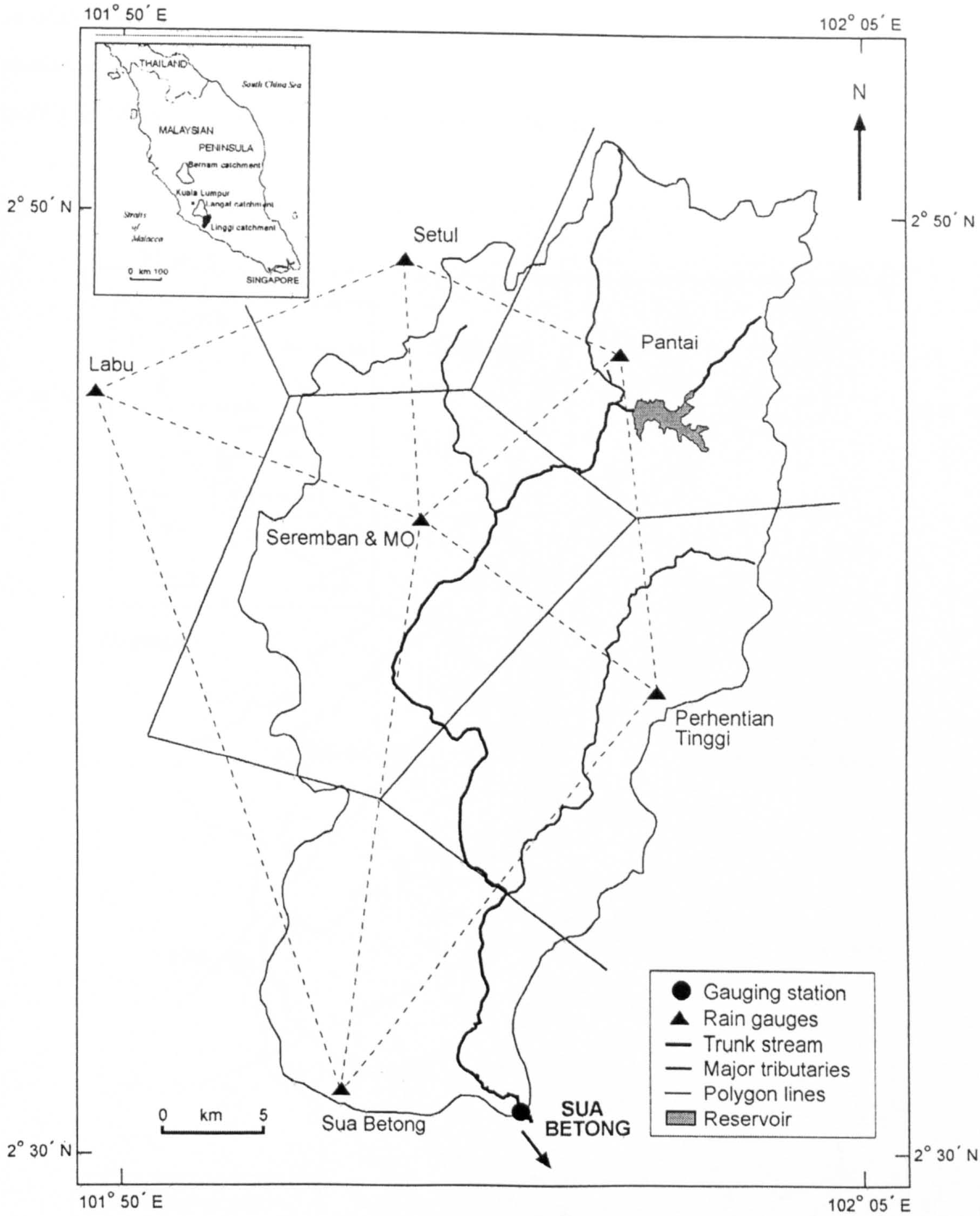


Figure 4.5: Linggi catchment: Areal rainfall estimation using Thiessen polygons

In Bernam, the establishment of Thiessen Polygon is complicated, since all of the limited number of available rain gauges are located in the lowlands and this provides no chance of constructing proper polygons to represent the whole of the catchment (**Table 4.2** and **Figure 4.6**). The only way to follow the principle of the Thiessen method in Bernam is by creating a perpendicular line to bisect evenly the lines between rain gauges. Prior to this, the catchment itself was divided into two 'regions', namely upland and lowland, by an arbitrary line along the 1000 metre contour. The estimation of areal rainfall for all lowland polygons will be based on the included point rain gauge readings; all the fractional areas located in the upland areas have been subjected to a multiplier derived from Langat's lowland-upland rainfall relationship.

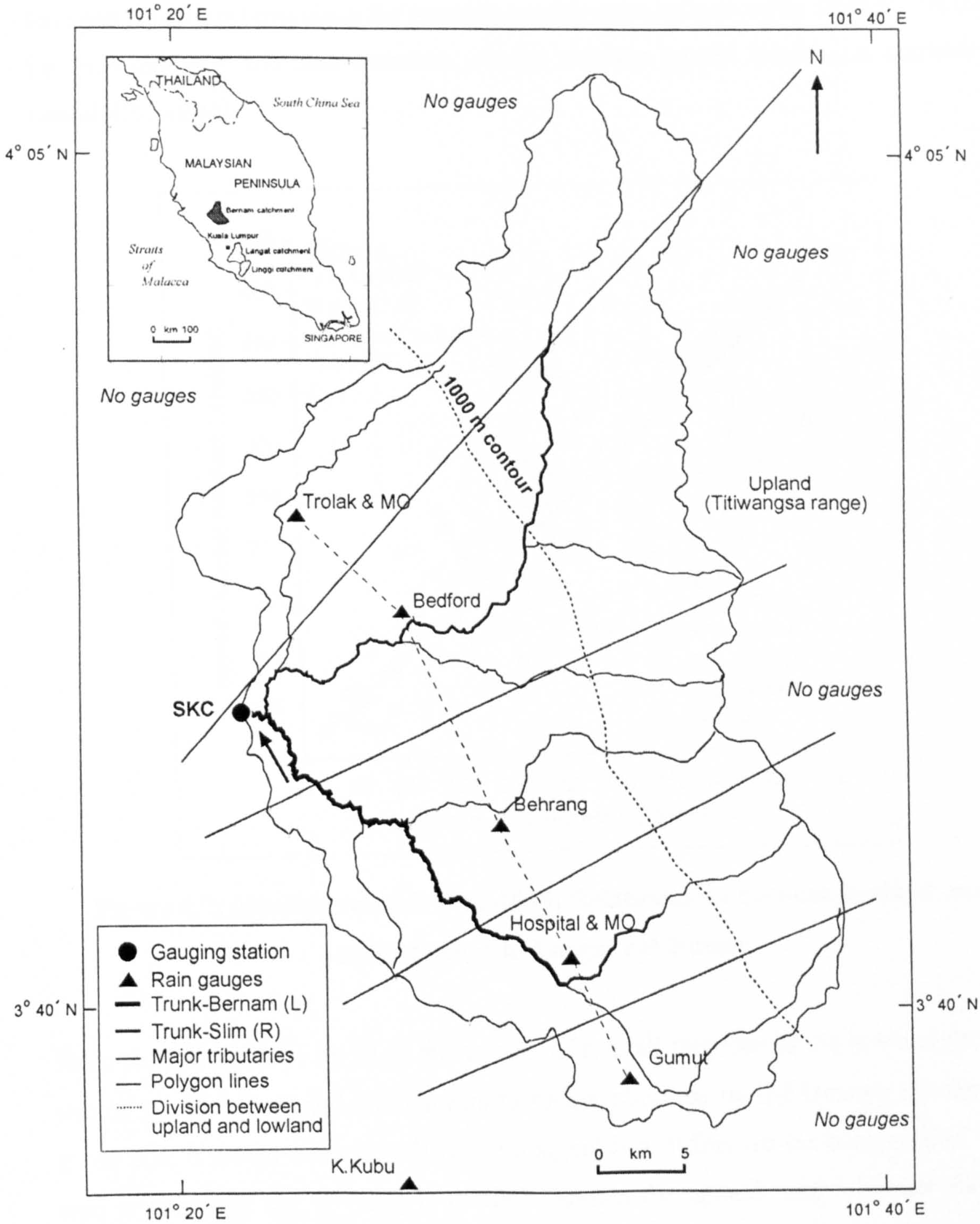


Figure 4.6: Bernam catchment: Areal rainfall estimation using Thiessen polygons

Here, a regression analysis has been developed to relate monthly rainfall data (1982-1995) for the DID gauge in Ampang and the Meteorological Office gauge at Langat reservoir (2000 metres above sea level; **Figure 4.7**). This period is representative of the climatic influence of El Nino and La Nina years and their effect on the amount of rainfall received in a particular year. The data variations between these two stations (12 km apart) are quite large since the monthly records were influenced by temporal factors, i.e., two monsoon and inter-monsoon seasons and also spatial factors, i.e. convective rainfall (localised).

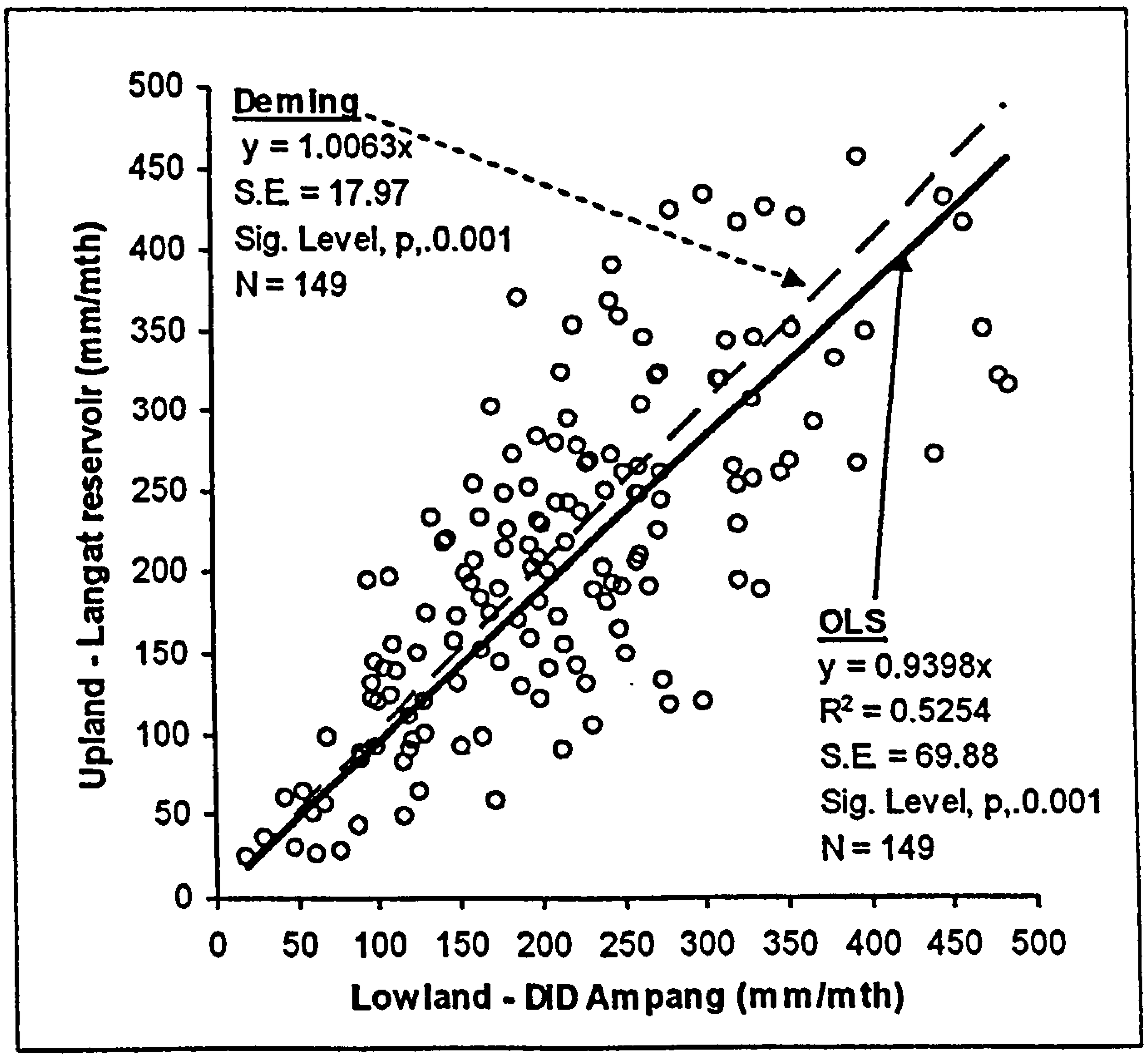


Figure 4.7: Monthly rainfall 1982-1995: Relationships between lowland and upland gauge in Langat catchment

From the relationships by OLS, the amount of rainfall recorded at the lowland gauge is almost 1:1 to upland and this appears to be corroborated by the Deming relation. So, given this, it would seem that there is no significant difference (as corroborated by (t-test) significance test, p=0.37) in rainfall between the uplands and lowlands allowing the use of all rainfall data from lowland gauges in Bernam. However, there is a question about the influence of occult precipitation particularly in Bernam where the amount of primary forest is large in the area. There is an attempt to use a suggestion fog precipitation value by Holder (2004) who conducted a study in the tropical mountain clouds forests of Guatemala (2400 km^2) effectively for elevations above 2550 metres. He suggested an approximate value for fog precipitation of 1 mm/day (during the wet season) and 0.5 mm/day (during dry season) which contributes to an annual value of 274 mm. If we consider the suggested value for the Bernam catchment which experiences yearly wet and dry seasons of equal length, a rainfall amount of 274 mm/yr should be added to the existing point rainfall in every polygon situated in an upland area to give a general indication about the function of fog precipitation in the catchment. But, this method is not relevant since the sites considered are very different geographically.

Occult precipitation is one of the factors that reduces the interception capacity. In the tropics, many of the rain storms occur in late afternoon after the atmospheric day-time sensible heating has reduced relative humidity and dried of of the leaf surfaces, so restoring interception capacity. This would mean an interception loss to evaporation unaffected by occult precipitation. This, in turn, leaves the question on how much fog drip has moistened the forest soil, so reducing absorbance of afternoon rainfall and promoting interflow or even saturation overland flow. It is undoubtedly a factor, but, with data limitations, its effect could not be quantified. The relation established from the Langat upland/lowland study suggested a multiplier of unity. So, in the absence of other information, it was decided to use a correction factor of near unity, derived from the Langat regression analysis.

Table 4.6: Descriptive statistics for Bernam Areal Rainfall based on three different methods of data treatment

Descriptive statistic	Lowland data	With lowland-upland t.function	With fog precipitation value	Met. Office T.Malim
Mean	2885	2815	3000	2790
Standard Error	45	43	45	50
Median	2902	2893	3017	2857
Standard Deviation	330	321	330	371
Range	1347	1310	1347	1470
Minimum	2194	2141	2309	1965
Maximum	3540	3452	3655	3435
Count	55	55	55	55

A comparative analysis of the annual areal rainfall calculations based on three different datasets (all lowland data; data after applied lowland-upland transfer function; and data with contributions from fog precipitation) has been conducted (**Table 4.6; Figure 4.8**). From this analysis, there is no significant difference in annual areal rainfall between all lowland data and data with a transfer function even though the 'all lowland' data previously recorded a much higher rainfall. If we consider the suggested fog precipitation values from Holder, the differences between areal rainfall based on the transfer function and annual areal rainfall based on fog precipitation is actually quite small, where the areal rainfall with fog precipitation is slightly higher by around 4% (126 mm/yr). However, the exact amount of the contribution of fog precipitation in the upland areas of Bernam remains unclear since no proper measurements have been taken. With this small difference, it is expected that the influence of the rainfall amount on the annual runoff ratio over the catchment is unnoticeable. Therefore, for this study, the lowland-upland transfer function has been applied to the Bernam areal rainfall estimation and used for further rainfall-runoff analysis.

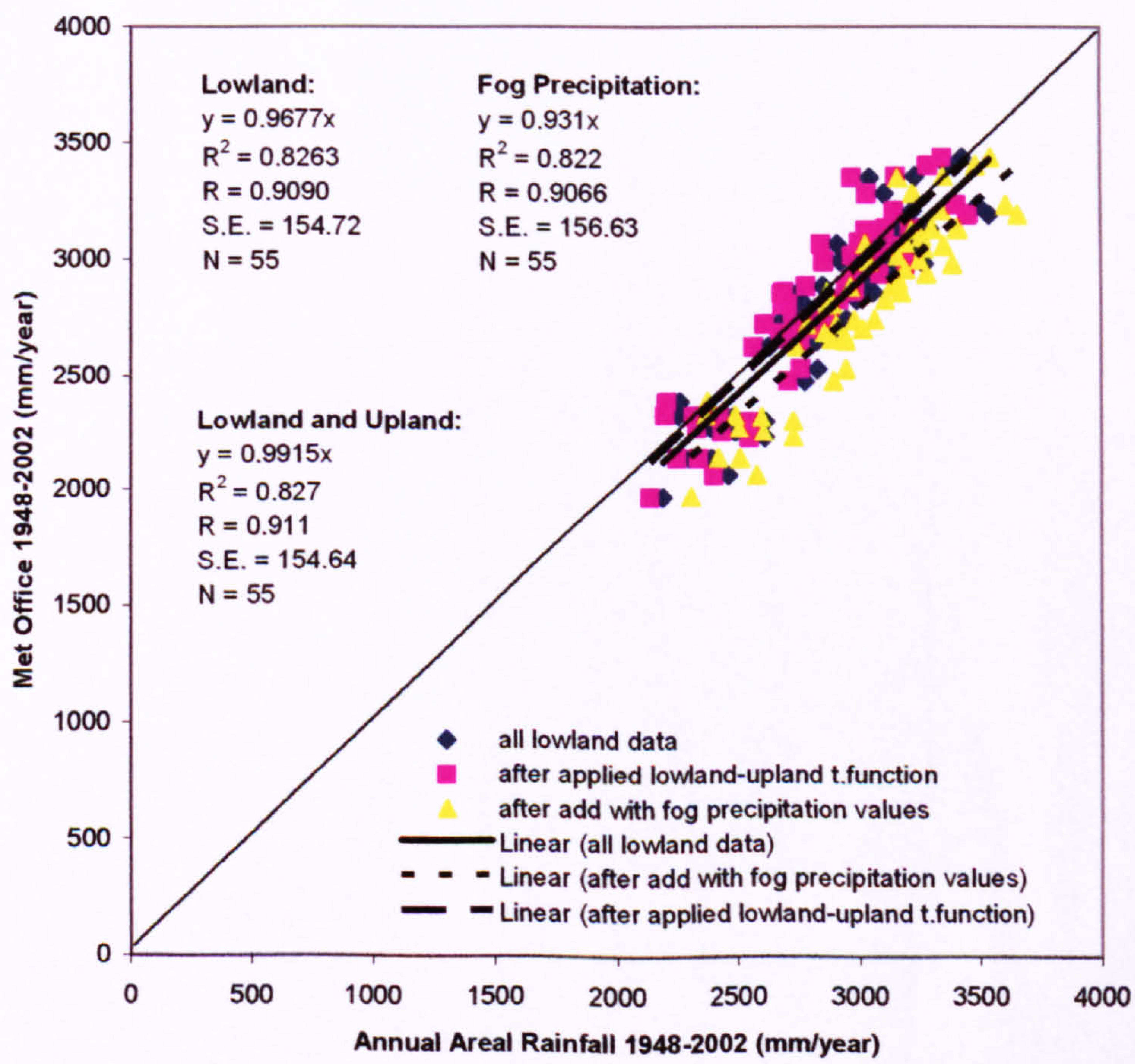


Figure 4.8: Bernam: Comparison of annual areal rainfall before and after the application of the transfer function factor and after the addition of fog precipitation values to Met. Office gauge, 1948-2002

After going through the various procedures for data screening and validation analysis, it is believed that the final output of catchment areal rainfall estimation for the Langat, Linggi and Bernam catchments are justified and that these can be used for further rainfall-runoff analysis. This is supported by a correlation analysis that compares the annual catchment areal rainfall with the Meteorological Office point record as the only 'credible' source available for all catchments. The results of this analysis (**Figure 4.9**) demonstrates a very close relationship (near-unity) between them which reflects the quality of the point rainfall data used and the ability of the Thiessen method to minimise the effects of spottiness and produce the best areal estimation for the research. The annual records are less complex than the monthly data, which are complicated by monsoon and inter-monsoon influences. Despite that, the quality of the point rainfall data still needs to be considered rigorously since there are gauges located close to each other that still do not produce similar or nearly similar records.

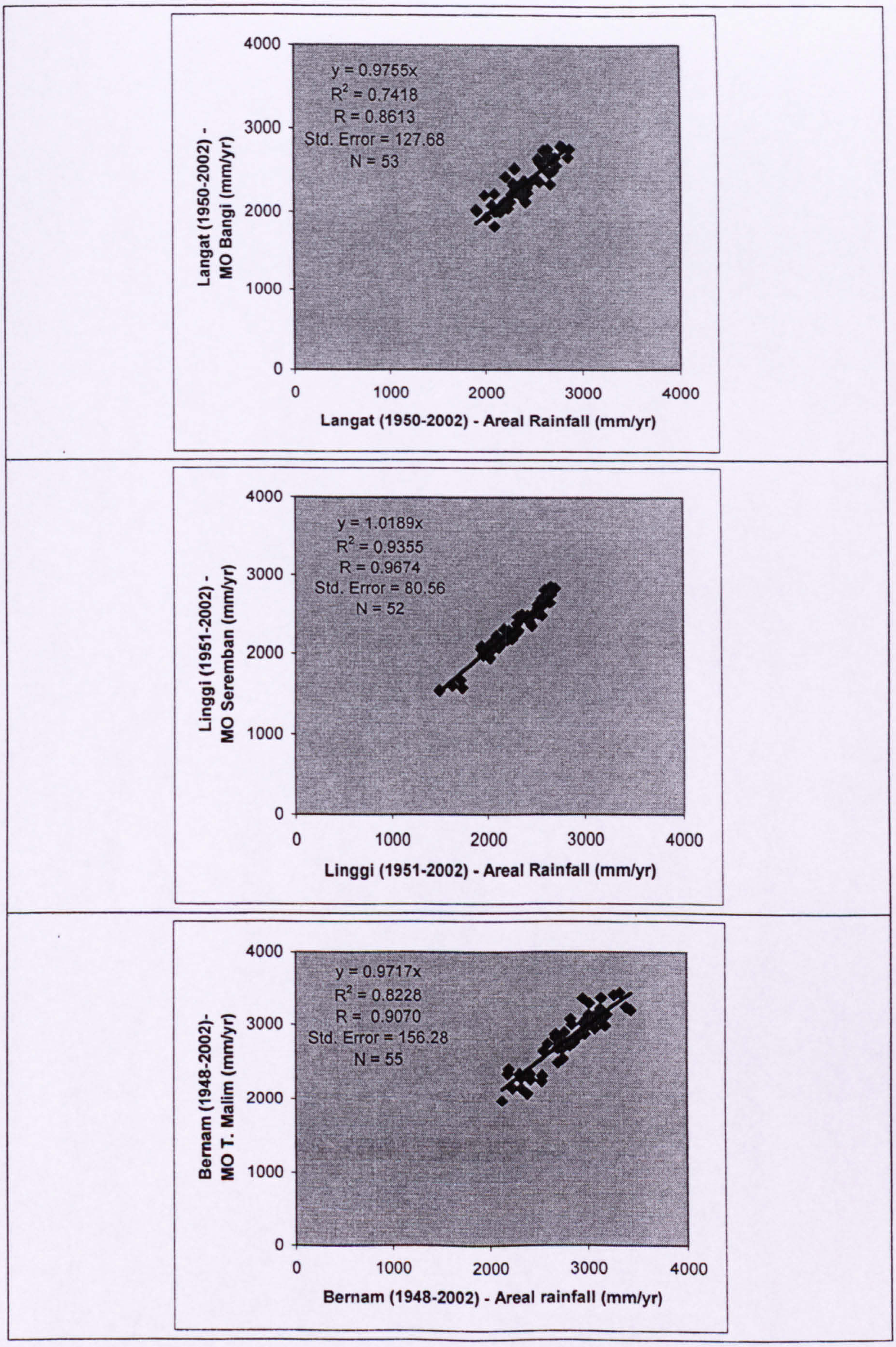


Figure 4.9: Met. Office rainfall versus Areal annual rainfall

4.2.1.2 River stage and discharge

09.00 daily stage (m) and discharge ($m^3\ s^{-1}$) data have been obtained from DID. The river discharge was gauged using current meters in order to establish a stage-discharge relation at each gauging site, and allow for the direct computation of river discharge from continuous water-level records. DID staff carry out a regular visit at each station in order to check for irregularities in the established DID rating curve.

During the 40 years of records, the rating curve has been changed several times, especially due to sedimentation. For the dataset supplied by DID for this research, there has been no need to apply a correction, since this has already been done by DID every time its database has changed. There are many missing values in the dataset, mostly due to instrumentation problems (water level recorder failure). During 43 years of records (1960-2002), there are 2,782 days (18 %), 1749 days (11 %) and 1577 days (10 %), missing for the Langat, Linggi and Bernam outlets, respectively. Although the amount of missing values seems small, they are spread out so that almost every single year contains incomplete records, whether days or months. For Langat, Linggi and Bernam, there were only 18, 23 and 27 years respectively with full records. None of these years are consecutive, which prevents provision an optimal of length of annual discharge for rainfall-runoff analysis.

So the study is only based on limited annual data, less than 70 % of a total of 43 years' records. In these cases, there is no intention of filling in the missing values because the gaps may include periods of changes in land-use, which may mean the introduction of inappropriate values. Therefore, for this study, the discharge analysis is based on complete and partially complete years. All of the available discharge data has been converted to runoff. Catchment water yield, or runoff depth per unit area, has been derived as equivalent depth in mm day^{-1}, month and year for rainfall-runoff analysis. In this study, the upland areas are highly likely to generate more runoff compared to lowland areas due to a contribution from fog precipitation. This makes it difficult to regard runoff as being uniform throughout a catchment. There is a possibility of high discharge measurements being recorded at catchment outlets due to the fog contribution even without lowland rainfall. However, the use of areal rainfall, which includes the potential contribution of rainfall from uplands areas, will hopefully provide a general catchment rainfall-runoff response, which would take into account the influences of rainfall from uplands and lowland within a catchment.

In this study, the interpretation of runoff is quick-return flow plus base-flow, unlike the normal situation where researchers concentrate on quick-return flow following hydrograph separation. Hydrograph separation has been used widely for water resources investigations. For example, the separation of streamflow hydrograph into base flow and surface runoff components is used to estimate the groundwater contribution to streamflow and to aid in the estimation of recharge rates. In addition, the base-flow characteristics determined by hydrograph separation draining different geological terrains will help to show the effect of lithology on base-flow.

The reason why the runoff has been defined as quick-return flow plus base-flow is because the hydrograph, based on available discharge records obtained from DID, could not be separated. Also, the hang-over from one storm to another cannot be clearly determined; to clarify the seasonal lag is also complicated, since the monsoon season plays a significant role in the amount of discharge recorded at gauging stations. Most researchers attempt to separate the hydrograph where they are interested in single storm response. In this study, it is not possible to define runoff based on a single storm because only daily records are provided. Therefore, it was decided to examine total basin outflow per unit time. This is best done over long period of time, in this case monthly and annually. However, the monthly data are affected by the monsoons. This explains why some of the relationships are complicated to describe (large scatter).

The rainfall-runoff relationship is an indicator used here to recognise any changes in water yield during pre- and post-development phases in the water catchments. Prior to the analysis, areal rainfall and runoff time series plots were examined for consistency in response patterns. A regression analysis of runoff on rainfall was carried out to obtain runoff coefficients. Since, there are many missing values in some datasets, partial and complete records were analyzed.

4.2.1.3 Suspended sediment concentration, discharge and sediment yield

Daily suspended sediment discharge (tonnes day^{-1}) data has been obtained from DID. These data were originally given as mean suspended sediment concentrations in mgl^{-1}, derived by sampling using a depth integrated sampling technique at flow/discharge measuring stations. Sediment concentration and water discharge were then used to compute a daily value for the suspended load.

Since the sediment rating curve also depends on the discharge record (stage-discharge rating curve), there are many missing values. For the Langat catchment, out of 24 years of record from 1977-2000, only two years have complete daily data and only five years contain less than 5% missing days. This would give less information for land use changes study. However, the Bernam catchment has much better data coverage with only one year containing missing values out of 23 years of record from 1977-1999. However, information from the Langat is vital since it has already undergone a varied phase of land development which could give some information for establishing a transfer function to predict what will happen in newly developed catchments like the Bernam.

The suspended sediment discharge data are based on an unknown rating curve or curves from 1960 till 2002. Since the rating curve(s) could not be obtained from DID, there is little hope of explaining the impact of land use development on sediment yield. As a consequence, a rating curve analysis was carried out using the limited information available for suspended sediment concentration in order to understand how the DID rating curves, used to generate the suspended sediment discharge were developed. This suggested that the DID sediment discharge data contained errors due to data processing. To overcome this problem, the available suspended sediment concentration data (mgl^{-1}) were obtained from DID, even though the records are very limited and only available for two of the catchments. For instance, suspended sediment concentration for the Langat catchment is available for the periods 1994 till 2002, which covers a period of development only, and for 1992 till 2002 in the Bernam. There is no record available for the Linggi.

As expected, the relationships between suspended concentration data and discharge are poor and the scatter is large. This is due to the complexity of the system (i.e. seasonal factors); while there is also the likely impact of equipment or operator error during sampling. Therefore, the predictions need to be treated with considerable caution.

With this limitation in mind, suspended sediment concentration was regressed on discharge using both ordinary least square regression and Deming regression. The rating curves were then used in conjunction with daily discharge data to calculate estimates suspended sediment yield. This gives some general view about the changing size of the suspended load of the river since the early stages of land development in the 1960s. Suspended sediment discharge data were divided by the area of the catchment (SSQ/A) to obtain the suspended sediment yield in tonnes km^{-2} day^{-1}. Since the rating curves used were based on a limited years of suspended concentration data, the results are treated with great caution.

In the first instance, Deming regression was used to derive a rating curve because it provides a less biased estimate of the relationship by assuming measurement errors in both X and Y variables. Deming regression can be used to indicate the impact of development on suspended sediment concentration as well as being used to extrapolate suspended sediment discharge (Ferguson, 1986). However, the use of Deming regression is problematic. For example, it cannot provide a standard error of the regression. Therefore, the ordinary least squares regression was used, particularly because it has been used universally by researchers.

However, suspended sediment concentrations and sediment discharge data generated from ordinary least squares regression rating curves based on discharge data are exposed to statistical bias, which leads to underestimates of the true value by up to 50% (Ferguson, 1986). In order to compensate, a simple correction factor ($2.65s^2$) has been applied to the rating curve in order to improve the estimates (Ferguson, 1986). The factor s^2 is the residual of the linear regression between SSC and Q. Since the rating curves for Langat and Bernam are based on logarithms to base 10, the correction factor for linear regression involves adding $2.65s^2$ to the intercept value

4.2.2 River water quality data

In Malaysia, the length of record and type of data available for water quality are variable due to various factors such as cost, equipment, experience of staff and numbers of possible parameters needing to be to measured at any one time. To date, there is no automatic monitoring even for parameters such as dissolved oxygen and temperature. Normally, samples are collected manually at supposedly 'fixed intervals', for instance, once in two months. There is no discharge measurement made during water quality sampling. Inconsistency in terms of date of sampling has caused problems with how to recognise the influence of wet and dry seasons on the level of pollutants entering the stream system.

The main obstacle is that the data collection is extremely sporadic, especially for heavy metal parameters and there is no simultaneous discharge data. This causes problems since the river flow dilutes the pollutant during the wet season and increases its concentration during the dry season. In attempting to use this data in a descriptive analysis, the data were set up as a time series. Later, water quality during discrete range of discharge data were analysed to minimise the impact of flow variability on the water quality data itself. However, the quantity of water quality data available within a discrete range of discharge is small, reducing the representativeness of the dataset. Despite this, these data have been used to attempt to recognise any trend in water quality due to land use activity in pre-, pro- and post-development periods.

The mean of two sequential days of daily discharge recorded was used to match against each water quality analysis. Since the discharge and water quality data came from different sources, use of the mean of two days' discharge was expected to suppress short-term fluctuations in the effect of flow during water quality sampling. With this limitation, the water quality analysis is more descriptive than quantitative and is only indicative of the magnitude and trend of pollutant discharge in the river systems due to various development activities.

In this research, water quality data (physical and chemical parameters) were obtained from the Department of the Environment (DOE), Malaysia. The length of the records only covers about 17 years starting from 1985 for Langat and Linggi, and from 1997 for Bernam, where there are few parameters measured, especially heavy metals and the amount of data is very sparse. Eight indicative parameters that can be used to describe the impact on water quality of land clearance, agricultural activities, urbanisation and industrialisation on water quality were chosen (**Table 4.7**). These are 5-day Biological Oxygen Demand (BOD), Suspended Sediment (SS), pH, Conductivity and Temperature, along with concentrations of Nitrate, Zinc, and Arsenic. The parameter most related to the higher amount of runoff produced by land clearance is suspended sediment concentration (SS). This parameter is expected to increase as runoff increases.

Other than this parameter, the level of water flowing in the river will play a significant role in diluting the level of pollutant concentration. A significant amount of pollutant could be released during the wet season, but this may not show in the monitored data because of dilution. Besides, pollution incidents may not be detected because the sampling is neither frequent nor consistent.

Table 4.7: Water quality parameters used in this study

Parameters	Possible sources
Suspended sediment concentration (SS)	Forest removal, agriculture conversion, soil erosion, etc
Temperature	Removal of forest canopy, current atmospheric temperature, industry waste, waste flow from irrigation sites
Biological oxygen demand (BOD)	Agriculture waste (oil palm and rubber), domestic waste
pH	Industry waste
Conductivity	Total ionic - general
Nitrate	Agriculture activity-fertilizer
Zinc	Industry waste, tin mining
Arsenic	Industry waste, agriculture-pesticides

4.2.3 Land use classification using data from Landsat and maps

Since the focus of this analysis is to get the historical spatial extent of land use areas for pre-determined categories, rather than a systematic and specific land use study, a simple classification system was designed with eight main classes, namely, forest, rubber tree, palm oil tree, transition class, cleared-felled area, built-up area, mining ponds and water body (**Table 4.8**). The transition class contains immature rubber and oil palm trees, grassland, pasture, horticultural land and other small crops. The transition class was formed since there is no clear division when separating low intensity vegetation cover in Landsat image processing due to pixel sharing. It is important to have the same number and type of land classification for both the land use maps and Landsat imagery so that changes can be detected through the two decades of the study periods.

All of the classified land use maps obtained from DOA, Malaysia, for the years 1984, 1990, 1997 and 2000 portray nine main categories, which themselves consist in total of between 34 and 46 smaller classes (**Table 4.9**). The number of small classes or sub categories seems to have increased over time, which may reflect the complexity of the land cover due to development expansion. These sub-classes were narrowed to 14 when the output of the Landsat imagery classification was produced so that the map and Landsat categorization corresponded (**Table 4.10**). Finally, further condensation provided eight main classes (**Table 4.8**).

Table 4.8: Land use classification scheme for all study maps

No.	Land use class	Description *
1.	Forest	Dipterocarp forest, reserve forest and wetland forest (mangrove, palm, "*Nipah*" and "*Gelam*")
2.	Rubber Tree	Rubber Tree plantation
3.	Oil Palm Tree	Oil Palm plantation
4.	Transition	Immature rubber and oil palm tree, grassland, pasture, horticultural lands and other small crops
5.	Cleared-felled Area	Within forest, rubber, oil palm or transition areas
6.	Built-Up Area	Settlements and associated urban areas
7.	Mining Ponds	Tin mining and other mining areas of standing water
8.	Water Body	Reservoir

* The description was established for the purpose of this study with some guidance from criteria established by the Department of Agriculture, Malaysia (2002)

The sub-category 'cloud' has to be formed because images for the Bernam catchment included clouds, especially in the uplands. All of the pixels that represent cloud lay over forest. The sub-categories of 'mining ponds' and 'water body', were difficult to differentiate on the Landsat images because the surface of the ponds is normally covered by algae which gives a green reflection.

The classes are similar to those used in land use studies by several researchers, such as Anderson *et al.* (1976). Kamaruzaman and Hasmadi (2000) used four broad classes, namely, primary forest, agriculture, urban/cleared land and water bodies in their studies of land cover change in the upper part of the Langat basin. Sharifah (1999) established six categories, namely, forest, agricultural, settlement/urban, grassland, bareland and water body for the whole Langat basin study. The objective of these two latter studies was to quantify and assess the rate of land cover change from 1993 to 1998 by using remote sensing techniques.

Since the focus of the present study is to investigate the impact of various types of land use change on hydrology and water quality, these eight main categories will act as an indicator in recognising change, especially forest conversion to agriculture or urban areas, and also agriculture conversion to urban. A summary of the possible impact from these eight land categories on hydrology and water quality relative to natural forest can be found in **Table 4.11.**

Table 4.9: Land use categories for maps of 1984, 1990, 1997 and 2000 produced by the Department of Agriculture (DOA), Malaysia

No	Main and sub land use categories	Map			
		1984	1990	1997	2000
1	**Settlements and associated non agricultural areas**				
	1.1 urban and associated areas	√	√	√	√
	1.2 cemetery		√	√	√
	1.3 recreational areas		√	√	√
	1.4 poultry		√	√	√
	1.5 main road		√	√	√
	1.6 railway		√	√	√
	1.7 timber storage site		√		√
	1.8 gas pipe		√	√	√
	1.9 estate buildings and associated areas	√	√	√	√
	1.10 tin mining areas	√	√	√	√
	1.11 other mining areas	√	√	√	√
	1.12 power/electric line	√	√	√	√
2	**Horticultural land**				
	2.1 agriculture stations	√	√	√	√
	2.2 mixed horticulture	√	√	√	√
	2.3 market gardening	√	√	√	√
3	**Tree, palm and other permanent crops**				
	3.1 rubber	√	√	√	√
	3.2 oil palm	√	√	√	√
	3.3 coconut	√	√	√	√
	3.4 pineapple	√	√		√
	3.5 cocoa	√	√		√
	3.6 banana	√	√		√
	3.7 fish and hyacinth ponds	√	√	√	√
	3.8 coffee	√	√	√	√
	3.9 pepper	√	√		√
	3.10 arecanut	√	√	√	√
	3.11 sago	√	√		√
	3.12 tea	√	√	√	√
	3.13 orchards (tropical fruits)	√	√	√	√
	3.14 sugarcane	√	√	√	√

4	**Cropland**				
	4.1 diversified crops	√	√	√	√
	4.2 paddy	√	√	√	√
	4.3 shifting cultivation	√	√		√
	4.4 tobacco		√		√
5	**Improved permanent pasture**	√	√	√	√
6	**Grasslands**				
	6.1 cyperus, unimproved coarse pasture and/ or scrub grassland	√	√	√	√
	6.2 grass covered erosion scars	√	√		√
7	**Forest land**				
	7.1 forest	√	√	√	√
	7.2 treated forest		√	√	√
	7.3 scrub	√	√	√	√
	7.4 forest/scrub		√	√	√
	7.5 newly cleared land	√	√	√	√
	7.6 reclaimed area		√		√
8	**Swamps** (mangrove, palm-nipah, gelam), **marshlands and wetland forest**	√	√	√	√
9	**Unused land**				
	9.1 unused land	√	√		√
	9.2 unclassified		√		√
	9.3 water (rivers, pond, etc)		√	√	√
	Total of all sub categories	33	46	34	46

Table 4.10: Pre-classification land use categories for Langat, Linggi and Bernam

Category	14 sub-land categories	Langat			Linggi			Bernam		
		B&W map	coloured map	Landsat	B&W map	coloured map	Landsat	B&W map	coloured map	Landsat
1	forest	√	√	√	√	√	√	√	√	√
2	rubber	√	√	√	√	√	√	√	√	√
3	oil palm	√	√	√	√	√	√	√	√	√
4	horticulture and other crop	√	√	nd	√	√	nd	√	√	nd
4	grassland	√	√	nd	√	√	nd	√	√	nd
4	pasture	√	√	nd	√	√	nd	√	√	nd
4	paddy (grassland)	√	√	nd	na	na	na	na	na	na
4	grassland/pasture/immature oil palm/rubber			√			√			√
5	newly cleared-felled area	√	√	√	√	√	√	√	√	√
6	built-up area/urban	√	√	√	√	√	√	√	√	√
7	mining areas - pool (tin and other mining)	√	√	√	√	√	√	√	√	√
8	water body (dam, river, mining pond)	√	√	√	√	√	√	√	√	√
7-8	clouds shadow and water body/mining pool			√			√			√
1	clouds			√			√			√

Notes:
B&W – black and white map
Na – not available
Nd – not detected

Table 4.11: Response/impact of 8 different land uses on hydrology and water chemistry relative to natural forest–early hypothesis

Response	Land Uses Category							
	Natural Forest	**Newly cleared-felled area** * conversion forest area to agric./urban/etc * conversion agric. area to agric./urban	**Urban** (residential, institutional, commercial, industry, open spaces, UNESCO 1990)	**Rubber** * early stage * immature * mature	**Oil Palm** * early stage * immature * mature	**Transition: Pasture/Grassland/ Immature Crops/Horticulture/ Other Crops**	**Mining** * during activity * after (pools)	**Water body (dam)** * during construction * after
Hydrological	high evapotranspiration	reduced evapotranspiration (increased soil moisture, subsurface flow, groundwater, baseflow, annual streamflow, water yield)	reduced evapotranspiration (rapid surface runoff, groundwater table fall, baseflow reduced, increased storm runoff,	reduced evapotranspiration (different canopy, leaves)	reduced evapotranspiration (different canopy, leaves)	reduced evapotranspiration (different canopy, leaves)		
	high canopy interception , less raindrop impact and increase atmosphere humidity to generate rainfall	reduced canopy interception (reduced litter layer/ground cover/understorey, increased raindrop impact) and reduces dry period streamflow	artificial surfaces reduced interception cause high peak flow, high flash flood and high water yield.	reduced canopy interception (different canopy, leaves). Established crop cover will decrease peak discharge	reduced canopy interception (different canopy, leaves). Established crop cover will decrease peak discharge	reduced canopy interception (different canopy, leaves).		
	high tree root strength	reduced tree root strength, increased soil detachment,		reduced tree root strength at beginning	reduced tree root strength at beginning	reduced tree root (short crop)		
	high infiltration	reduced infiltration.	disturbs natural top soil cause less infiltration. artificial drainage system increase percentage runoff	reduced infiltration (but ground cover could decreased water yield, erosion and sedimentation	reduced infiltration (but ground cover could decrease water yield, erosion and sedimentation	low infiltration and high water yield increased storm flow and peak flow immediately following conversion orchard/other crop paddy (water covered)-effective control soil erosion		

	low baseflow, low surface runoff, less surface erosion, delaying flow of water, rise in stream water level much slower and floods take longer time to recede. forest litter aid weathering process (organic acids)- allow dissolution of metals (Fe and Al) at common soil pH	high runoff peak rate, increased surface runoff/overland flow, high total discharge, increased flash flood freq., short lag time (much sharper peak), increased surface erosion (soil loss), increased annual sediment yield) and time to peak and recession time were faster severe changes in soil nutritional/chemical result from erosion	short lag time between rain and flood peak, reduced low flow	**conversion from forest:** increase freq. and rate of peak flow, duration and amount inter flow, an total annual discharge; raise ground water, increase soil water storage in subsoil, decrease soil water in surface layer	In establishing perennial crop full canopy and deep root system will cause little long term effect on runoff rate and amount and total annual discharge; at the beginning cause drastic initial increase in water yield, high overland flow and inter flow, changes landscape stability causing mass wastage, high sediment load in overland flow	conversion of forest to grassland increases surface runoff, higher peak flow, earlier peaks in stream conversion forest to grazed pasture or grassland may increase sediment density, increase dissolved load in surface runoff and interflow and decrease soil organic matter	increase runoff, reduced flow, reduction in water table/water distraction increase erosion/siltation/ sedimentation low base flow, high storage and could trap sediment	water distraction, increases sedimentation, reduce water level during construction after, water table rise, effect water release on stream flow
Hydrochemistry (sources of pollutant)	under natural forest, all organic material are at natural level	deforestation will increase chemical water-borne sediment at downstream (pesticides, fertilizers, metals, salts, micro organism and other substances)	domestic waste, factory discharge and metal element **Sources pollutant:** -sediment -nitrate -phosphorous -microbes -sewage overflows -waterborne pathogens -toxic metals -pesticides	sediment, fertilizer, pesticides	sediment, fertilizer, pesticides	animal waste, fertilizer, sedimentation	organic material (clearance topsoil), metal element (copper, zinc) - high turbidity	organic material

4.2.4 Methods of analysing land use imagery and map interpretation

Land use data are important in making an assessment of the quantity and areas affected by changes brought about by different types of land use activities, especially forestry and artificial surfaces. The main sources for these data are Landsat Imagery (Landsat TM) which was obtained from the Malaysia Centre for Remote Sensing (MACRES) and covers the periods from 1988 to 2002, and printed land use maps (coloured and monochrome) which use standard land use classes as determined by the Department of Agriculture, Malaysia and cover the period from 1984 till 2000. The Landsat Imagery path/row of the scenes covering the catchments are 127/58 (Langat), 126/58 (Linggi) and 127/57 (Bernam). The frequency of these data is 4-5 years, with more frequent information (where available) for the periods of rapid development.

There were a few occasions of overlap between the Landsat imagery and the maps, which provides an invaluable means of 'supervising' the Landsat imagery. Since, a Landsat file comes as raw data, each has to go through a process of classification using software such as Erdas Imagine®. Catchment land use maps with eight categories of land use classification along with discrete hydrological and water quality characteristics were to be developed. An unsupervised image classification (an automatic process based on spectral recognition) has been used and rated against information from printed maps for same years as the Landsat images or those nearest, as a way of getting around the lack of ground truth information. Catchments were delineated on the printed land use maps and Adobe Photoshop was used to colour-code areas according to land use. These were then used to calculate the fractional areas of each land use in each catchment using Erdas Imagine®.

4.2.4.1 Landsat TM imagery and digital image processing

The Thematic Mapper (TM) has considerably greater spatial, spectral and radiometric resolution than a Multispectral Scanner (MSS) which was used by the earliest Landsat 1, 2, 3 and 4 in 1972, 1975, 1978 and 1982, respectively. It has seven spectral electromagnetic radiation sensor bands with an instantaneous field of view at nadir of 30 metres spatial resolution and signal conversion over a quantization range of 256 digital numbers characterized by 8 bit data (Lillesand and Kiefer, 1994). Bands 1, 2 and 3 are in the visible portion of the spectrum. Bands 4, 5 and 7 are in the reflectiveinfrared portion of the spectrum, whilst band 6 is in the thermal portion (ERDAS, 1999). The ERDAS Field Guide (1999) provides a more detailed description of the spectral resolution of the Landsat Thematic Mapper. Landsat 5 has been in service since March 1, 1984, meanwhile the Landsat 7 Enhanced Thematic Mapper (ETM) is the most recent satellite platform, launched on April, 15, 1999.

The seasonal conditions (wet or dry) can significantly affect the images because of sun azimuth and differences in vegetation. Hame (1988) suggested that for land use change detection purposes, summer is the best season because of its 'phenological' stability. By selecting the summer, or the driest period of the year for the study location, spectral separability will be enhanced whereas the spectral similarity due to excessive wetness prevailing during other periods of the year will be minimized (Colwell and Hicks, 2005). In this study, the image recorded by the Landsat sensor during wet conditions for the Bernam (1995) seems to experience this situation. It was found to have a similar (i.e. overlapping) spectrum between forest and rubber and oil palm and also urban surfaces (concrete/asphalt) and newly cleared areas (bare soil) (**see Table 5.1 in chapter 5**).

A land use change detection study between catchments would ideally have similar acquisition dates and similar platforms in order to minimise the potential effects of wet and dry atmospheric conditions which may introduce uncertainties in direct image comparison (Civco *et al.*, 2002). However, image availability is not always complete for the same date and comparisons have to be made with some reservations.

In this study, eight datasets of Landsat Thematic Mapper (TM) images of the three study catchments were obtained from the Malaysian Centre for Remote Sensing (MACRES) (**Table 4.12 and Figure 4.10**). All images were geo-referenced to RSO with a spheroid named Modified Everest. Normally, satellite images (raw data) recorded by sensors can contain errors in geometry and radiometry caused by atmospheric conditions. Under the geometric condition, the raw data normally contain distortion in the altitude, attitude and velocity of the sensor platform which need to be corrected to make sure it can be used as a map. Meanwhile, the radiometric correction involves a sun elevation correction and Earth-Sun distance correction to make sure it gives a correct reflectance for ground features at different times or locations (Lillesand and Kiefer, 1994).

Table 4.12: Landsat data characteristics

Catchment	Scene path/row	Satellite sensor	Image acquisition date	Season
Langat	127/58	Landsat-5 TM	06/03/1990	Wet
		Landsat-5 TM	28/11/1994	Wet
		Landsat-7 ETM+	20/09/2001	Wet
Linggi	126/058	Landsat-5 TM	12/06/1988	Dry
		Landsat-7 ETM+	08/05/2001	Dry
Bernam	127/057	Landsat-5 TM	07/06/1989	Dry
		Landsat-5 TM	14/10/1995	Wet
		Landsat-7 ETM+	19/06/2002	Dry

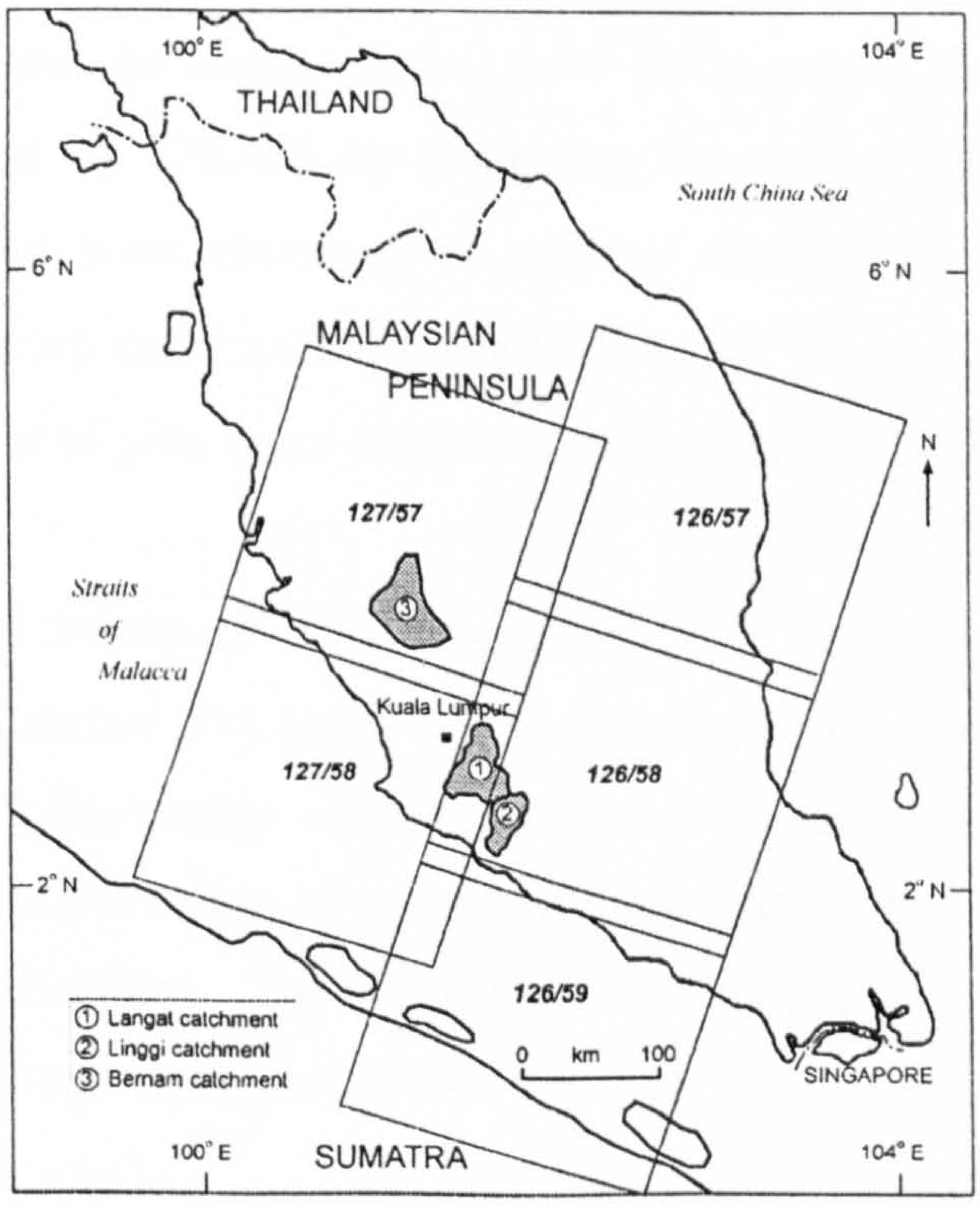


Figure 4.10 : Landsat coverage of the study catchments in Peninsular Malaysia

These errors were initially corrected by MACRES to remove the image speckle and eliminate noise waves to make the data more interpretable and presentable for further image processing associated image enhancement, classification and, lastly, the construction of a land use map. With the limited availability of clear, cloud-free images due to typical tropical atmospheric conditions, the scenes were selected from the best with cloud cover of less than 5%. The Landsat TM data were initiated by selecting the representative subsections of the scenes that covered a square shape incorporating the study areas. In many cases, Landsat TM scenes are much larger than the project study area. So, in this study the size of the multi-band data images was reduced (sub-setting) to small and manageable files to include only the area of interest with the catchments being delineated by overlaying images with catchments boundaries. This not only eliminates the unwanted data in the file, but also speeds up processing due to the smaller amount of data being processed.

Other material and reference data used in this study were land use maps (1:50 000) for the same or the nearest year, since ground-truth information was not available to verify the Landsat classification. These maps were used to determine land use categories in the final stage of an unsupervised classification process. These maps were also used as reference data in order to establish the level of accuracy for the unsupervised classification produced by ERDAS by comparing the output for every single class, especially where there were problems of spectral overlap in the same pixels. A comparison between map and Landsat interpretation for the same area and years was also carried out in order to give some confidence to the unsupervised classification.

In order to understand the nature of the images before work on classification, different combinations of the Landsat TM bands can be displayed to create different composite effects. With adequate knowledge of band properties and the appropriate combination of Landsat TM bands, extraction of numerous land use classes can be achieved for various mapping applications. The following combinations are commonly used to display images (Lillesand and Kiefer, 1994):

(i) Bands 3, 2, and 1 in red, green and blue, which are considered the natural colour composition, are normally used to display the background images as they appear to the naked eye.

(ii) Bands 4, 3, and 2 are the combination of visible near infrared, red and green to create a false colour composite, which is a familiar band combination in Landsat data. Band 4 has a high reflectance that can distinguish several vegetation types. In false colour combination, vegetation will appear as red tones whist the brighter reds will indicate more vigorously growing vegetation.

(iii) Bands 4, 5, 3 in red, green and blue are normally used in land cover analysis where they can provide the best distinction between vegetation types.

In this study, land use data from digital Landsat imagery were derived by computer-assisted image classification techniques involving manipulation and interpretation by ERDAS Imagine® Spectral Analysis tools version 8.5. The workflow of these tools was easy to follow and helped to obtain a result or classification extracted from a hyper-spectral dataset, which in this case was Landsat TM. An unsupervised classification was used. This automatically assigns land use signatures based on pixel reflectance values. It allows specification of parameters that the computer should use to uncover statistical patterns in the data (ERDAS, 1999). Once this process is completed, the image analyst determines the land use type for each class based on image interpretation, ground truth information, maps and field reports, and assigns each class to a specified category by aggregation (ERDAS, 1999). The data were classified using Iterative Self-Organizing Data Analysis Techniques (ISODATA) - a clustering algorithm. This uses a minimum spectral distance formula to form a cluster. Each time the clustering is repeated, the mean spectral signature is shifted and this new mean is used for the next iteration (ERDAS, 1999).

The ISODATA utility repeats the clustering of the image until either a maximum number of iterations have been performed, or a maximum percentage of unchanged pixel assignments have been reached between two iterations. For this process, a convergence threshold was specified at 0.95, which means that as soon as 95% or more of the pixels stay in the same cluster between one iteration and the next, the utility should stop processing to prevent it from running indefinitely. After an unsupervised classification was performed a number of classes based on different electromagnetic spectra were produced. From here, a raw image (unclassified), which can be displayed by many band combinations, was compared to this new classified image in order to recognise the point at which class separation should occur according to spectral differences before they were assigned to the nearest land use category.

The following steps as shown by flow chart (**Figure 4.11**) and text below were used in processing and interpreting Landsat TM image:

i) Firstly, a geo-rectified catchment boundary file was overlain on the raw images and re-mosaicing was carried out to produce a Landsat image with correct catchment boundaries.

ii) Since there was no ground truth information available, an unsupervised classification (Isodata) was performed to generate a set of 40 classes in the first instance. It was expected that these 40 spectral classes would provide sufficient separation to determine the eight major land use types, which had already been decided for this study through the combination of 46 small classes. These eight classes form the basis for analysis of the impact of land use on hydrology and water quality.

iii) A colour composite enhancement was carried out using band combination. Kamaruzaman and Hasmadi (2000) conducted a land use classification study in the Langat and suggested that a combination of Bands 2, 3 and 5 is effective for separation of vegetation type and a combination of Bands 3, 4, 5 and 7 separates primary forest, forest, rubber and oil palm. In this study, the combination of Bands 5, 4, 2 and 7, 4, 2 gave a good result in discriminating major features of land cover, for examples forest, rubber trees, oil palm trees and short crops. Post classification refinements based on the nearest land use map were applied to reduce classification errors caused by the similarities in spectral responses of certain classes such as forest and crops and crops and the 'transition class'.

iii) Before finalising the land use categorization and obtaining the area (in km^2) of each class, an assessment of accuracy was carried out. This consisted of merely picking particular classes to ensure they are classified as they should be. This procedure was done manually since the proper Kappa statistical analysis for accuracy cannot be performed due to lack of ground truth information. Finally, a land use map was produced.

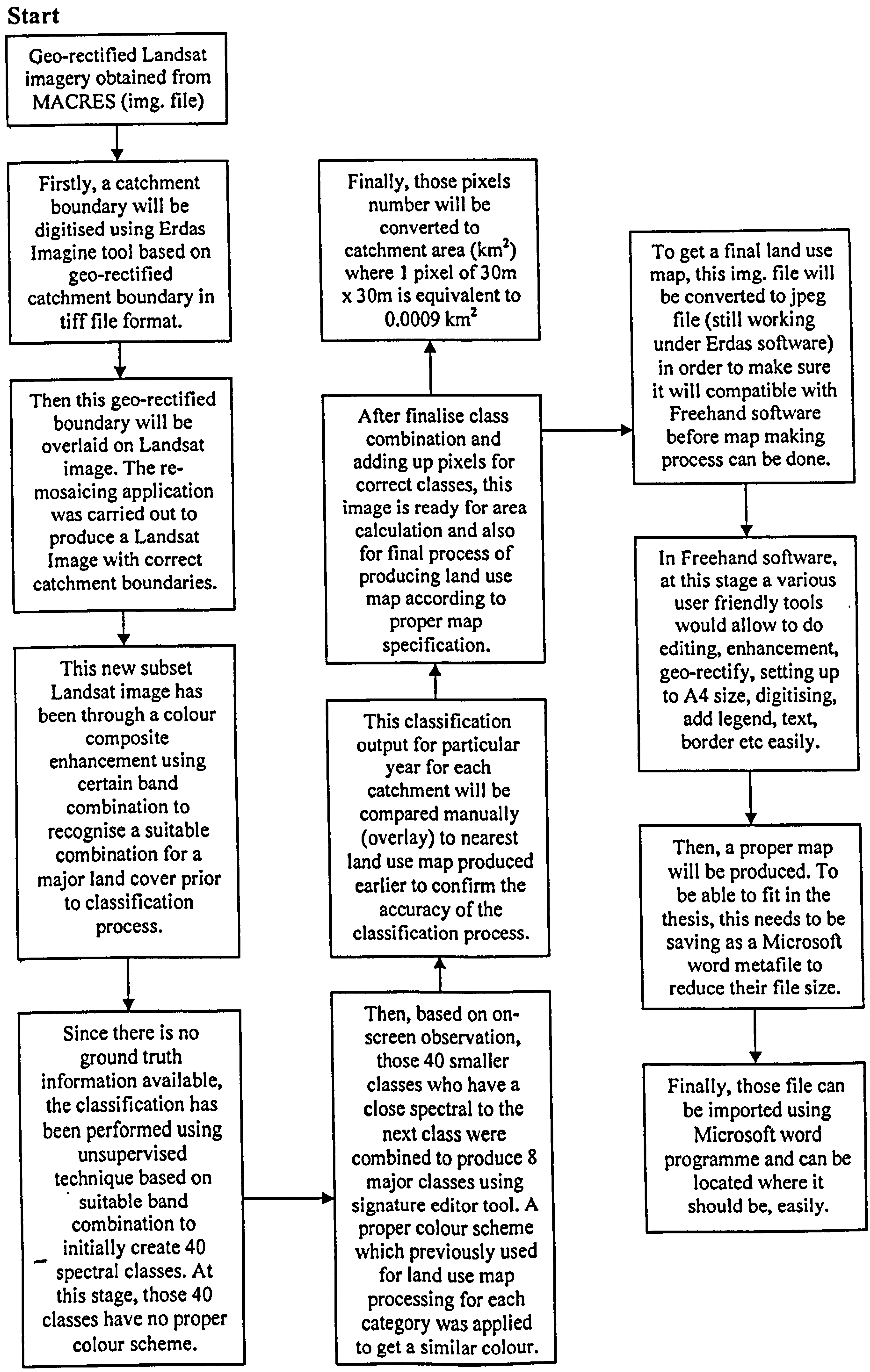


Figure 4.11: Procedures used to process and interpret Landsat Imagery derived from the Malaysian Centre for Remote Sensing (MACRES)

4.2.4.2 Land use maps processing

Twelve multi temporal classified land use maps (four maps for each of the catchments) were examined to obtain historical land use data (**Figure 4.12, Appendix 3 for larger scale and Table 4.13**). Maps of various scales were obtained from the Department of Agriculture, Malaysia (DOA). Landsat images provided supporting information for intervals not covered by re-mapping. Both of these sources of data have been combined to provide a unified time-series for land use change.

The earliest map available is from 1984, followed by 1990, 1997 and 2000. Since there are no images/maps available before 1984 - vital for describing the conditions in the pre-development period, especially for Langat and Linggi - an economic and development report from the local authority dated between 1970-1980 will be integrated in order to provide earlier information on land use. Even though it was hoped that Langat and Linggi would provide the relationships and information from pre- to post development periods and act as an analogue to the Bernam catchment, they were not able to give clues about the pre-development conditions due to lack of data. Therefore, there is an attempt to use a study of the early period of pre-development in Bernam from 1984 to 1997 to give some clues and help in understanding the early land use scenarios for Langat and Linggi. But this step will not detract from the focus of using analogues in this study.

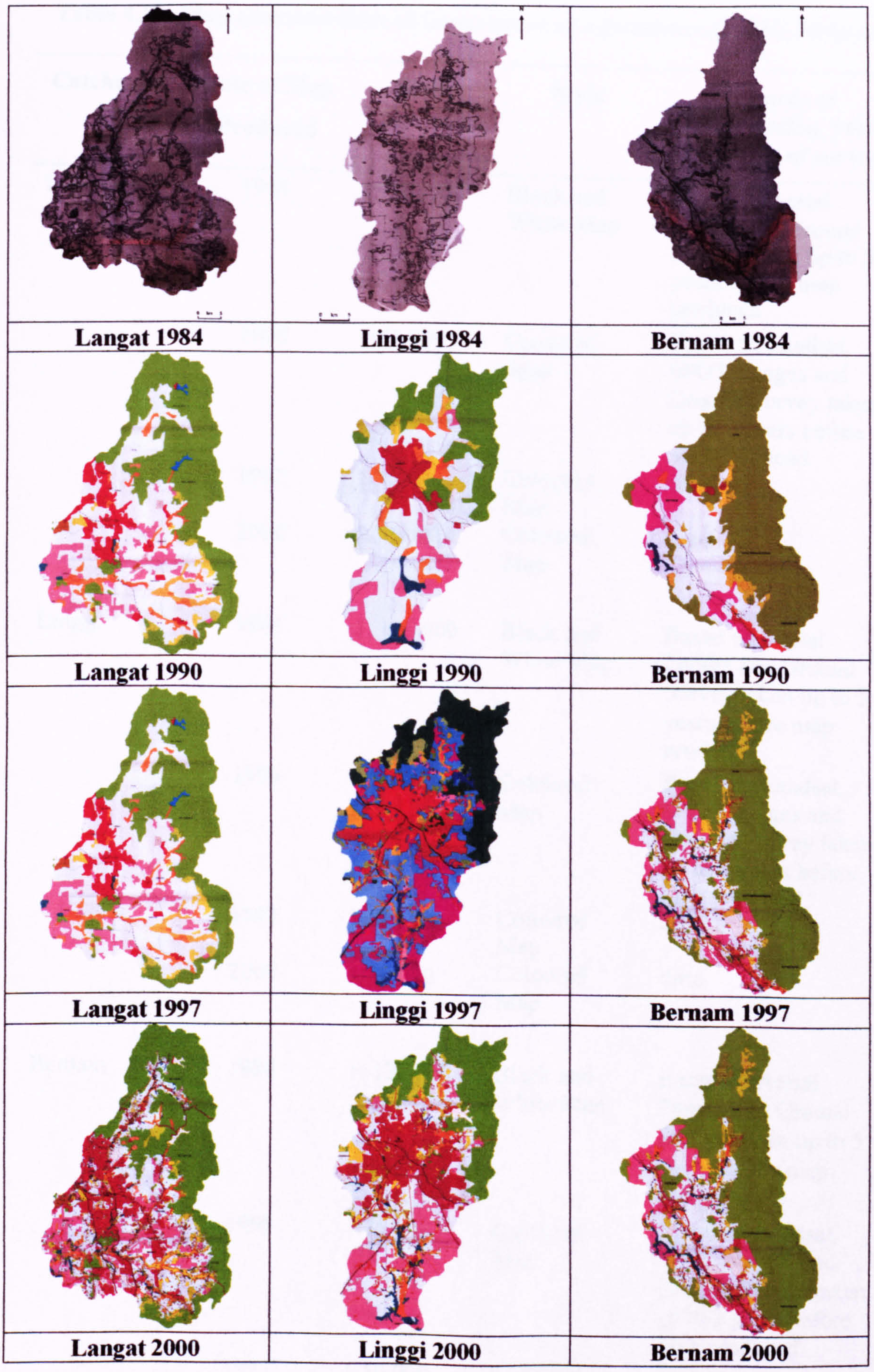


Figure 4.12: Classified land use maps for all three catchments, from Department of Agriculture (DOA)

Table 4.13: Map characteristics of Department of Agriculture (DOA), Malaysia

Catchment	Date of Map Produced	Scale	Style	Source of information, year and date of survey
Langat	1984	1: 126 000	Black and White Map	Based on Aerial Photos and Ground Survey taken up to 5 years before map produced
	1990	1:75 000	Coloured Map	Based on Landsat, SPOT Images and Ground Survey taken up to 2 years before map produced
	1997	1:70 000	Coloured Map	ditto
	2000	1:75 000	Coloured Map	ditto
Linggi	1984	1: 126 000	Black and White Map	Based on Aerial Photos and Ground Survey taken up to 5 years before map produced
	1990	1:50 000	Coloured Map	Based on Landsat, SPOT Images and Ground Survey taken up to 2 years before map produced
	1997	1:50 000	Coloured Map	ditto
	2000	1:50 000	Coloured Map	ditto
Bernam	1984	1: 126 000	Black and White Map	Based on Aerial Photos and Ground Survey taken up to 5 years before map produced
	1990	1:75 000	Coloured Map	Based on Landsat, SPOT Images and Ground Survey taken up to 2 years before Map produced
	1997	1:50 000	Coloured Map	ditto
	2000	1:75 000	Coloured Map	ditto

All of the land use maps used in this study, except that of 1984, are based on Landsat Images, SPOT Images and Ground Surveys, which involve about two years work prior to the year they are produced. All of these maps are assumed to be reliable for the purposes of this study. The classification has been used as a reference and guidance in finalising the land use categories contained in the Landsat images. Despite the fact that the quality of the maps produced by the Department of Agriculture is high, there is some uncertainty about the quality of the class separation on all the maps. The separation boundaries which appear on the maps are often straight, whilst in Landsat, it is extremely difficult to separate the classes due the close similarity of pixels between adjacent classes. So, it has to be assumed that the maps have been corrected and partially stylized by the Department of Agriculture or corrected using additional ground truth or survey information produced for a detailed land use map. Therefore, it can be argued that the land use data gathered from these published maps are acceptable from the point of view of the level of accuracy. In any case, they are the only source available for the various periods relevant to this study.

The 1984 black and white map was based on aerial photographs and ground surveys taken up to five years before 1984. A land use record which covers about a 4-5 year interval is expected to be sufficient to detect any land use changes, since any changes in land cover normally take a few years to appear in the satellite imagery or map. The quinquennial interval reflects the pace of economic development and also the intentions of government. Given this, the punctuated spatial time-series should be able to provide indicators of the impact of land use changes on water relations. The map data have been integrated with the Landsat image data to provide a land use history for the period 1984 to 2002.

To extract the land use data (area in km^2) from the maps, they have been through a number of processes, as described by the flow chart below and the text **(Figure 4.13)**:

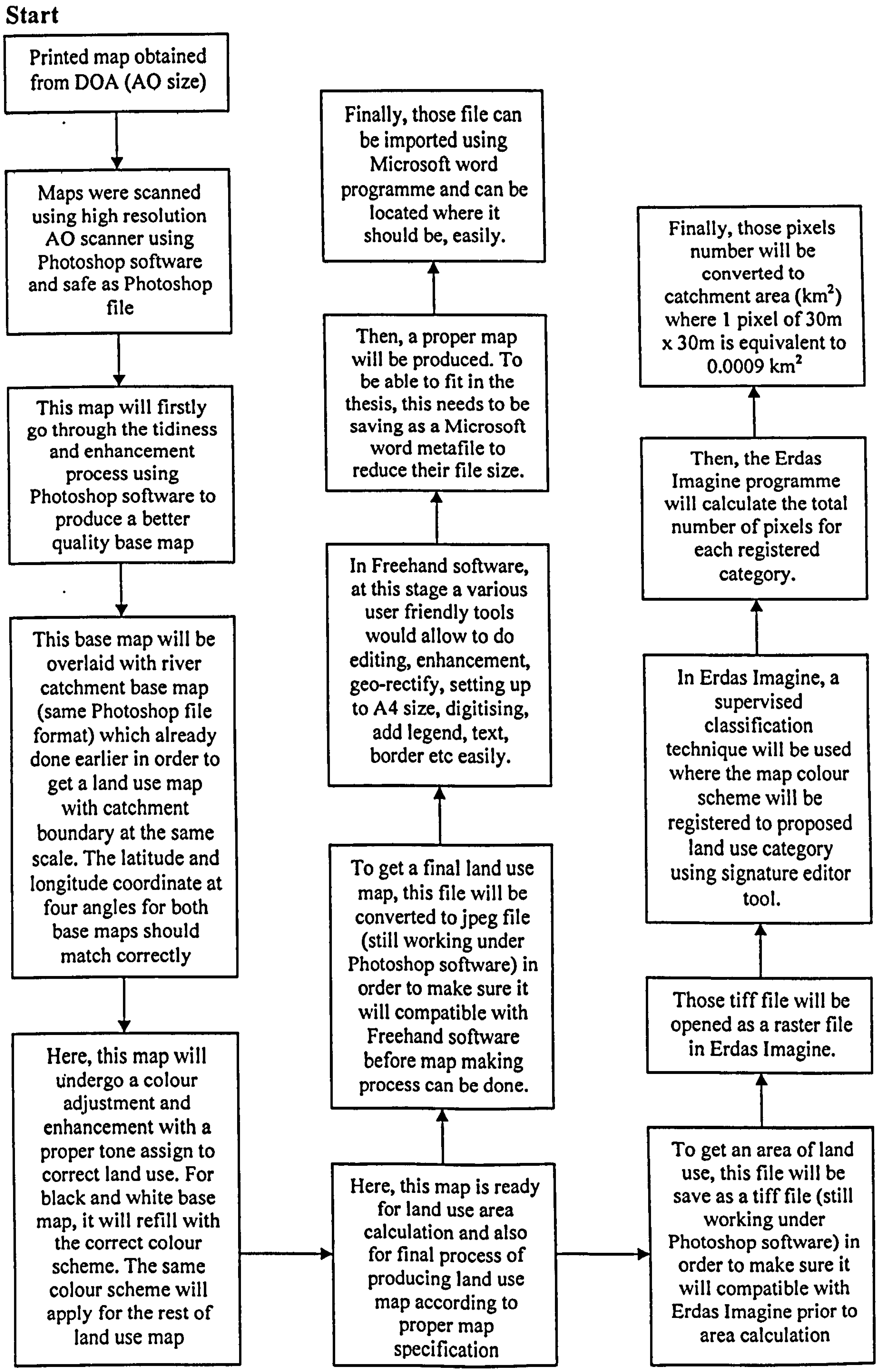


Figure 4.13: Procedures used to process and interpret land use maps from Department of Agriculture (DOA)

i) Firstly, all of the classified maps (based on latitude and longitude coordinates) were scanned using a high-resolution scanner.

ii) A geo-rectified catchment boundary map was overlaid to produce a catchment classified land use map.

iii) An adjustment to the colour scheme was made (when required), especially for black and white maps, to maintain compatibility with the other types of map.

iv) Finally, class areas were calculated by applying a supervised classification technique in ERDAS Imagine. After the signatures for each land cover category have been defined, the software then uses these signatures to classify the remaining pixels (ERDAS, 1999). The total number of pixels for each class was obtained and later converted to catchment area in km^2 to produce sets of catchment land use class data. There has been no accuracy assessment involved in this classification because the supervised classification was based on the signature from the original source map.

4.2.5 Land development data

Records of economic development (reports, statistics, master plans, etc), especially for deforestation, agriculture, urbanisation and industrialisation, which bring significant levels of land disturbance in Peninsular Malaysia, in particular within three catchments, are important supporting and complementary information when assessing the impact of land development on hydrology and water quality. This information will help to identify the influences of land use changes on rainfall-runoff coefficients, levels of sedimentation and water quality by recognizing pre-development, development and post-development stages. However the availability of information that could be accessed is very limited. This information has been gathered from agencies in Malaysia such as Local Authorities, the Forestry Department, the Agriculture Department, the Rural and Urban Department and also private developers.

Accessible data consists only of the statistical figures for various types of land use development, which are documented in local authority master plans, both in the past and for the next 20 years, for all three catchments. In addition, figures were obtained from the proposed new development and housing estate for Bernam, the source of the main pollutant for the Langat catchment in the 1990s and a few reports regarding the general impact of land use change on the environment undertaken by universities. In the local authority master plan, they have listed the size and location of areas that have been subjected to new urban and industrial development. This will help to recognise of the possible causes of land use change on rainfall-runoff relationships in general, especially in the Langat and Linggi. For Bernam, this land development data will help in the prediction of hydrological and water quality impacts due to possible future development plans. However, there is no indication of how long each new development project will take, which could help to understand the scale of impact from this activity. Some of the projects finish according to plan, but some do not. Other than that, the data only makes it possible to speculate on the possible sources that affected the hydrological and water quality characteristics within catchments. The lack of information about the scale of changes in agriculture activity (re-plantation or conversion to other land use) also causes uncertainties when trying to assess impacts. This obstacle will be minimised by using the information from the land use maps and Landsat to provide some assistance in understanding these circumstances.

4.3 Consideration of data sources, computation methods and statistical analysis

Malaysia gained independence in 1957. Most of the early hydrological data were collected by the former colonial government which stressed the importance of collecting good data. This can be seen especially for rainfall data, for which there is a complete record from 1940 to 1960. Since then, there have been breaks in regular data collection and this affects the number of datasets available and the number of monitoring/gauging stations available for analysis. The reasons include administrative instability following independence, lack of trained local engineers and technicians, and a lack of budget to repair and purchase new equipment. This caused existing stations not to be maintained, new data not to be collected and led to some data archives being lost.

To provide useful, reasonable predictions based on historical hydrological data using statistical analyses, data must cover a sufficient length of time. For instance, in stream discharge measurement ideally there should be no gauge movement, no change in observer, no change in method of recording data and no channel re-configuration at the gauging stations (Gordon *et al*, 1992). In reality, many stations have dataset problems, some of them missing more than a year of record, and some of them missing a few months. Some of them have a complete record, but analysis suggests that the data is unreliable.

It is important to convey that this study is dealing with imperfect datasets. For example, 58, 47 and 37 % of the annual discharge data from Langat, Linggi and Bernam were discarded because they were considered to be imperfect/unreliable. All of the available suspended sediment discharge data from 1977-2000, which was based on unexplained rating curves from DID for Langat and Bernam, were also discarded. Meanwhile, the water quality data is discontinuous and very sparse and the Bernam catchment only has data from 1998 onwards. Most of the chemical parameters data are unreliable. However, these are the only sources of data for historical land use, water quality, rainfall and runoff.

Notwithstanding the data limitations, all available records were initially screened using various types of analysis. For example, time-series were scrutinized for the consistency of historical datasets of rainfall and runoff in order to identify anomalies in the sequence of observations. This allows the prediction of future values of the time-series variables (Wright, 2001 and Pallant, 2001). The analysis is based on the assumption that successive values represent consecutive measurements taken at equally spaced time intervals. Once patterns are established, these can be interpreted and integrated with those derived from other data to investigate related phenomenon, e.g., runoff flowing through the river system as a function of rainfall amounts in different seasons (Salkind, 2000 and Wright, 2001).

Another important descriptive statistic used in this study is a test of normality in the data frequency distributions (using the Kolgomorov-Smirnov test statistic) prior to rainfall-runoff analysis using either ordinary least-squares regression or Deming regression (Pallant, 2001). From this study, only the runoff data is normally distributed despite the fact that the rainfall data were subjected to transformation using base-10 logarithms. This suggests that the rainfall data should be treated with caution if used as an independent variable.

Double-mass analysis was also deployed in order to examine any peculiarities of rainfall and runoff data within the catchments. This technique commonly employed to determine the necessity of corrections to hydrological data, to account for changes in data collection procedures, or local conditions (Dingman, 1994 and Shaw, 1994). These changes may result from a variety of things, including changes in instrumentation, changes in observation procedures, or changes in gauge location. But, most important may be significant changes in land cover within the catchment and its impact on water yield or water quality.

Correlation analysis (Pearson, 2-tailed) was also widely used to establish the relations between rainfall gauges, indicating the strength and direction of covariation (Wright, 2001 and Pallant, 2001). Through this kind of analysis, transfer functions for inter-station correlation for rainfall analysis were established and later used to advance the rainfall-runoff analysis.

Ordinary least-squares regression (OLS), commonly used in hydrological studies, was also used here for establishment of the rainfall-runoff relations and transfer functions (Ferguson, 1986). Because OLS does not allow observational errors in the independent variable, Deming regression was used in the analysis of suspended sediment concentration (Linnet, 1998). It is particularly useful for understanding the nature of complicated datasets i.e. when there is no clear relation between suspended sediment concentration and water discharge.

Student's *t*-test has been used to assess the significance of any differences in suspended concentration data during pre- and post-development periods in the same catchment and between catchments (Wright, 2001 and Pallant, 2001). It is used to help recognise land use change impacts in the Langat and Linggi basins and, therefore, the likely impact of such changes following new developments in the Bernam catchment.

4.4 Summary

This chapter explains the procedure taken to validate the historical hydrological data and establishes which datasets can be used in further analysis and discussion. Transfer functions for rainfall have been derived through inter-station correlation. The chapter highlights those limitations of the available datasets obtained from various government sources that arise from errors in either field operations or data transcription. In contrast, the quality of land use data available to this study is acceptable. The procedure used to interpret and analyse both land use maps and Landsat imagery are described. The statistical methods used to analyse the relations between hydrological and land use change parameters are discussed.

In Chapter Five, the trend of land use changes that have occurred in the study catchments between 1984-2002 will be discussed.

CHAPTER FIVE:
CATCHMENTS LAND USE HISTORY

5.1 Introduction

The objective of this chapter is to assess the trends in land use changes due to development during the period 1984-2002, based on map and Landsat imagery. Continuous economic and population growth (2.4% per year over the last ten years) in Malaysia since the 1990s has led to the rapid development of land use in both urban and rural areas. Since the sustainable yield and quality of water depends significantly on forest cover, it is very important to recognise the degree of land use changes pre-, during and post- development. To assess land use changes, a temporal data set is required. Satellite images (Landsat TM) and land use maps can be expected to provide appropriate information. This chapter describes firstly the process of obtaining the temporal land use data and producing land use maps from Landsat imagery using ERDAS™ Imagine software. The land use database is then presented and discussed, together with information about the background to land use change, in particular deforestation, agriculture and urbanization. The influence of land use changes on water yield and water quality will be discussed in Chapter Six.

During the past centuries, human beings have taken an increasing role in the modifying the global environment, especially through the alteration of land use (Meyer and Turner 1992). To better understand the impact of land use change on terrestrial ecosystems, the factors affecting land use must be more fully examined. The growing human population has increased pressure on the landscape as demands for resources such as food, water, shelter, and fuel increase. These socioeconomic factors often dictate how land is used regionally. Land use change has become a central component in current strategies for managing natural resources and monitoring environmental change (Kamaruzaman and Hasmadi, 2000). Over the last few decades, data from Earth sensing satellites has become important in mapping the Earth's features and infrastructure, managing natural resources, and studying environmental change.

5.2 Landsat and map classification accuracy assessment

Validation is an important step in the processing of remote sensing data in order to determine the value of the output data to a study. When classifying satellite imagery, single supervised or unsupervised classification techniques are often not enough to classify an image effectively. Automated classification accuracies can often be unacceptably low, < 80%, at the required level of categorical detail for many applications (Bolstad and Lillesand, 1992). Therefore, modifications of image classification techniques and support from ground truth are most often required in order to assess for classification accuracy.

The systematic error matrix and kappa coefficient have become a standard means of assessment of image classification accuracy in ERDAS. This method allows a comparison of certain pixels in a thematic raster layer to reference pixels (ground truth/field samples) for each class. In this study, this accuracy assessment cannot be performed due to unavailability of ground truth data as a reference. As an alternative, a manual calculation of the percentage of pixel sharing (overlap) between each consecutive class has been adopted to provide a general level of accuracy. This procedure is based on an examination of the spectral signature and involves work on-screen to recognise how many classes are shared on one row of pixels that lie along the boundary between two classes. If a majority appear to belong to one class, the pixels will be assigned to that class.

The results of this analysis are illustrated in **Table 5.1.** They show that the percentage of all classes assigned to a correct land use category without overlapping with other categories is between 87-92 %. The most complicated classes to assign are forest, rubber, oil palm and the transition class due to general features of green vegetation and other atmospheric factors such as rainfall season. For example, the Landsat image for Bernam in 1995 recorded a high overlap between forest and rubber and between rubber and oil palm because the image was taken during the wet season. The final land use datasets from Landsat which have used for further analysis and discussion in this chapter have already gone through this validation process. The other approach to accuracy analysis involves comparing Landsat images and land use maps of the same year (1990). In this case, the sources only allow an analysis of the Langat catchment. The land use map was originally derived from Landsat by the Department of

Agriculture (DOA) (map provider), but it has been through a proper ground truth verification based on at least two year's of information; therefore, this map is more comprehensive and believed to have considerably higher quality control. As a consequence, it can be used as guidance to help assess the accuracy of the unsupervised classification of the Landsat imagery. The output from this analysis is shown in **Table 5.2.**

Table 5.2: The land use comparison between Landsat and Map, year 1990 for the Langat catchment

Land use category		**Map 1990**	**Landsat 1990**			
No.	**Description**	**area km^2**	**area km^2**	**area difference-error km^2**	**percentage difference**	**percentage coincidence similarity**
1	Forest	488	468	20 (20)	4	96
2	Rubber Tree	486	478	8 (8)	2	98
3	Oil palm Tree	120	130	-10 (10)	-8	92
4	Transition	61	87	-26 (26)	-43	70
5	Cleared-felled Area	1	1	0 (0)	0	100
6	Built-Up Area	76	84	-8 (8)	-11	90
7	Mining ponds	19	3	16 (16)	84	16
8	Water Body	6	6	0 (0)	0	100
	Total	**1257**	**1257**			**83**

From table **Table 5.2** shown, the small output differences suggest a reasonable degree of accuracy in the Landsat classification when compared with the reference map. The recognition of forest and rubber tree plantation by Landsat is slightly low, falling short by 4 % (20 km^2) and 2 % (8 km^2), respectively. The area of oil palm tree plantation is overestimated by 8 % (10 km^2). Classification using Landsat overestimates the transition land use and built-up area categories up to 43 % (26 km^2) and 11 % (8 km^2), respectively which is believed to be due to the spectral sharing complication. An example of the spectral sharing complication for land use classification output between Map and Landsat 1990 are show in **Figure 5.1.** This figure also shows that the Landsat would not be able to detect the grassland area (yellow) (under Transition land use class) as it clearly recognised by the map. Meanwhile the cleared-felled area and water bodies are shown exactly no difference which reflect to more highly distinguish of their spectral characteristics. The levels of Landsat accuracy for forest, rubber, oil palm and built-up area categories compared with the map are 96 % (20 km^2), 98 % (8 km^2), 92 % (10 km^2) and 90 % (8 km^2), respectively. However, for the transition land use area category, the level of accuracy is only about 70 % (26 km^2) and this demonstrates how difficult the classification process is in distinguishing between short green agricultural crops and other vegetables. For newly cleared areas there is also some confusion between soil and cloud surfaces. For mining ponds, the accuracy is only 16 % (3 km^2 out of 19 km^2) and this is due to too many pixels being classified as a water body. Overall, the Landsat accuracy compared to the map is about 83 % (1043 km^2 out of 1257 km^2). The ANOVA shows there is no significant difference (significance level >0.05) between them map and Landsat for class determination and this confirmed the 'similarity' of the output data. It is also corroborated by the strong correlation (r^2=0.91) between these two sources as show in **Figure 5.2.** However, similarity only lies at 83 % (1043 km^2) of the pixels (on average) and the balance of 17 % (214 km^2) are still shared between two or more classes. The findings should be treated cautiously. A reference to every single class should be made when justifying the magnitude of land use changes.

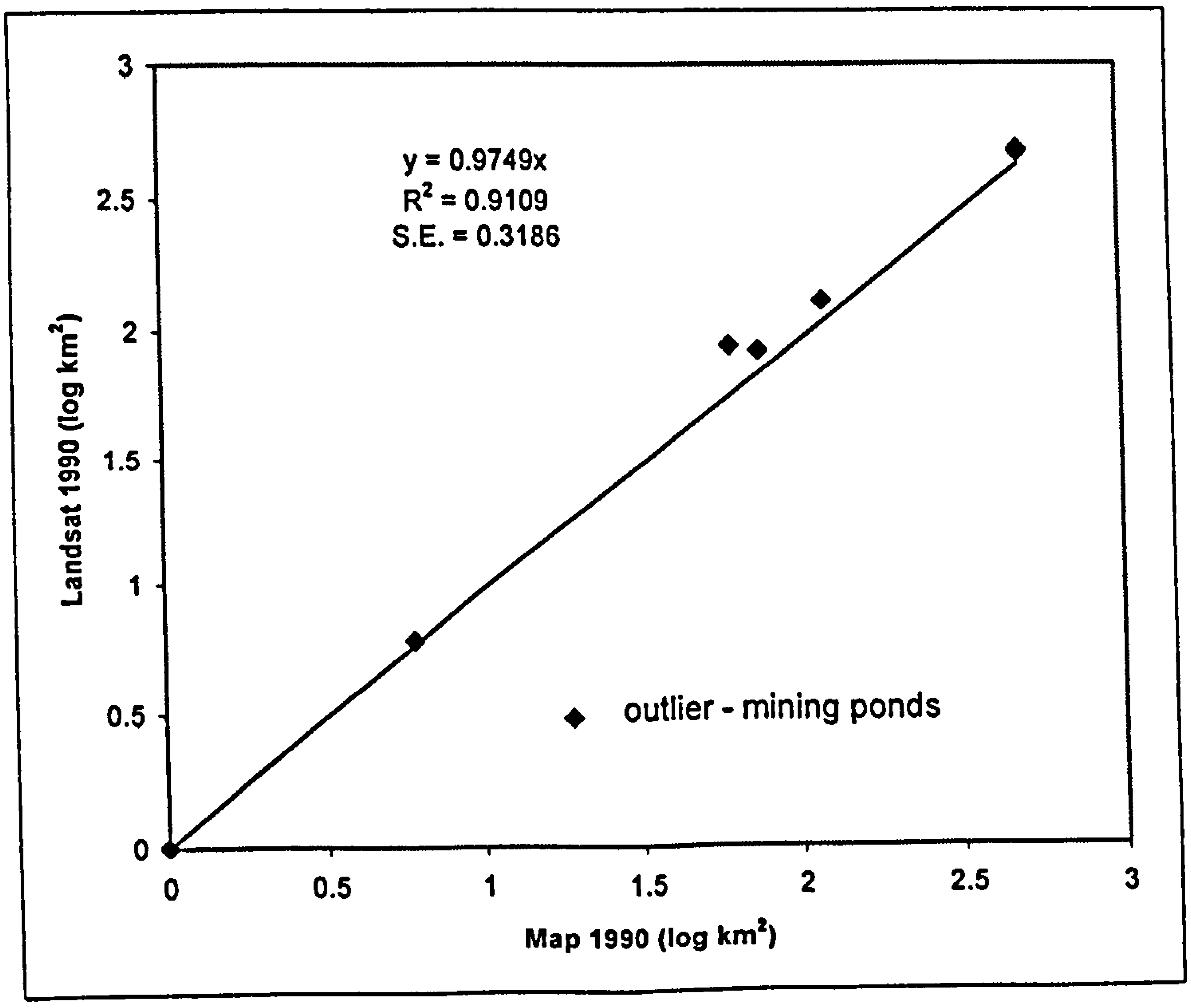


Figure 5.2: Area assigned to land use categories by Landsat and Mapping Agency - 1990 for Langat catchment

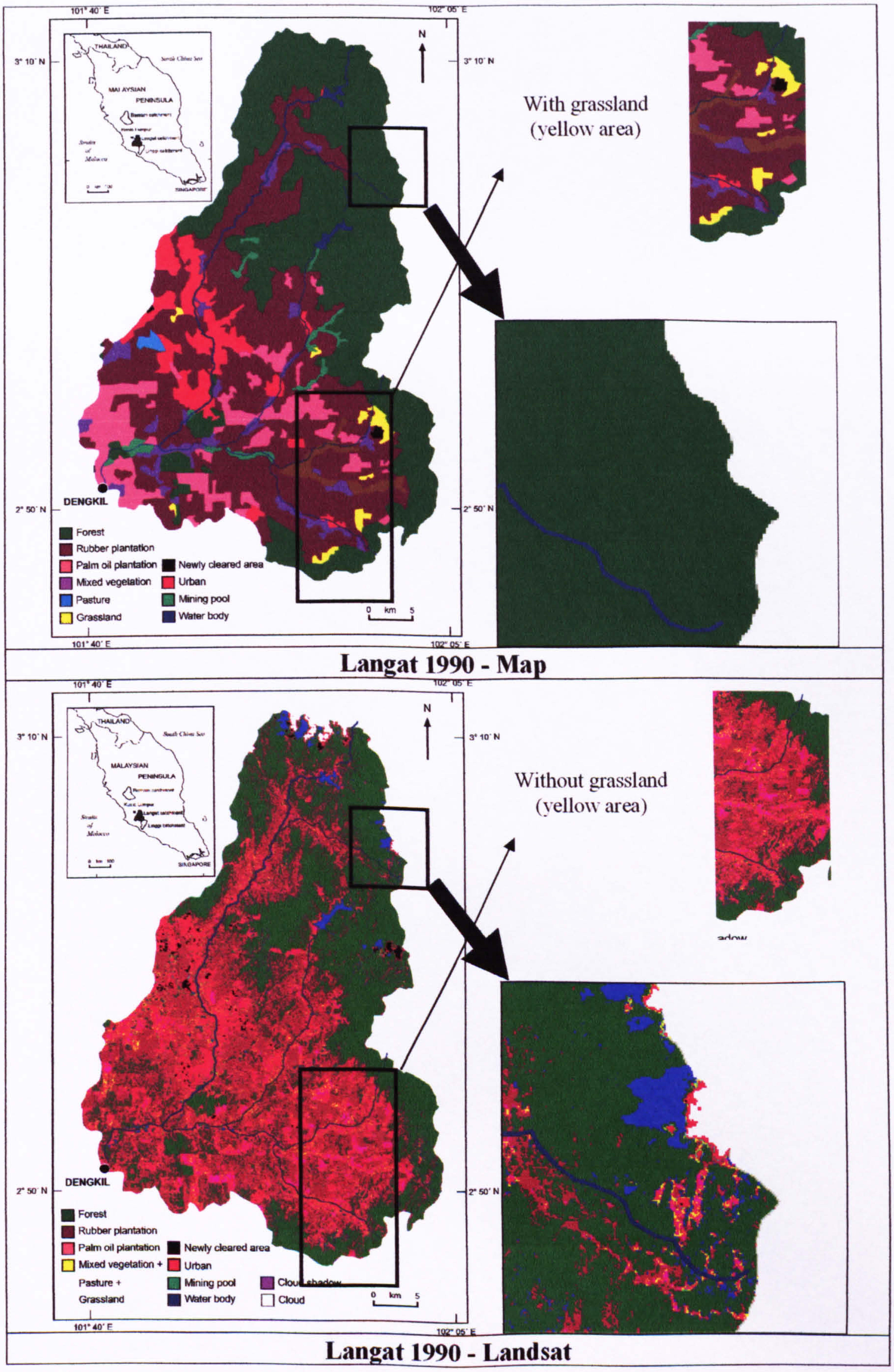


Figure 5.1: Example of spectral sharing complication for land use classification output between Map and Landsat 1990 for Langat catchment

[The area (refer to rectangle in top map) has a very solid green colour which indicates forest, but in the Landsat output, this area appears to have forest (green), water (blue), rubber (brown) and palm oil (magenta)]

Table 5.1: Percentage of area overlapped between each consecutive class based on the unsupervised classification spectral signature editor for Landsat

Land use category overlap	Langat			Linggi		Bernam		
	Landsat 1990	Landsat 1994	Landsat 2001	Landsat 1988	Landsat 2001	Landsat 1989	Landsat 1995	Landsat 2002
	area (km^2) overlapping	area (km^2) overlapping	area (km^2) overlapping	area (km^2) overlapping	area (km^2) overlapping	area (km^2) overlapping	area (km^2) overlapping	area (km^2) overlapping
Forest-Rubber	55.2	52.8	50.5	na	na	35.7	45.8	32.9
Forest-Oil Palm	na	na	na	18.1	20.6	na	na	na
Rubber-Oil Palm	34.2	36.7	32.6	16.2	18.9	25.1	32.4	28.1
Forest/Rubber/Oil Palm-Transition	24.5	30.4	22	18	8	27	21.5	12.8
Transition-Newly cleared/Built-up areas	9.3	9.4	7.2	15.6	na	na	na	20.8
Newly cleared-Built-up areas	na	5	nd	nd	7	na	na	na
Total overlapped area between classes/Total area	123.2/1257	134.3/1257	112.3/1257	67.9/528	54.5/528	87.8/1123	99.7/1123	94.6/1123
Percentage overlapped area from total catchment land use	9.8	10.7	8.9	12.9	10.3	7.8	8.9	8.9
Percentage error	9.8	10.7	8.9	12.9	10.3	7.8	8.9	8.9
Percentage area assigned to correct classes without overlapping	90.2	89.3	91.1	87.1	89.7	92.2	91.1	91.6

Notes: na = not available; nd = not detected

According to Kamaruzaman and Hasmadi (2000), the minimum acceptable accuracy for Landsat classification based on full supporting information from ground truth is about 80 %. In their study in Langat, the accuracies for Landsat 1993 TM, 1996 and 1998 are 89 %, 92 % and 88 %, respectively. Yin *et al.* (2005) who conducted a study about changes in built-up areas using two Landsat images of Cairo recorded an 87 % of accuracy for both images. Meanwhile, Yuan *et al.* (2005) used four Landsat images to chart land cover changes in Minnesota and reported an average of 94 % accuracy. Çayuela *et al.* (2006), who studied tropical forest fragmentation in Chiapas, Mexico, obtained 91 % and 94 % accuracy for Landsat 1990 TM and Landsat 2000 ETM, respectively. This present study appears to have 83 % (1043 km^2 out of 1257 km^2) accuracy when comparing data between Landsat 1990 and reference data (Map 1990). This included the problem area of mining ponds. This is slightly lower than previous studies using Landsat for land use classification. If the mining ponds are omitted, the accuracy increases to 92 % (1156 km^2 out of 1257 km^2)and this is within an acceptable range, even without sufficient support from ground truth data/information. However, monitoring of land use change based on remote sensing data is an imprecise task (Foody, 2002) and it is important to acknowledge that image processing might contain errors.

In another example of accuracy assessment between map and Landsat (**Table 5.3**), five main land use categories (forest, agriculture, urban, water and transition) showed strong correlations between Landsat and the land use map for Langat, Linggi and Bernam with r^2 values of 0.90, 0.83 and 0.99, respectively, (see **Figure 5.3**). There is one data point in each case of Langat and Linggi that appears to be as an outlier. This relates to the transition land use (short crop/vegetation). This data point, in particular, reflects the detection ability of Landsat to distinguish between green vegetation which provides more or less the same spectral signature. Although there is a one-year separation of each pair (except Bernam, where the gap is two years), the two methods of data analysis recorded similar land use areas for all main categories. This close relation can be seen in the comparison of map and Landsat in **Figure 5.4.**

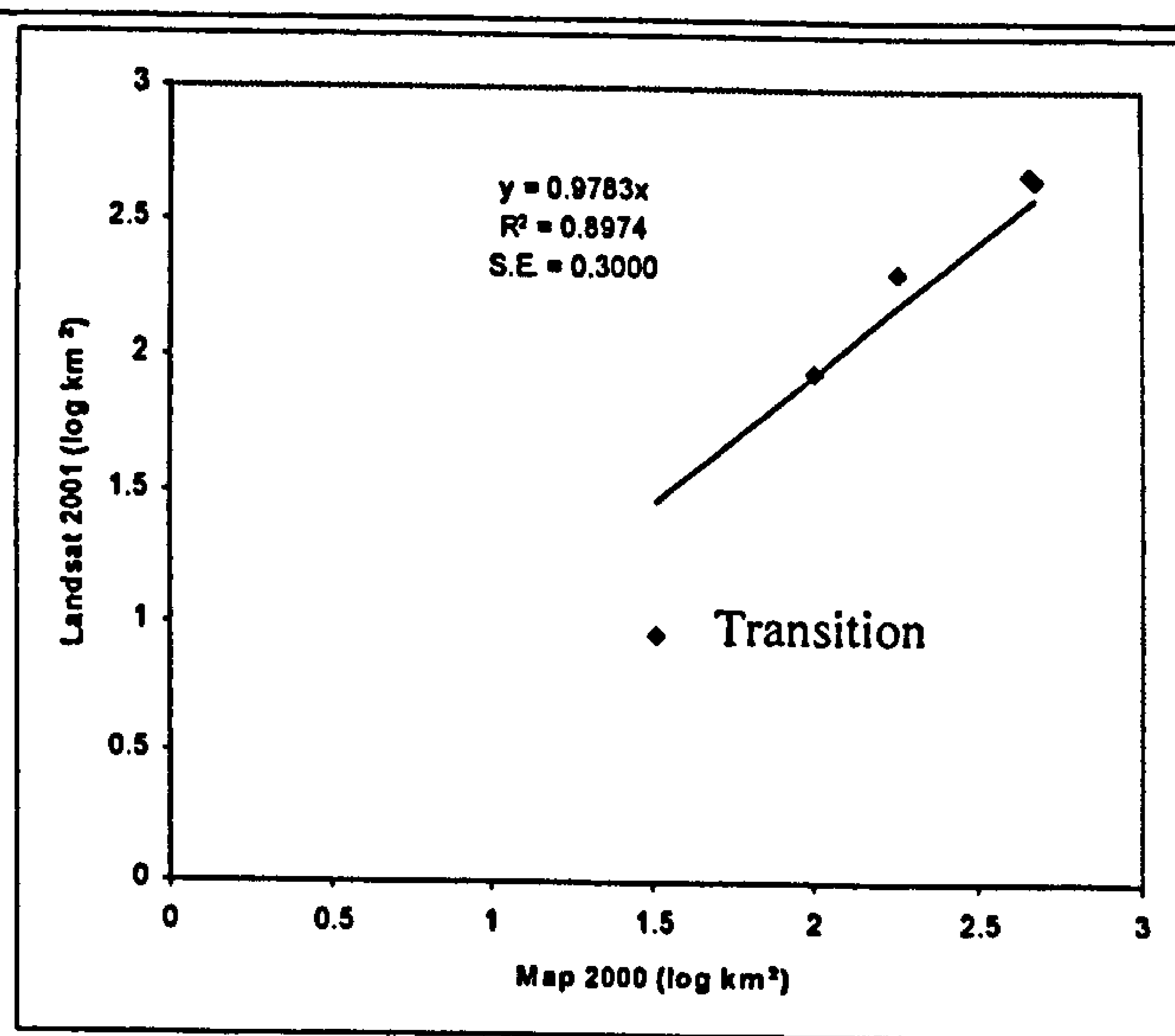
Figure 5.4a shows that there is no significant change in land use in the Langat catchment between 2000 and 2001, which corroborates the near-unity regression coefficient (0.98) in **Figure 5.3a**. This suggests that the major land use changes are difficult to detect within a very short interval even with support from latest Landsat information. The area had just recovered from severe economic recession, so, not much change was suspected to have occurred on the ground. However, in **Figure 5.4b,** there is a clear difference of forest cover area between the 2000 map and the 2001 Landsat in the Linggi catchment, which suggested the level of classification accuracy is high. This also applies in the Bernam, where the forest and cleared-felled areas are clearly separated in the 2001 Landsat and map of 2000 **(Figure 5.4c).**

Perfect agreement could not be expected due to the differences in the date of data collection, as well as different in the source of the data and also difficulties to recognise a correct class in Landsat classification. Not surprisingly, *t-test* indicated that the differences between them are not significant. This analysis also reveals that the area classified by Landsat (in this example, refer to agriculture) is slightly higher compared with output from map. This reflects the difficulties faced by the unsupervised technique to differentiate the very similar spectral signature in Landsat imagery which could belong to more than one land use category. Therefore, they are overestimated since the ground truth data are not available to reclassify. In addition, this analysis highlights the very small changes that occur in land use within a short interval of time in all three catchments. For example, the cleared-felled area more less same for Langat and Linggi with 8 % (31 km^2) and 6 % (5 km^2), respectively. This reflects the level of economic growth and development policy taken by central government and local authorities. There is also possibility that, the rate of urbanisation slightly low, or just to recover from the severe economic recession from 1997.

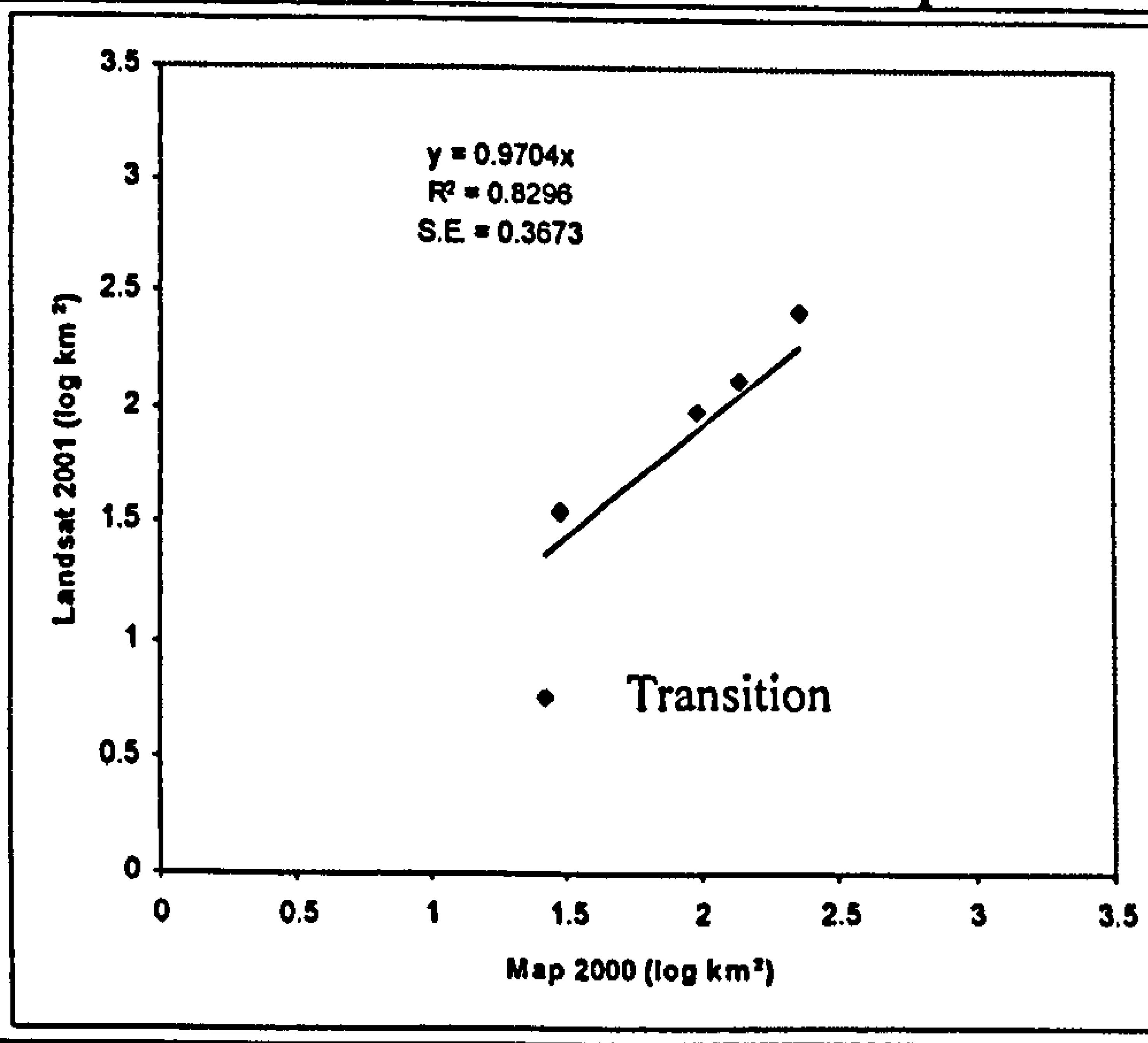
Table 5.3: Comparison of cover type area estimates from Landsat classification and the reference map from DOA, Malaysia

		Land use (%)				
Catchment	**Source-year**	**Forest**	**Agriculture [a]**	**Urban [b]**	**Water [c]**	**Transition**
Langat	Map 2000	38	37	8	15	3
	Landsat 2001	37	39	7	16	1
Linggi	Map 2000	26	45	6	19	5
	Landsat 2001	25	50	7	18	1
Bernam	Map 2000	56	34	5	4	1
	Landsat 2002	55	36	3	4	2

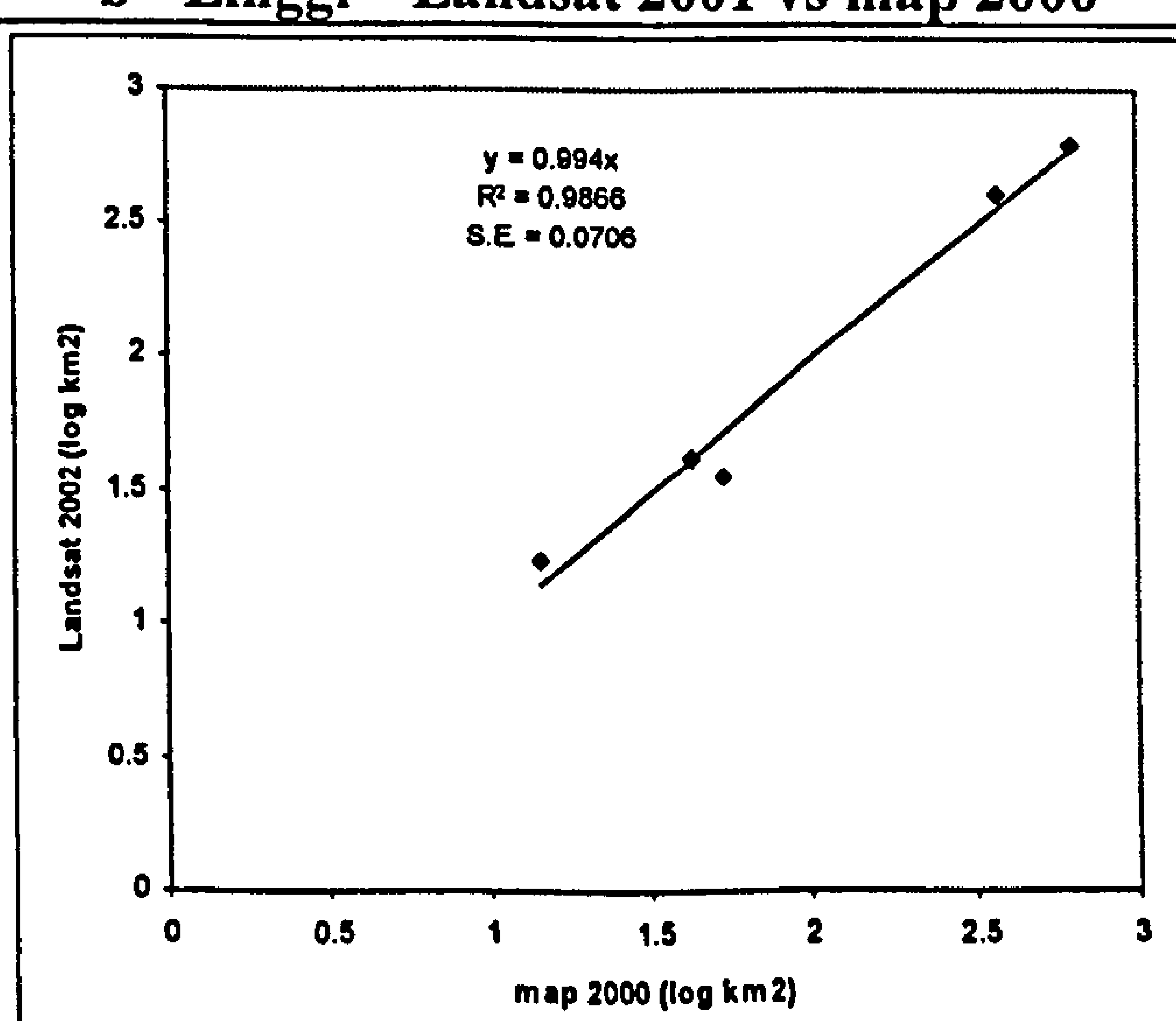
Notes: a-oil palms and rubber trees; b-built-up area and newly cleared area; c-water bodies and reservoirs



a - Langat – Landsat 2001 vs map 2000



b - Linggi – Landsat 2001 vs map 2000



c - Bernam – Landsat 2002 vs map 2000

Figure 5.3: Langat , Linggi and Bernam– a comparison between Landsat and map 2000 cover type area estimates for forest, agriculture, urban , water and transition classes

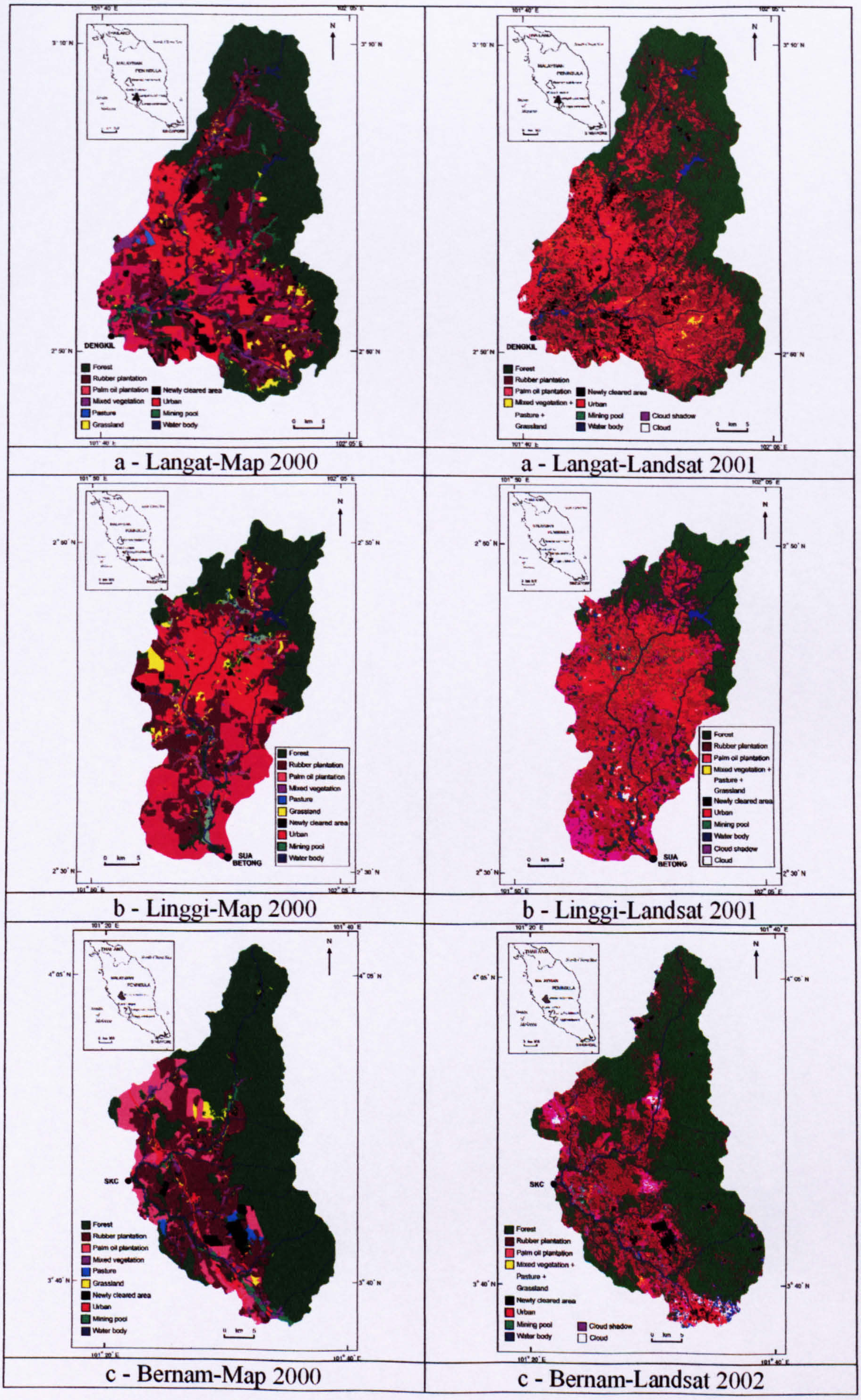


Figure 5.4: Langat , Linggi and Bernam– a comparison between Landsat and map 2000

5.3 Catchment land use change between 1984-2002 and its relation with water yield and water quality

In the early 20th century, the Malaysian economy was mainly based on alluvial tin mining. Later, when Malaysia achieved independence from Britain in 1957, rubber and palm oil trees were introduced for commercial purposes through the First Malaya Plan (1956-1960) which placed more focus on rural development. Many of the forest areas, especially on the west coast of the Peninsula where all the study catchments are situated, were cleared and replaced by these commodity crops under the Federal Land Authority. Under the New Economy Plan (1970-1990), the agriculture sector still kept on growing but, at the same time, much focus was put on industrialization to bring the Malaysian economy to the next level. During the period 1980-2000, the Langat and Linggi catchments were among the areas involved with this economic change, while the Bernam maintained its rural and agricultural status. Malaysia was consistently achieving more than 7% GDP growth along with low inflation from 1980 to 1996 before economic crisis struck between 1997 and 2002. The urbanization process, which significantly began in the 1980s, by which many forest and agricultural areas have been changed to impervious surfaces, is expected to have a significant impact on water relations.

The eighteen years, 1984 - 2002, considered in this study is a short interval of time in a long history of land use dynamics. This time period was chosen because of the availability of current and compatible satellite images and maps for change detection as well as a means of illustrating current land use trends. This period also coincides with a period of considerable increases in agricultural and urbanisation activities in the Langat and Linggi catchments which have an impact on water yield and water quality.

Landuse classification (DOA maps and Landsat sources) was conducted for all three catchments (**Figures 5.6-5.7**) and the individual class areas and change statistics for the period 1984-2002 are summarized in **Tables 5.4-5.6**. The larger scale catchment land use maps are attached in **Appendix 4**. Generally, the land use data from all catchments demonstrate that forest areas still remain a major land cover throughout the catchments in the early1980s with 40 % (503 km^2) and 65 % (731 km^2) of total catchment areas for Langat and Bernam, respectively. For the Linggi catchment, the forest area covers only about 29 % (151 km^2) as a function of the relatively small mountainous area upstream and it has been subjected to rapid land use change since the 1970s. The forested area in the Bernam is relatively high at this stage because the area was still yet to be developed by comparison with Langat and Linggi which had already been subjected to various phases of earlier land development. Between 1984 and 2002, the forested area decreased by 7 % (37 km^2), 13 % (20 km^2) and 15 % (109 km^2) for Langat, Linggi and Bernam, respectively. In Bernam, the percentage and absolute change is quite high and it is still at an early stage of development in which the focus is still on deforestation and agricultural expansion. Despite this, the percentage area covered by natural forest in 2002 is still high at 55 % (622 km^2). At the same point in time, the Langat and Linggi only had a cover of 37 % (466 km^2) and 25 % (131 km^2), respectively. In Linggi, with a total catchment area only half that of the Langat and Bernam (528 km^2), the demand of urbanisation of land is greater and this led to higher rates of conversion of forest to other land uses. The location of Linggi catchment, which is about 50 km south east of Kuala Lumpur, has triggered the need for urban expansion.

During the 1980s, almost half of the catchment area of the Langat and Linggi was covered by commodity crop plantations, namely rubber and palm oil, which were originally converted from natural forest. In Bernam, these crop plantations only cover approximately 30 % (312 km^2) of the area. Between 1960 and 1980, the agricultural sector was focused on expanding rubber estates in the rural areas since it contributes a high export income to the economy. The focus slightly changed in late the 1980s due to a fall in the international rubber price and attention turned to palm oil for which Malaysia became the biggest supplier in the world. During this period (1984-2002), many rubber estates were converted to oil palm estates, but the conversion of natural forest land was quite small. The rubber plantation area decreased by 28 % (138 km^2) and 41 % (105 km^2), whereas the area of oil palm increased by as much as 30 % (30 km^2) and 92 % (38 km^2) by 2001 in Langat and Linggi, respectively. In the Bernam catchment, both rubber and oil palm area increased by 13 % (33 km^2) and 56 % (66 km^2) from 1984 to 2002, respectively, but the expansion of these was at the expense of forest land.

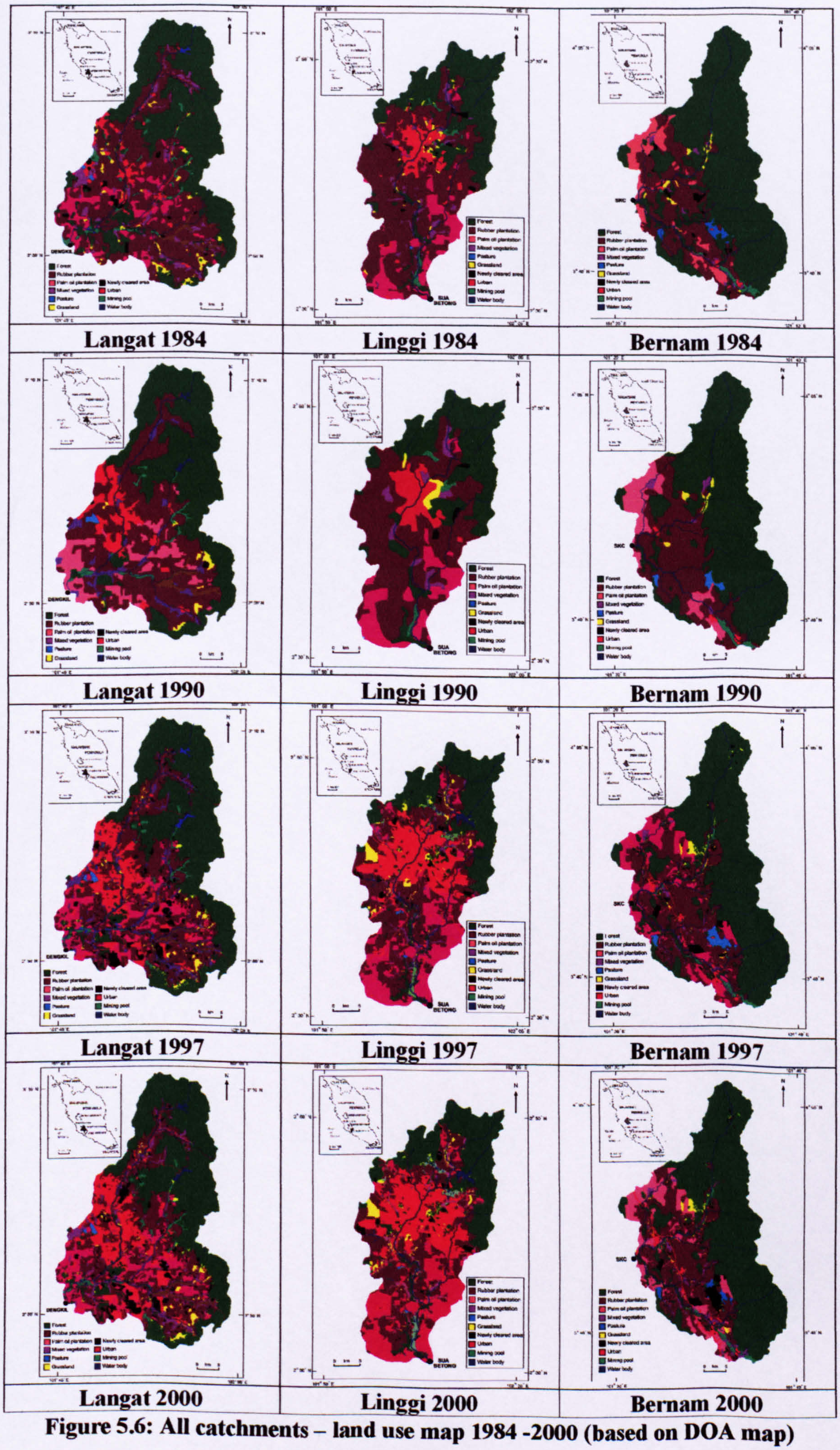


Figure 5.6: All catchments – land use map 1984 -2000 (based on DOA map)

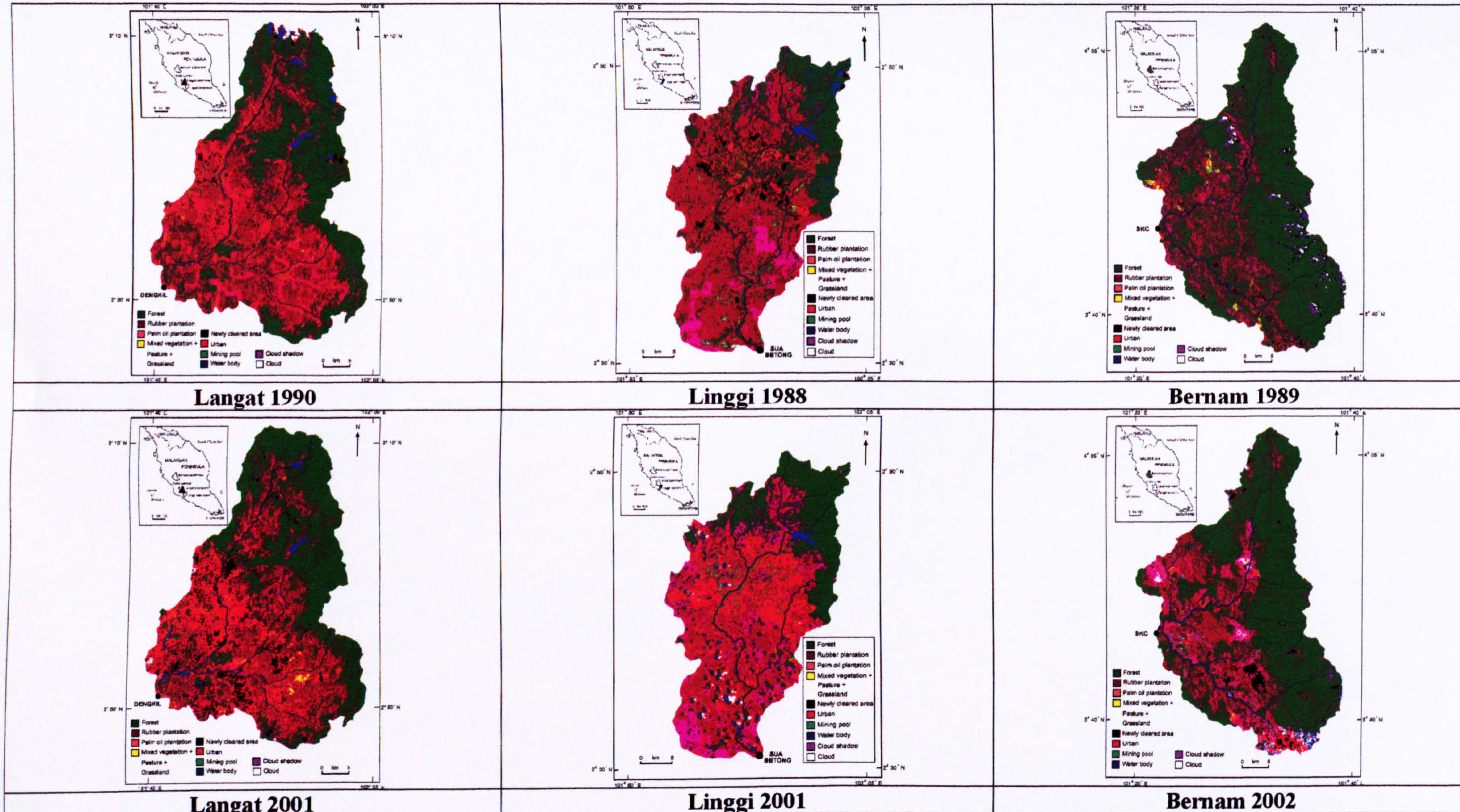


Figure 5.7: All catchments – land use map 1988 -2002 (based on Landsat)

Table 5.4: Langat - summary of map and Landsat classification area statistics for 1984, 1990, 1994, 1997, 2000 and 2001

No	Land cover	Map 1984		Landsat 1990		Map 1990		Landsat 1994		Map 1997		Map 2000		Landsat 2001		Relative change*, between 1984 and 2001 (%)
		area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	
1	Forest	503	40	469	37	489	39	474	38	487	39	483	38	466	37	-7
2	Rubber tree	500	40	478	38	486	39	416	33	361	29	313	25	362	29	-28
3	Palm oil tree	97	8	130	10	120	10	155	12	143	11	147	12	127	10	30
4	Transition land use	80	6	87	7	61	5	76	6	79	6	100	8	90	7	12
5	Cleared-felled area	14	1	1	0	1	0	27	2	32	3	31	3	30	2	119
6	Built-up-urban	38	3	84	7	76	6	96	8	125	10	152	12	174	14	364
7	Mining ponds	22	2	3	0	19	2	3	0	19	2	21	2	3	0	-87
8	Water body - reservoir	3	0	6	1	6	0	10	1	13	1	12	1	6	1	94
	Total	1257	100	1257	100	1257	100	1257	100	1257	100	1257	100	1257	100	

Note: na = not available

* Example of relative change calculation;

$$\frac{\text{Area (km}^2\text{) 1984}}{\text{Area (km}^2\text{) 2001}} \times 100$$

Table 5.5: Linggi - summary of map and Landsat classification area statistics for 1984, 1988, 1990, 1997, 2000 and 2001

No	Land cover	Map 1984		Landsat 1988		Map 1990		Map 1997		Map 2000		Landsat 2001		Relative change*, between 1984 and 2001 (%)
		area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	
1	Forest	151	29	137	26	148	28	137	26	137	26	131	25	-13
2	Rubber tree	255	48	245	46	245	47	163	31	141	27	150	28	-41
3	Palm oil tree	59	11	61	12	67	13	91	17	96	18	112	21	92
4	Transition land use	19	4	29	6	19	4	30	6	30	6	35	7	89
5	Cleared-felled area	6	1	10	2	3	1	5	1	5	1	1	0	-88
6	Built-up-urban	33	6	40	8	39	7	87	16	93	18	94	18	183
7	Mining ponds	7	1	2	0	7	1	9	2	21	4	2	0	-69
8	Water body - reservoir	0	0	4	1	0	0	5	1	6	1	4	1	na
	Total	528	100	528	100	528	100	528	100	528	100	528	100	

Note: na = not available

* Example of relative change calculation;

$$\frac{\text{Area (km}^2\text{) 1984}}{\text{Area (km}^2\text{) 2001}} \times 100$$

Table 5.6: Bernam - summary of map and Landsat classification area statistics for 1984, 1989, 1990, 1995, 1997, 2000 and 2002

no	land cover	map 1984		Landsat 1989		map 1990		Landsat 1995		map 1997		map 2000		Landsat 2002		Relative change*, between 1984 and 2002 (%)
		area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	area (km^2)	%	
1	Forest	731	65	721	64	689	61	653	58	632	56	631	56	622	55	-15
2	Rubber tree	255	23	243	22	303	27	295	26	280	25	268	24	288	26	13
3	Palm oil tree	77	7	88	8	87	8	97	9	115	10	114	10	120	11	56
4	Transition land use	34	3	23	2	30	3	37	3	52	5	53	5	35	3	4
5	Cleared-felled area	8	1	23	2		na		1	15	1	24	2	17	2	109
6	Built-up-urban	5	0.4	15	1	5	1	19	2	15	1	19	2	25	2	394
7	Mining ponds	14	1	10	1	9	1	12	1	13	1	13	1	17	2	27
8	Water body - reservoir	0	0		na		na		na	2	0	2	0		na	na
	Total	1123	100	1123	100	1123	100	1123	100	1123	100	1123	100	1123	100	

Note: na = not available

* Example of relative change calculation;

$$\frac{\text{Area (km}^2\text{) 1984} \times 100}{\text{Area (km}^2\text{) 2002}}$$

The urban area in Langat and Linggi increased by 364 % (24 km^2) and 183 %, (15 km^2) respectively in the period 1984-2001. By 2001, Langat was covered by 14 % (174 km^2) of 'artificial surfaces' compared with 3 % (38 km^2) in 1984 and the Linggi catchment was covered by 18 % (94 km^2) compared with 6 % (33 km^2). The Bernam catchment also showed a very high percentage increase in urban area by 394 % (20 km^2), but in reality the area coverage by 2001 was only 2 % (25 km^2) of the total catchment. The expansion of this urban area had just started in 2000 with 2 % (19 km^2) of catchment area covered, whereas, in 1984, it was only 0.4 % (0.5 km^2). Despite a very high percentage of urban expansion, especially in Langat and Linggi, it has not been at the expense of the natural forest area. Rather urban areas expanded have inroads in agriculture areas, especially the rubber estates. It can be seen that, in 20 years, the depletion of the forest area has been only 7 % (38 km^2) in Langat and 13 % (20 km^2) in Linggi. However, the rubber plantations were depleted by 28 % (138 km^2) in Langat and 41 % (105 km^2) in Linggi. The conversion process involved a land clearance (urban) and trees clearance (conversion to palm oil tree); this is expected to have an impact on water yields and water quality.

The other significant change to occur in the Langat and Linggi due to pressure of urbanisation has been the decrease in the mining ponds where they have been reclaimed by land-fill processes to create 'new land' for urbanisation. In 2001, the mining ponds in Langat covered about 0.2 % (3 km^2), a decrease from 2 % (22 km^2) in 1984, while there were 0.4 % (2 km^2) in the Linggi, a decrease from 1 % (7 km^2) in 1984. Meanwhile, in Bernam, the mining ponds have remained as they were because the level of urbanisation has been small. This reclamation processes is also expected to have a significant impact on the urban hydrology, especially storm water management, where the ponds once functioned as balancing units, reducing flood flashiness.

Despite the significant changes in land surface mainly due to conversion of one type of agriculture to another and agriculture to urban area since 1984, economic recession set in during 1997 seems to have had a significant impact in slowing the rate of vegetation conversion until 2000. **Table 5.7** demonstrates that urbanisation and land conversion from forest to oil palm or rubber to urban area occurred rapidly before the economic recession, especially in the Langat and Linggi. For instance, during 1984-1997, the rubber area decreased from 28 % (139 km^2) and 36 % (92 km^2) to 13 % (48 km^2) and 14 % (22 km^2) in the period 1997-2000, respectively. The urban areas which were the main indicator of economic growth also showed a very small increment with 22 % (22 km^2) and 7 % (6 km^2) in 1997-2000 compared with 233 % (77 km^2) and 162 % (60 km^2) during 1984-1997 for the Langat and Linggi, respectively. Throughout this period (1984-1997), the conversion of natural forest to other surfaces is considerably smaller for Langat and Linggi, with 3 % (29 km^2) and 9% (14 km^2), respectively. Even for the period of 1984 to 2001, it is clear in **Figure 5.8** and **Figure 5.9** for Langat and Linggi, respectively, that the trend of forest change is small. This would suggest that, the catchments have passed the peak time for forest conversion to agriculture crops (rubber and oil palm trees) which began in 1956. However, the forest clearance rate in the Bernam is slightly higher, with 14% (99 km^2) during 1984-1997, which would reflect the capacity of a newly developed catchment (**Figure 5.10**). Therefore, the Bernam catchment has just been through the process of land conversion from natural forest to other land use, especially rubber and oil palm trees, in order to fulfil the expansion of the agricultural economy planned by the government. In the Langat and Linggi, where the rubber tree area significantly decreased after 1990 due to demand from oil palm industry, there was rather, urbanisation and industrialization (**Figure 5.8** and **Figure 5.9**).

Table 5.7: Catchment land use changes during development and recession periods

No	Land use category	Relative change 1984-1997 [a] (%)			Relative change 1997-2000 [b] (%)		
		Langat	Linggi	Bernam	Langat	Linggi	Bernam
1	Forest	-3.1	-9.2	-13.5	-0.9	-0.1	-0.2
2	Rubber tree	-27.9	-36.0	9.7	-13.3	-13.6	-4.2
3	Palm oil tree	46.6	56.2	49.5	2.8	4.5	-0.6
4	Transition land use	-2.2	61.8	53.7	26.8	1.0	2.3
5	Cleared-felled area	133.3	-10.0	81.3	-2.5	-1.9	64.1
6	Built-up-urban	232.5	162.2	200.0	21.7	6.7	28.7
7	Mining ponds	-14.3	41.5	-4.4	9.9	123.9	-2.3
8	Water body - reservoir	290.6	na	na	-8.0	na	na

Notes:
a, development period for Langat and Linggi; pre-develop period for Bernam
b, period of economic recession; comparison between map

Figures 5.8-5.10 reveals that land use change detection based on map sources can recognise such change with a 6-7 year gap. The speed of economic growth is reflected in the changes. There clearly a significant shift in the area of rubber trees in Langat and Linggi catchments and a shift in forest in Bernam. The use of current Landsat imagery with support from ground truth would be able to detect any significant changes on the ground within a short period, especially an expansion of the urban area at the expense of agriculture.

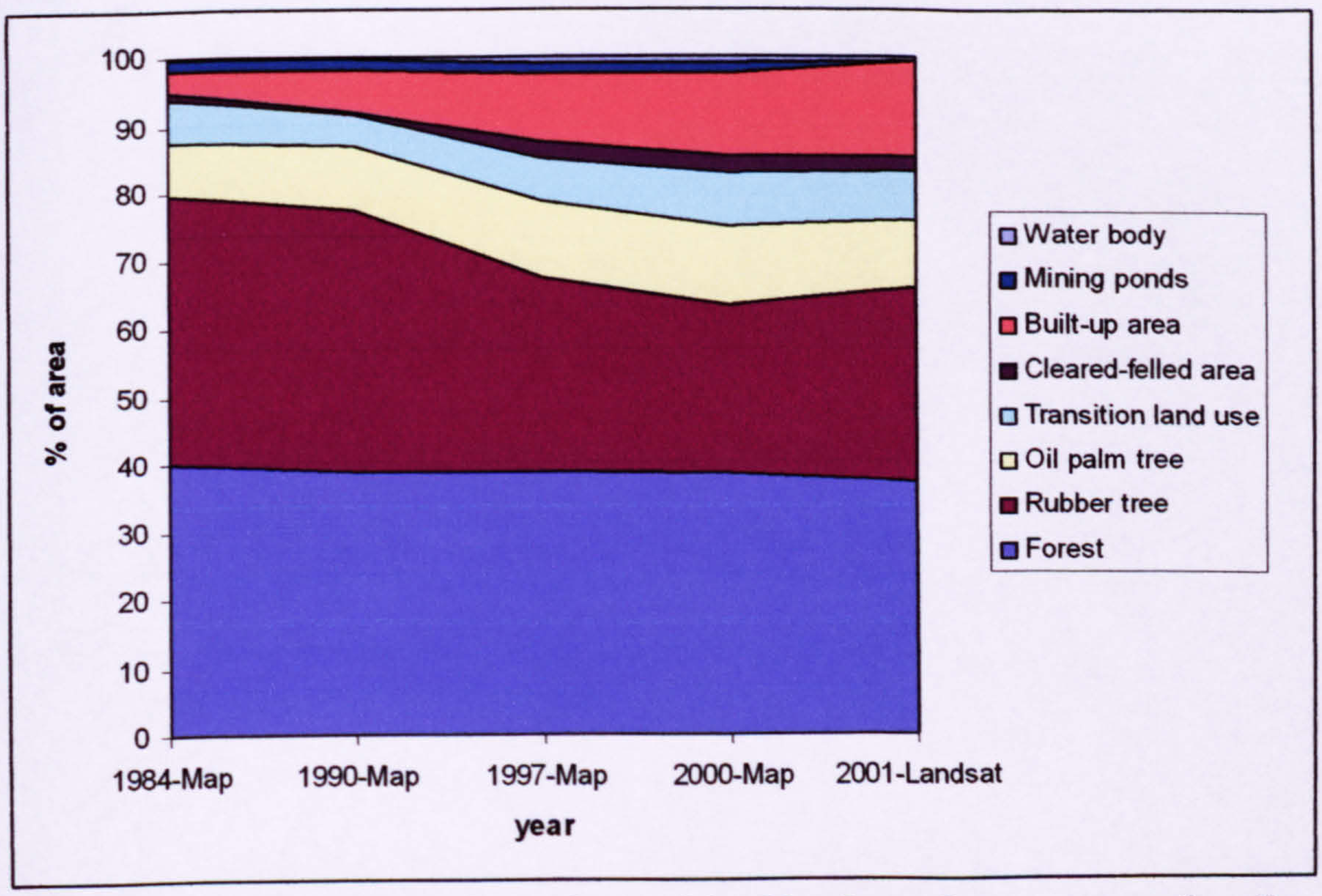


Figure 5.8: Langat – Figure shows the combined land use changes proportionally assigned to provide land use statistic for catchment between 1984-2001

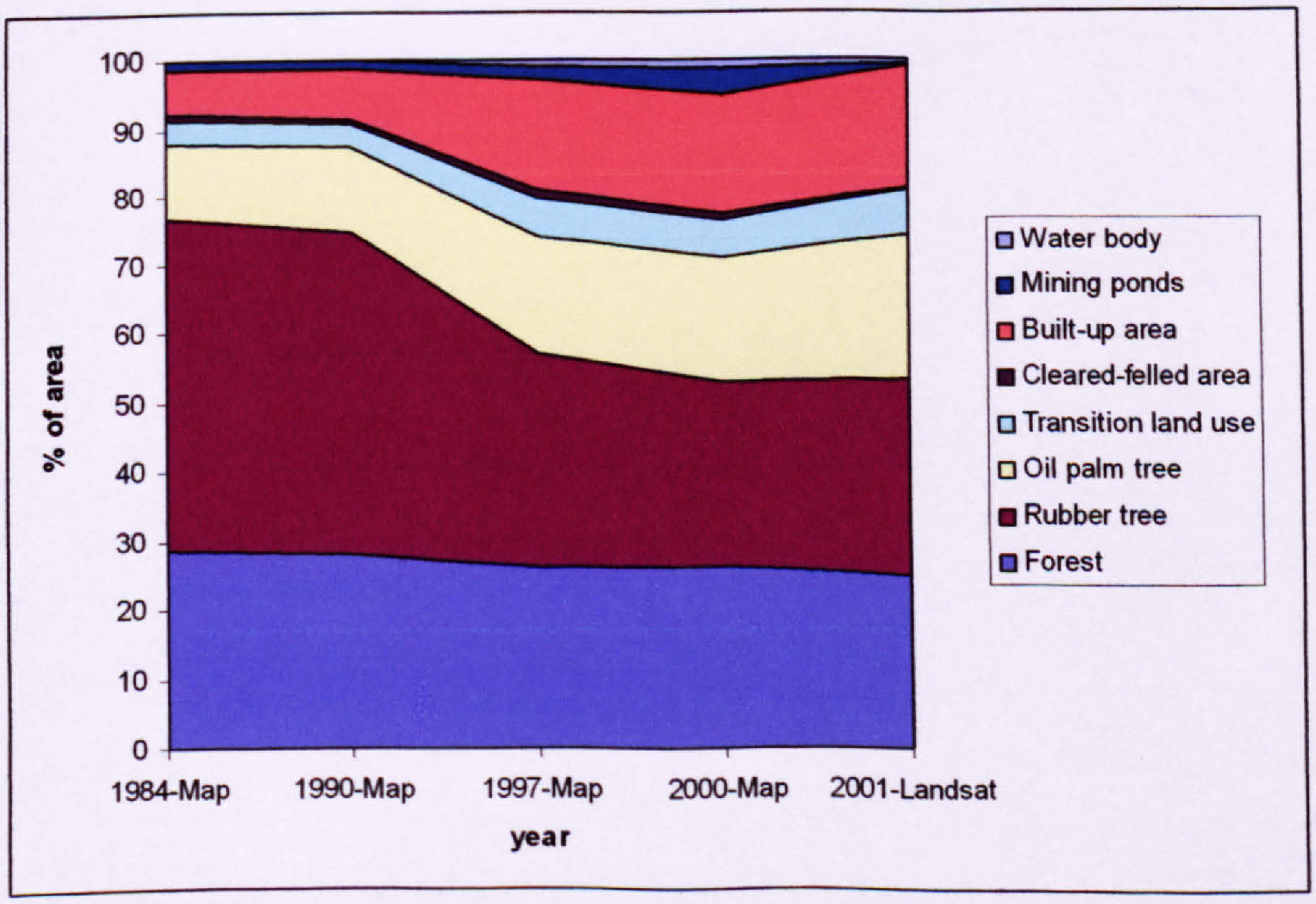


Figure 5.9: Linggi - Figure shows the combined land use changes proportionally assigned to provide land use statistic for catchment between 1984-2001

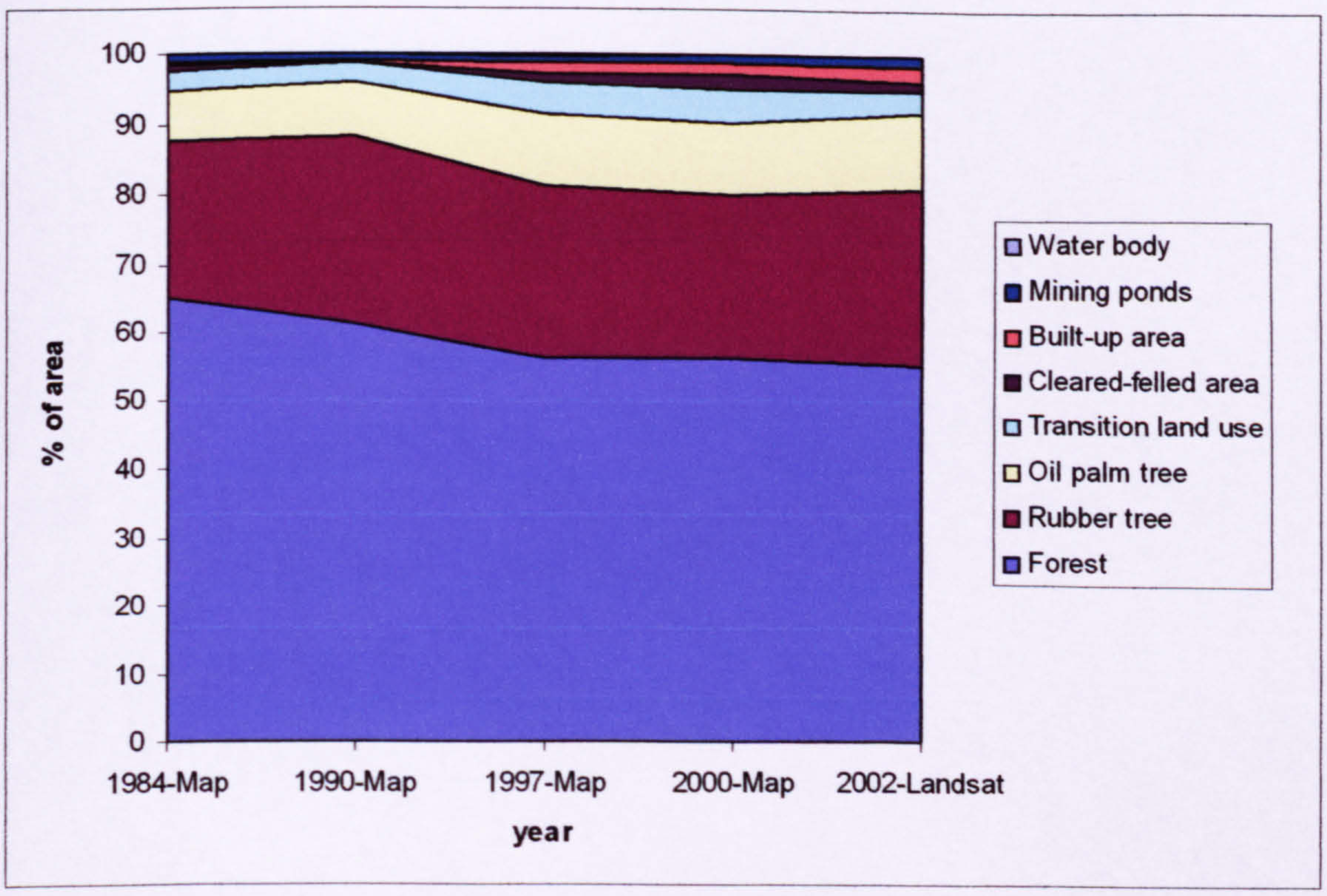


Figure 5.10: Bernam - Figure shows the combined land use changes proportionally assigned to provide land use statistic for catchment between 1984-2002

Historically, most of the towns in Malaysia have been transformed from early settlements situated alongside the river bank, as the population relied heavily on the resources provide by the river. All these early settlements have expanded to small towns and, later, bigger towns with various economic, social and cultural functions. This scenario can be seen in the three study catchments where the urban areas (red colour) have been through very rapid expansion along the river bank and, in some areas, upstream, involving the conversion of agriculture areas and hilly forested areas.

Figures 5.11 and **5.12**, especially maps A-D clearly show the expansion of urban areas in Langat and Linggi, respectively, from 1984-2000. The Cheras town in the Langat catchment was expanded towards Kuala Lumpur to the Northwest to form an extension of the Kuala Lumpur economic centre. The same happened in the Linggi, where Seremban, which is the capital of the Negeri Sembilan State, also rapidly expanded towards the Northeast. The urban areas have been developed at the expense of rubber trees (brown colour) areas and the speed of change over 13 years is shown by maps A-1984 and C-1997 for the Langat and Linggi. The bottom part of the Langat catchment was also subject to development of a new town which expanded southeast towards

Seremban to support the expansion of the Seremban administrative and economic centre. Maps E-H in **Figure 5.11** show the urban and palm oil areas expanding at the expense of the rubber areas, especially after 1990. The expansion of the lower Linggi catchment involves less urban development, but shows an increasing replacement of rubber tree area with palm oil as the government maintained the contribution of the agricultural sector towards the country's economy alongside industrialisation.

However, within the Bernam, land use planning is still focussed on agriculture at the expense of natural forest (green). Maps A-D clearly shows the expansion of rubber and palm oil trees (magenta colour) in the Sungkai area (upstream of the Bernam-Slim junction). There are not many changes in urban area, as can be seen in **Figure 5.13**, maps E-H, where the Tanjong Malim town is situated. The start of the new development project for the Bernam Valley can be seen by 2000, where areas have been cleared (black colour) for Proton City and the Behrang 2020 housing and business estate development.

It can be recognised that the period between 1984 and 1997 involves substantial land use changes between types of agriculture and between agriculture – urbanisation especially in the Langat and Linggi cartchments. For Bernam, the changes involve forest – agriculture, agriculture – agriculture and agriculture – urbanisation. All these activities will have a certain amount of impact on runoff, suspended sediment yield as well as other water quality parameters, such as BOD.

A study of the relation between urban area expansion and distance from the river artery and outlet was undertaken. The aim was to recognise changes which could relate with the time for runoff to travel toward the artery and move down to the outlet. As urbanization plays a significant role in changing the peak discharge, lag time, total runoff and flood frequency within urbanised catchments (Leopold, 1968, Poff *et al.*, 2006; Chin, 2006), it is important to understand how direction of urban changes could contribute to this issue. As the urban surface increases, peak discharge will increase which could bring more domestic waste, decrease the lag time and often cause flash floods. This scenario often happens in Malaysia, such as in the Klang Valley, where the expansion of Kuala Lumpur city centre shifted upstream and caused large upstream areas to be transformed to concrete surfaced (Ithnin and Sakke, 2001). This caused very frequent (3-5 times a year) flash floods downstream in Kuala Lumpur recently and the municipal drainage network could not cope with the larger amount of runoff within short time.

From the analysis, it is clear that the urban areas are expanding from the existing areas toward the river banks in Langat and Linggi. **Figures 5.14** shows the urban areas increase close to the river artery (0-0.5 km) from 19 km^2 to 54 km^2 between 1984 and 2000, respectively, in Langat. Within this period, the percentage expansion actually decreased from 51% to 36% because large areas were developed outside the flood plain, increasing distance to the river artery in order to cope with development over-spill from the Klang Valley. A similar story happens in the Linggi (**Figure 5.17**), where areas within 0-0.5 km from river artery increase from 41% (18 km^2) to 54% (41 km^2) between 1984 and 2000, respectively. Most of the urban areas in Langat and Linggi were located between 0-3 km from a river artery. This will accelerate water towards the channels. In the Bernam (**Figure 5.19**), as the catchment is just starting to be developed, there is a slight increase in urban area within the flood plain, the absolute area increasing from 3.7 km^2 to 5.6 km^2 within 0-0.5 km of an artery between1984 and 2000, respectively. But it shows a similar trend to the Langat and Linggi. This is because Tanjong Malim town, where the new development projects such as Proton City and Behrang 2020 which involves lot of infrastructure building such as housing estates, factories and business centres, and these are located just at the foothills of the Main Range. There will be a tendency to copy what was happened in the Klang Valley if a proper plan is not in place.

In terms of direction of urban expansion upstream or downstream, the Langat and Linggi catchments seem to be expanding in both directions (**Figures 5.15** and **5.18**) between 1984 and 2000. The distance to the centroid (i.e. 50% of urban area is located shifted from 27 km to 34 km from river outlet between 1984 and 2000. The movement upstream is caused by the new urban areas on the left hand side of catchment, where the Semenyih tributary is an alternative area for the overcrowded urban areas of Cheras and Kajang. This is clearly demonstrated by **Figure 5.16**. Meanwhile, in Linggi, the expansion is more significant downstream and the relatively small upland areas remain intact. The centroid of the urban area decreased from 32 km from the river outlet in 1984 to 27 km in 2000. A similar pattern occurs in the Bernam, where the distances from the river outlet fell to 31 km from 33 km (**Figure 5.20**). As the entire development plan focuses on the Bernam trunk, the Slim tributary, which is covered largely by native forest, remains intact (**Figure 5.21**). This promises relatively clean water and may safeguard water resources. More attention is required of development managers when dealing with urban projects as this change the catchment surfaces permanently. The conversion of forest to agriculture or agriculture to a different type of agriculture also has an impact on the water yield and water quality, but, it is believed, not as much as is cause by urban growth (Ruslan, 2000).

To assess the general impact of land development on the water yield and water quality, the discrete historical land use data for forest, rubber, palm oil tree, urban and cleared-felled areas based on DOA maps were compared with the annual runoff (five-year running mean), suspended sediment yield (five-year running mean) and BOD (median value). There is no intention to investigate the effects of detailed changes in land use, especially urban, on water yield and water quality indicators as this would need more specific information about the possible surfaces response to periods of rainfall.

The effect of increasing urban population on water quality (BOD) in the Langat and Linggi catchments is clearly demonstrated by **Figures 5.23** and **5.24**. The expansion of the urban area from 1984 and 2000, shown in **Figures 5.6** and **5.7,** is mirrored by the increase in levels of BOD in the river, especially in the Langat. In the Langat, the urban area has expanded along the trunk channel from Cheras towards Dengkil, downstream. In the Linggi, the urban area expanded on both the left and right river banks at Seremban and towards Sua Betong, downstream. Higher pollutant load in a water body increases the cost for water treatment. The upward trends in pollution decrease after 1997, especially in the Linggi, as a function of implementation of new amendments to water regulations, enforced by DOE.

The impact of forest or agriculture conversion within medium scale catchments on runoff is not normally straightforward. An increase in vegetation removal would normally be accompanied by a proportionate increase in water yield in small tropical experimental catchments. Changes in water yield mainly reflect different evaporation characteristics between mature topical forests, young or secondary growth. However, for catchments which are still covered by large areas of vegetation, a rapid return of runoff to pre-disturbance levels is expected as a function of young secondary growth (Brown and Lugo, 1990). This would apply to all of the study catchments (**Figures 5.25 -5.27**). This seems to be contradicted with Lal (1983) who found that a change from native forest to agricultural cropping caused a permanent change in water yield in sub-humid Nigeria. This could be because of the size of study site, local climatology and also physical characteristics of the catchment.

Because the general indicators do not show any significant impact of land use changes on water yield, it does not mean that the development manager can maximise development for the benefit of the economy. There is need for conservation and proper planning because pollution loads such as suspended sediment concentrations would decrease the cleanliness of the water. Related issues such as increased flashiness of the flood hydrograph are still a nuisance because most urban development is located on the flood plain just downstream from the highland area.

5.4 Summary

This chapter has described the trends in land use change which have occurred within the three study catchments from 1984 and 2002. It also highlights the detailed procedure used to classify land use from map and Landsat imagery. The analysis shows that rapid land development, especially in the Langat and Linggi, has had a significant impact through conversion of forest and agricultural areas to urban use. The forest area decreased from 37 % (503 km^2) and 29 % (151 km^2) to 30 % (466 km^2) and 25 % (131 km^2) for Langat and Linggi, respectively, between 1984 and 2001. The urban area increased from 3 % (38 km^2) and 6 % (33 km^2) to 14 % (174 km^2) and 18 % (94 km^2), respectively. This change has had an impact on water quality. In the Bernam - yet to be developed – there were no significant changes on urban area but forest decreased from 65 % (731 km^2) to 55 % (622 km^2) between 1984 and 2002, respectively, as a function of agricultural development within the catchment.

Chapter Six examines in detail the rainfall and runoff characteristics and their relation with land use development which has occurred within all three study catchments. This will indicate the significance of land use change or water quality and water yield.

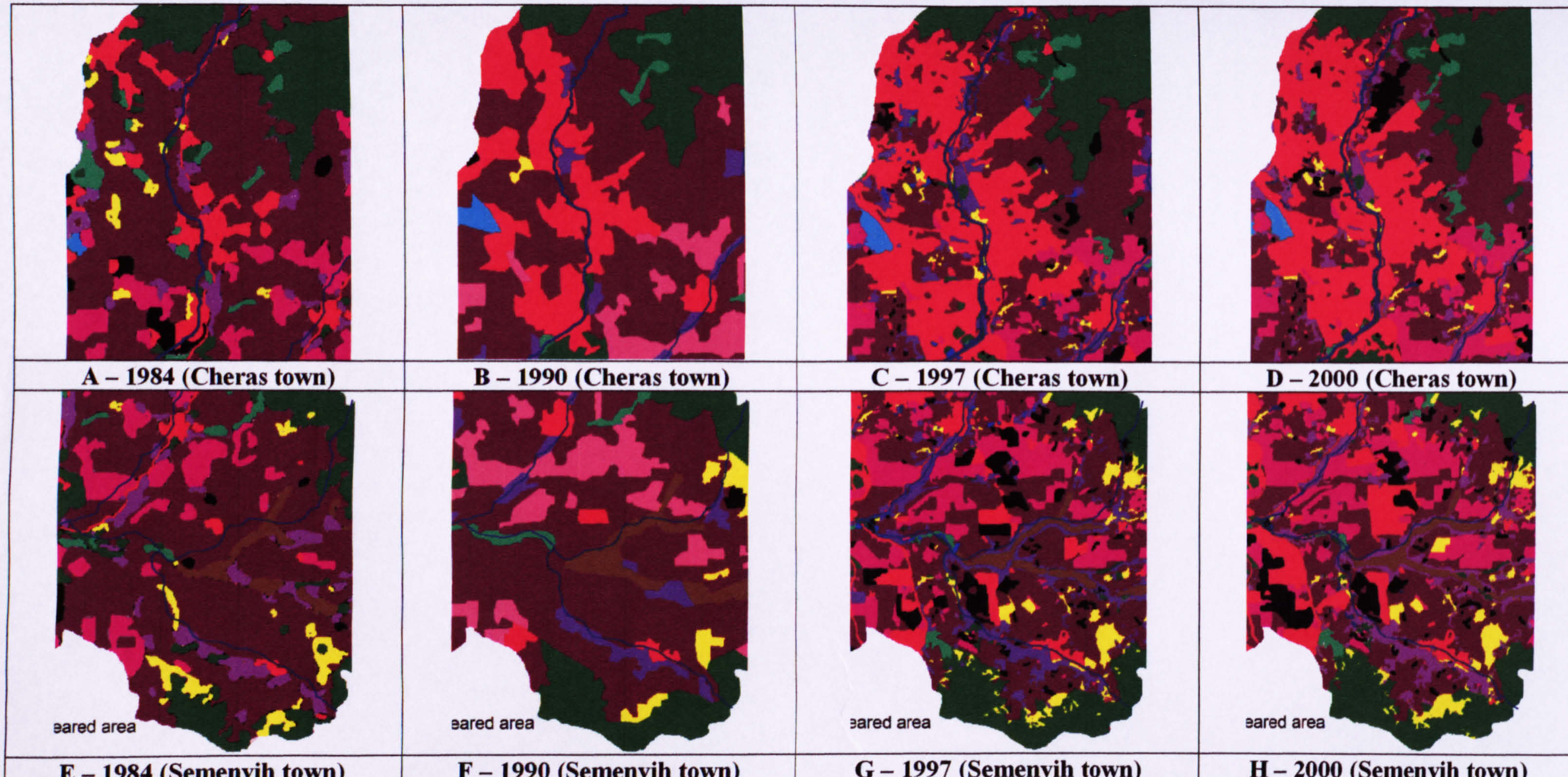


Figure 5.11: Langat – major land use changes between 1984 to 2000 based on map source DOA
(Full scale map which shows these two part of catchment can be found in Appendix 5-Map 1984)

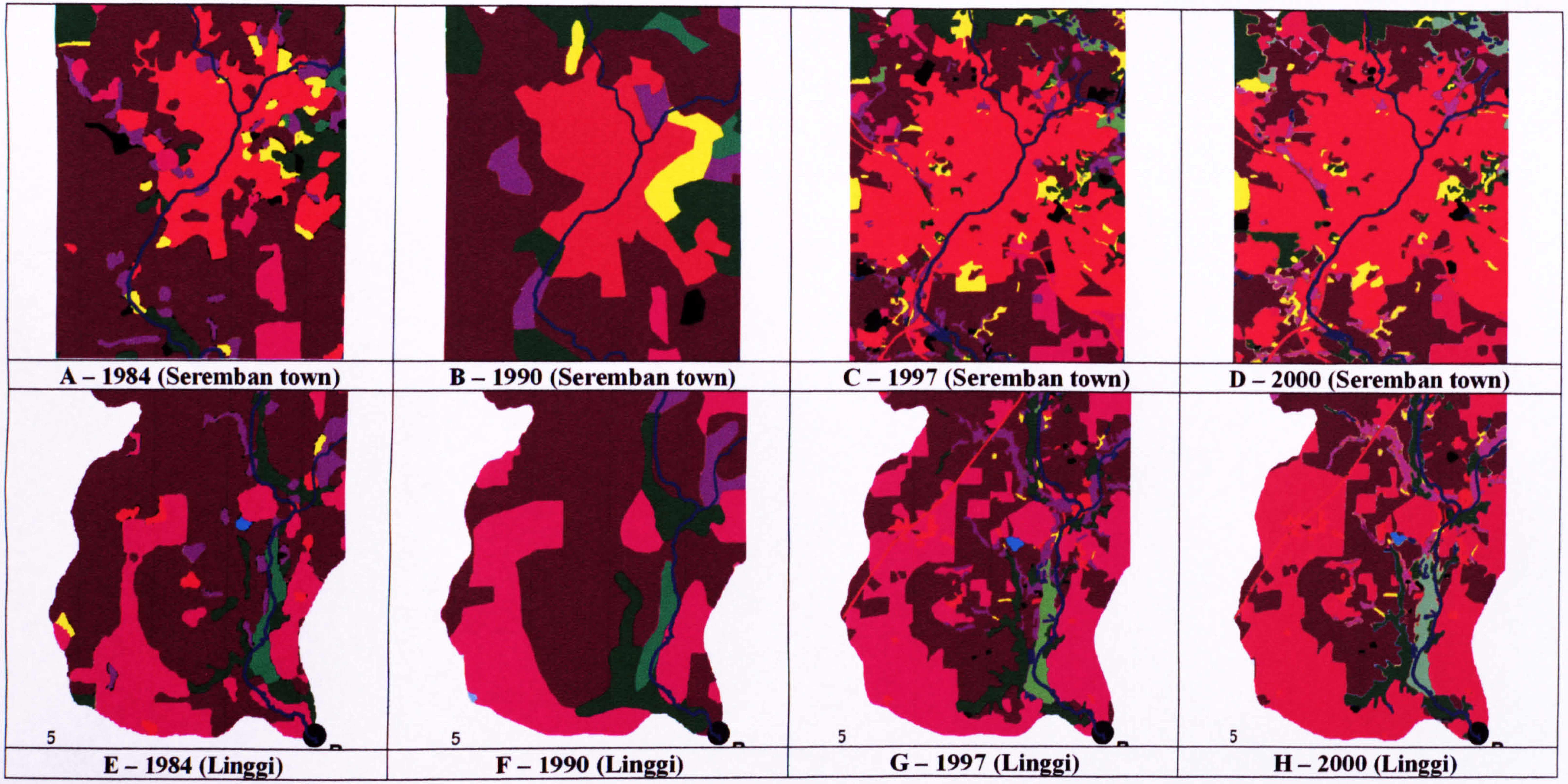


Figure 5.12: Linggi – major land use changes between 1984 to 2000 based on map source DOA
(Full scale map which shows these two part of catchment can be found in Appendix 5-Map 1984)

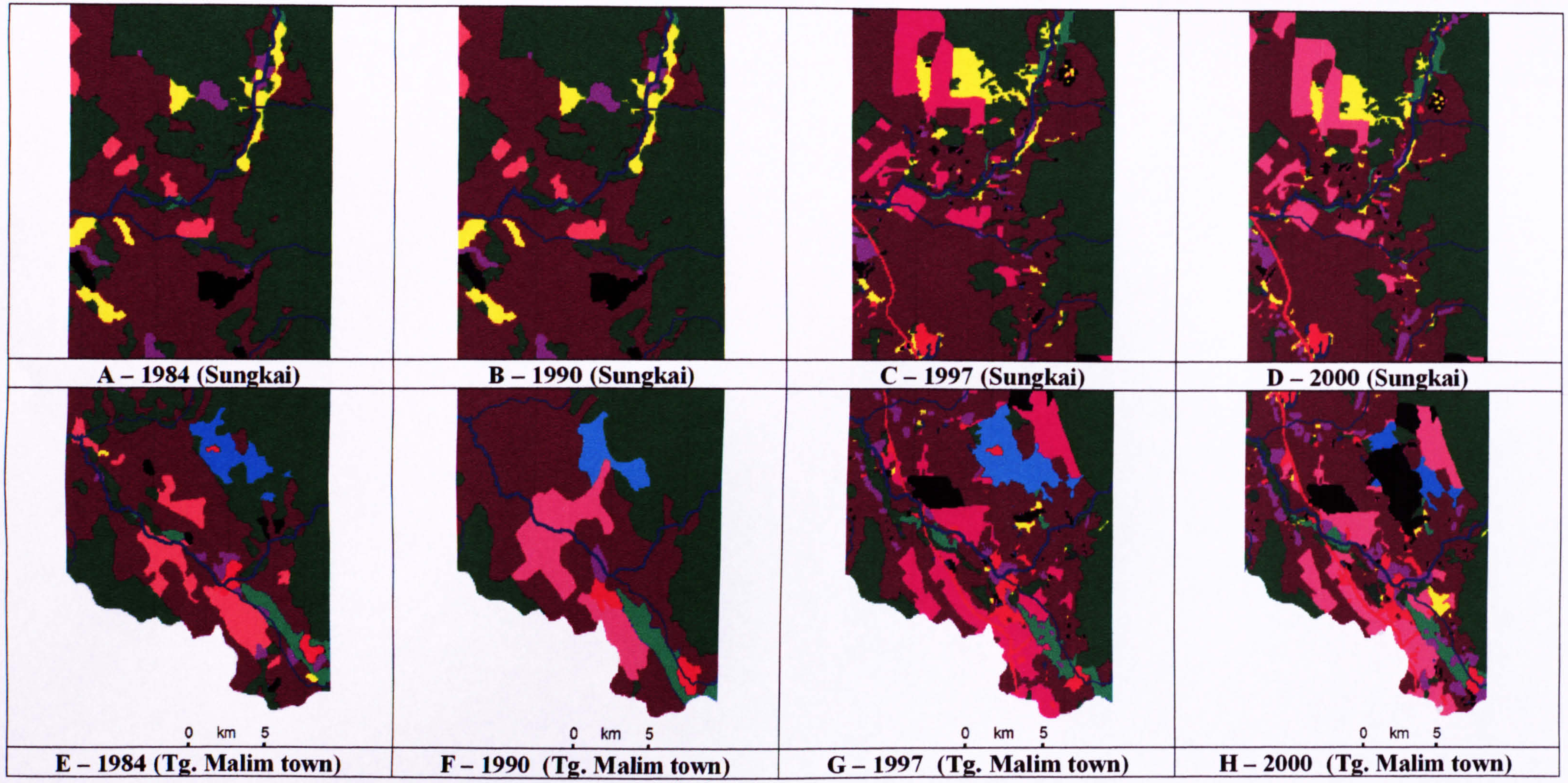


Figure 5.13: Bernam – major land use changes between 1984 to 2000 based on map source DOA
(Full scale map which shows these two part of catchment can be found in Appendix 5-Map 1984)

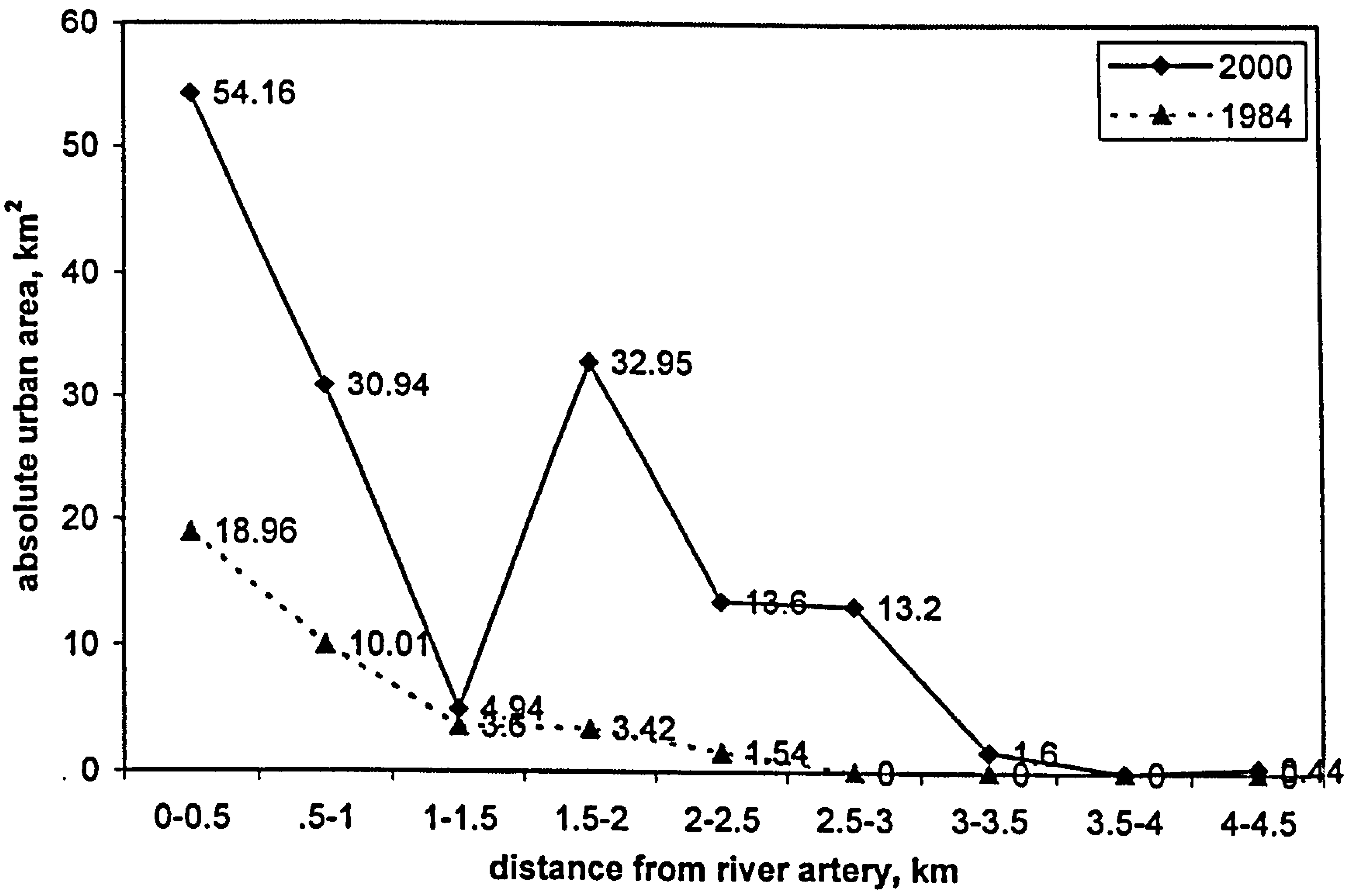


Figure 5.14: Langat – 1984 and 2000 urban area from river

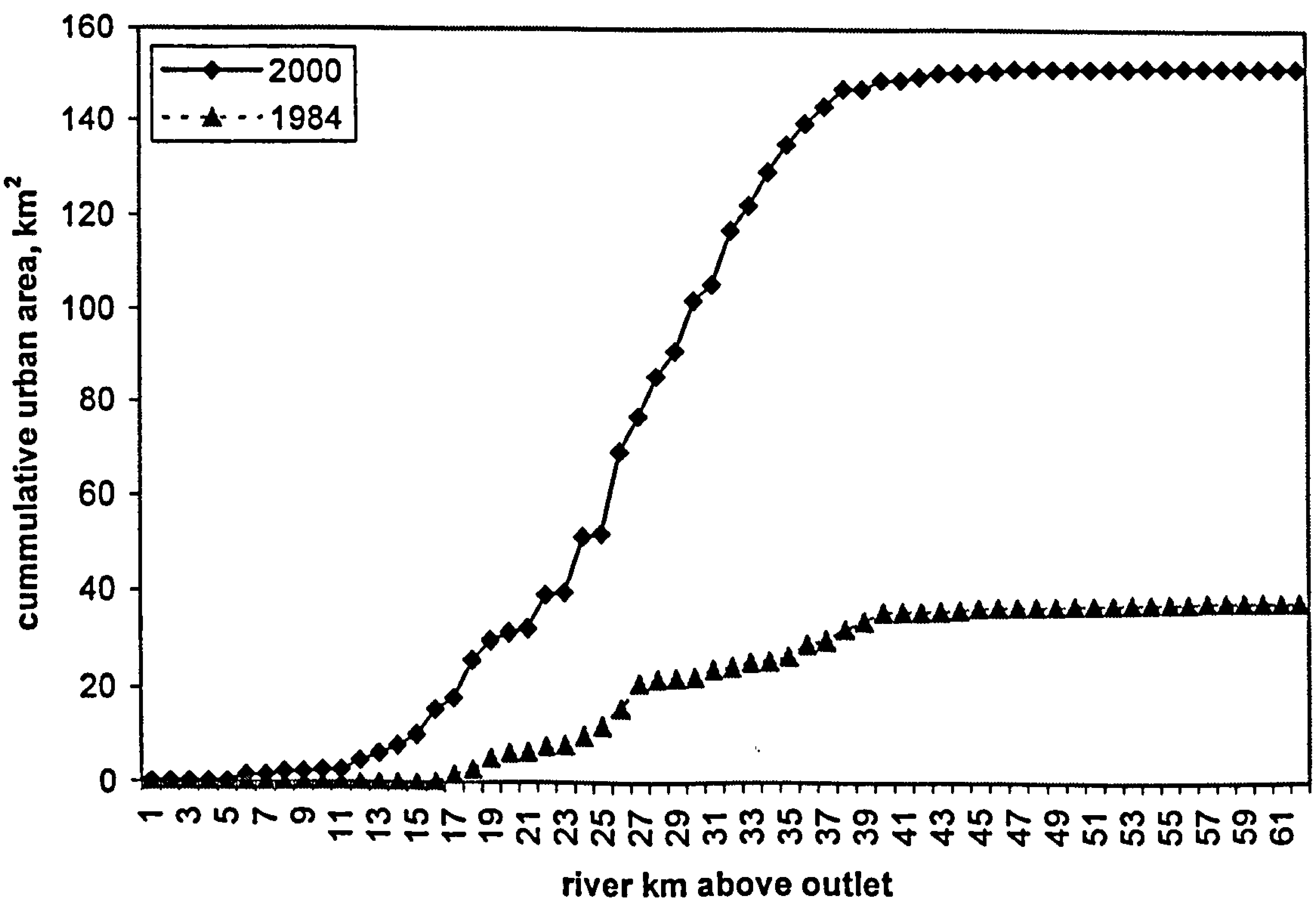


Figure 5.15: Langat – 1984 and 2000 cumulative urban area (km^2) with distance above outlet

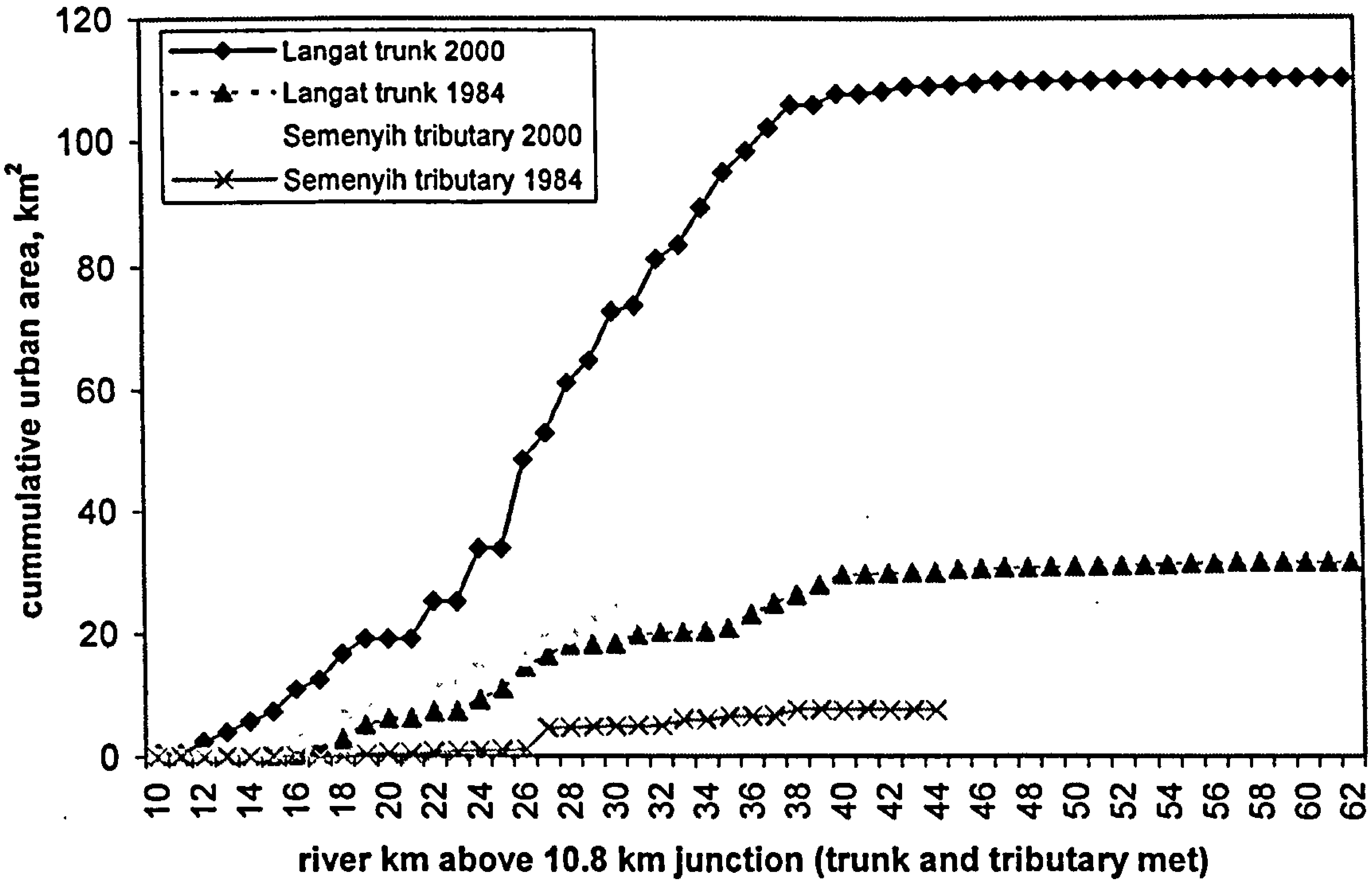


Figure 5.16: Langat – 1984 and 2000: comparison of cumulative urban area (km²) above junction between trunk and tributary

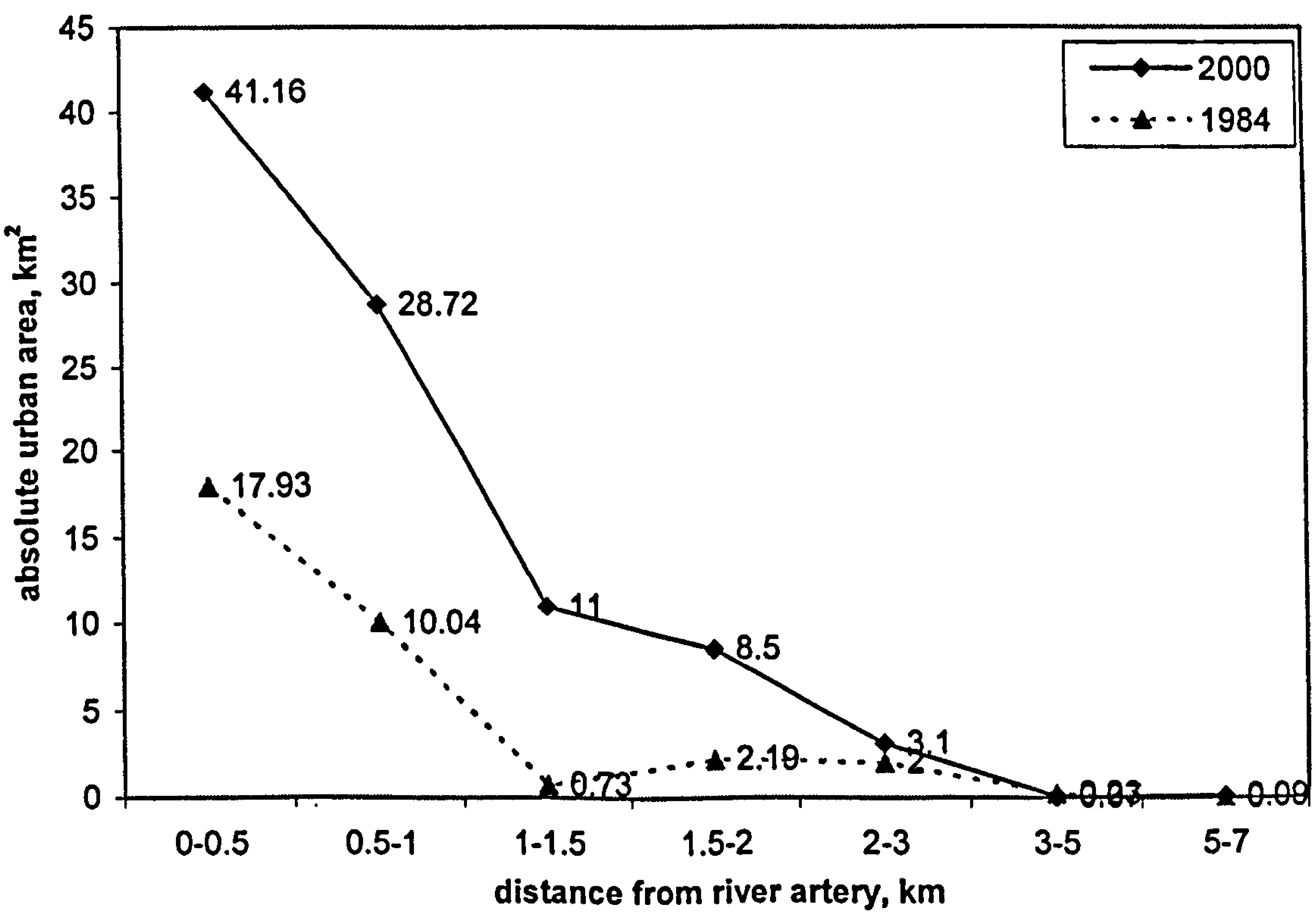


Figure 5.17: Linggi – 1984 and 2000 urban area from river artery

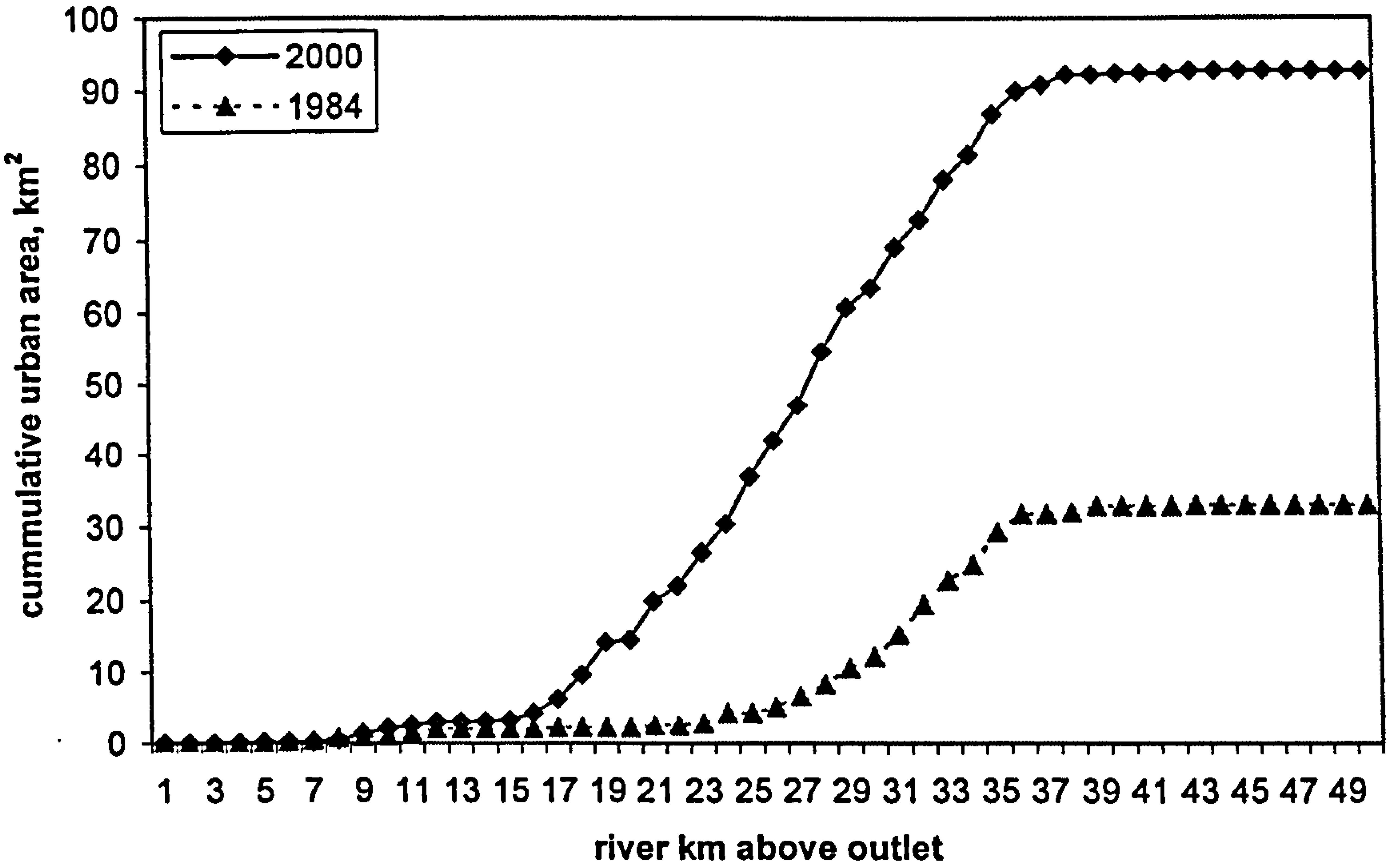


Figure 5.18: Linggi – 1984 and 2000 cumulative urban area (km^2) with distance upstream of outlet

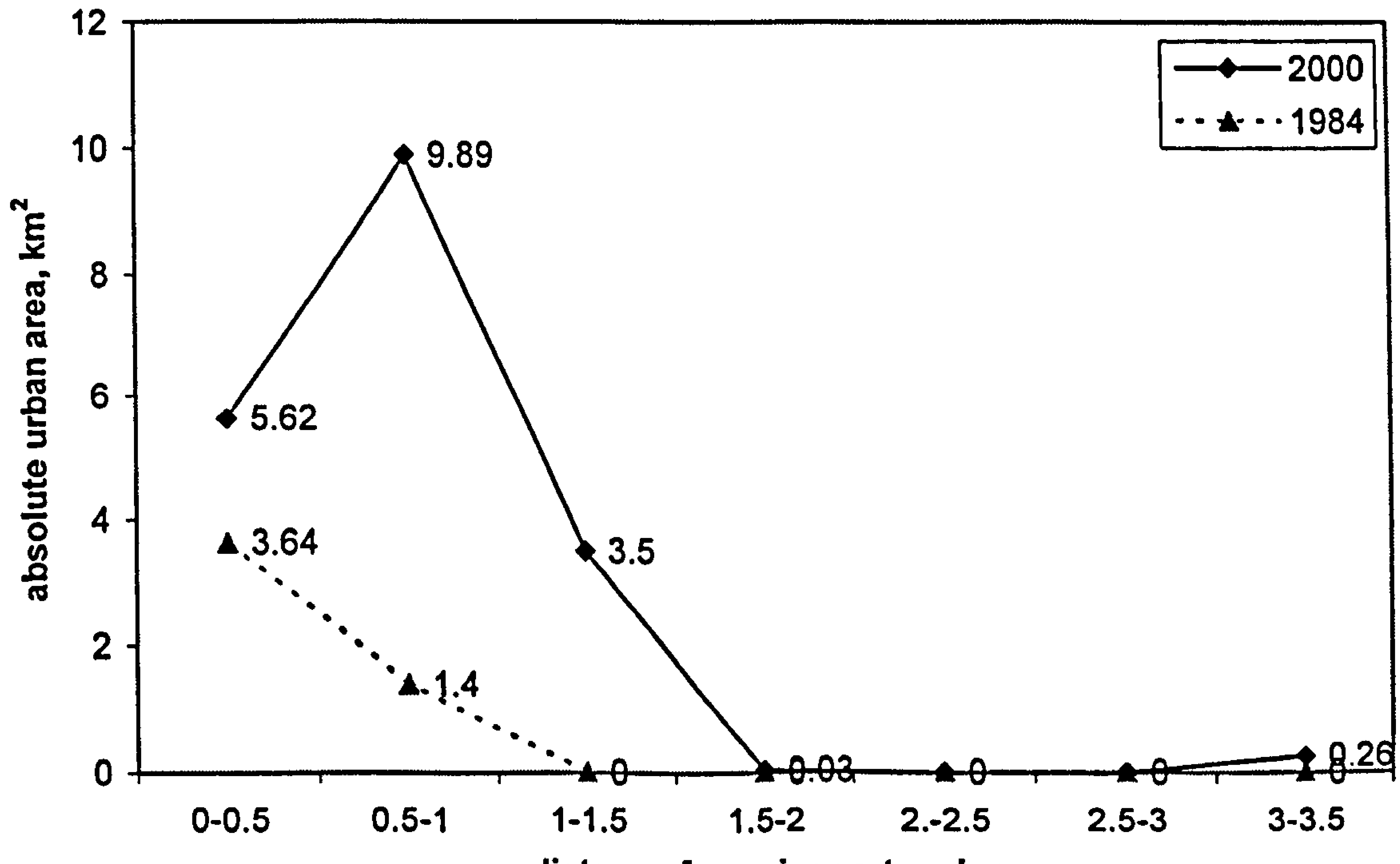


Figure 5.19: Bernam – 1984 and 2000 urban area from river artery

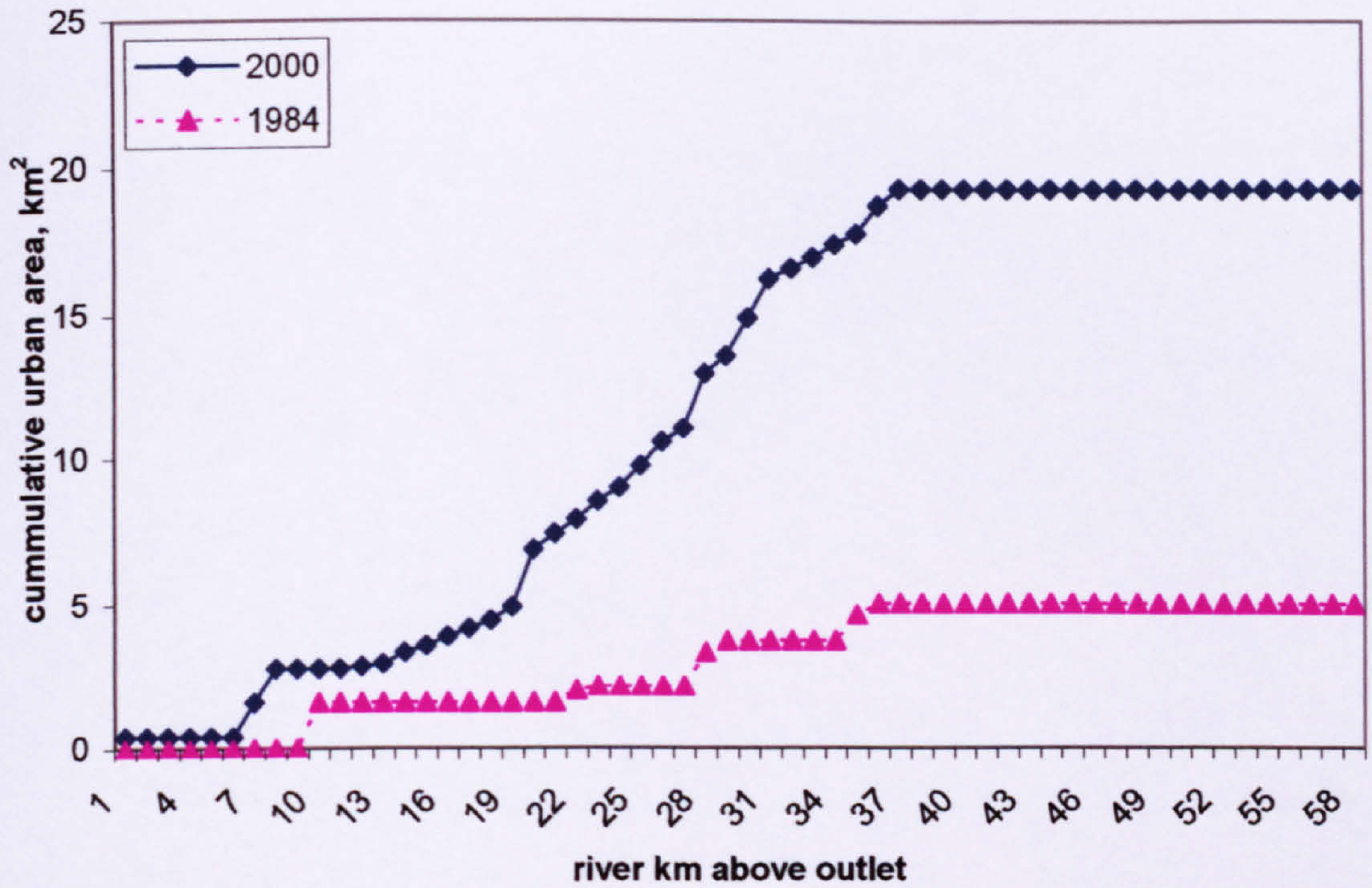


Figure 5.20: Bernam – 1984 and 2000 cumulative urban area (km²) with distance upstream of outlet

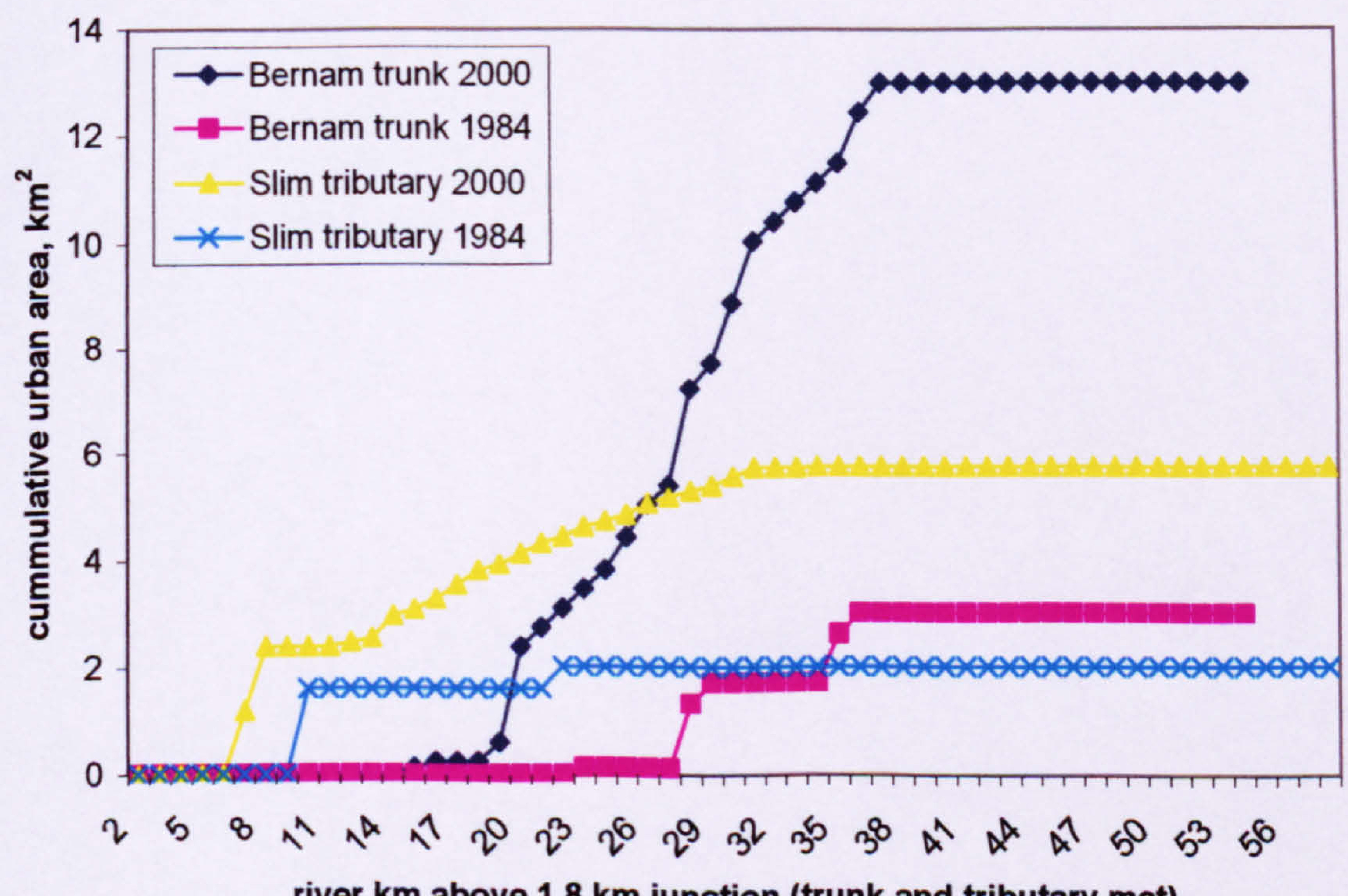


Figure 5.21: Bernam – 1984 and 2000: comparison of cumulative urban area (km²) above junction between trunk and tributary

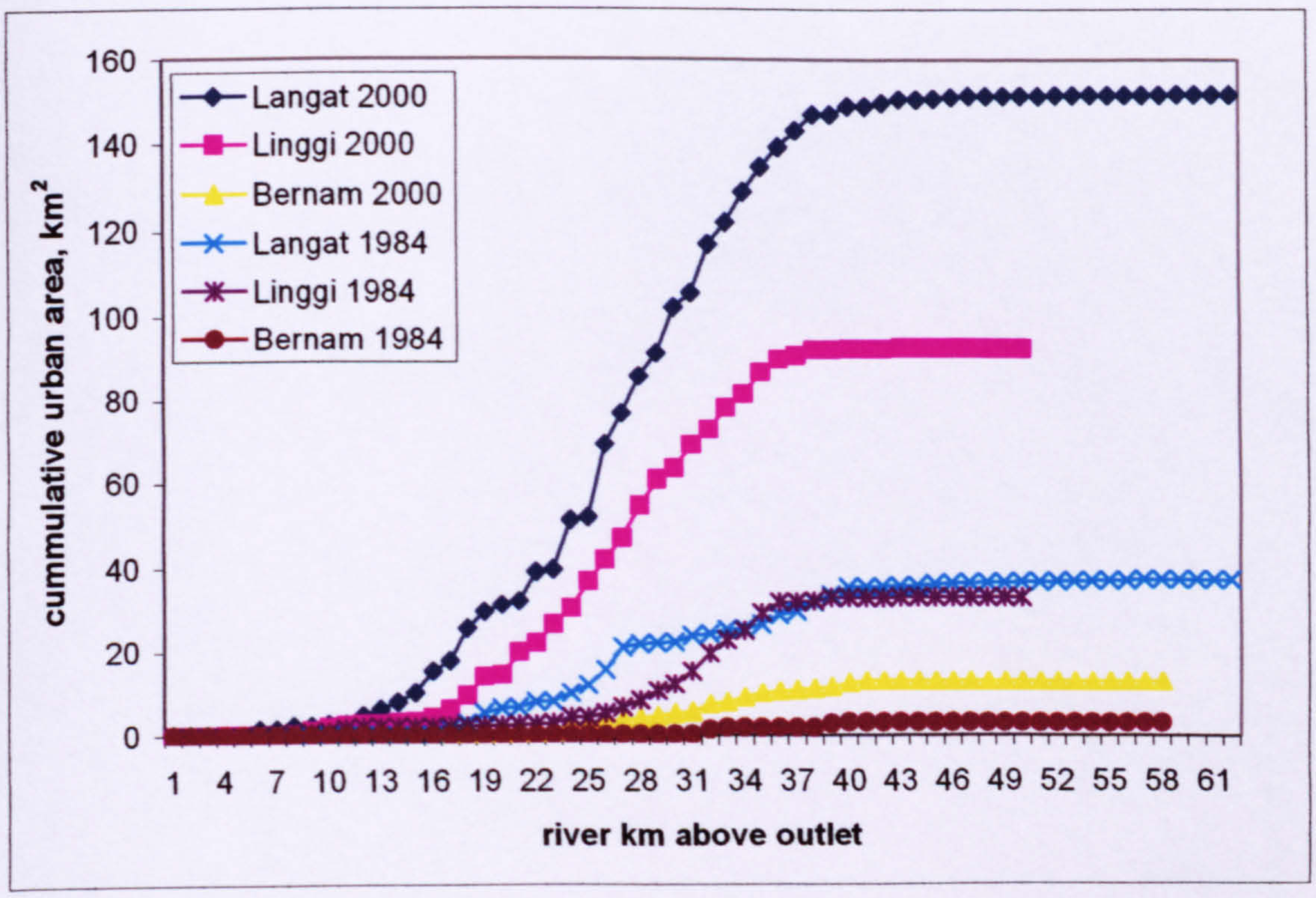


Figure 5.22: All catchments – 1984 and 2000: cumulative urban area (km^2) with distance upstream of river outlet

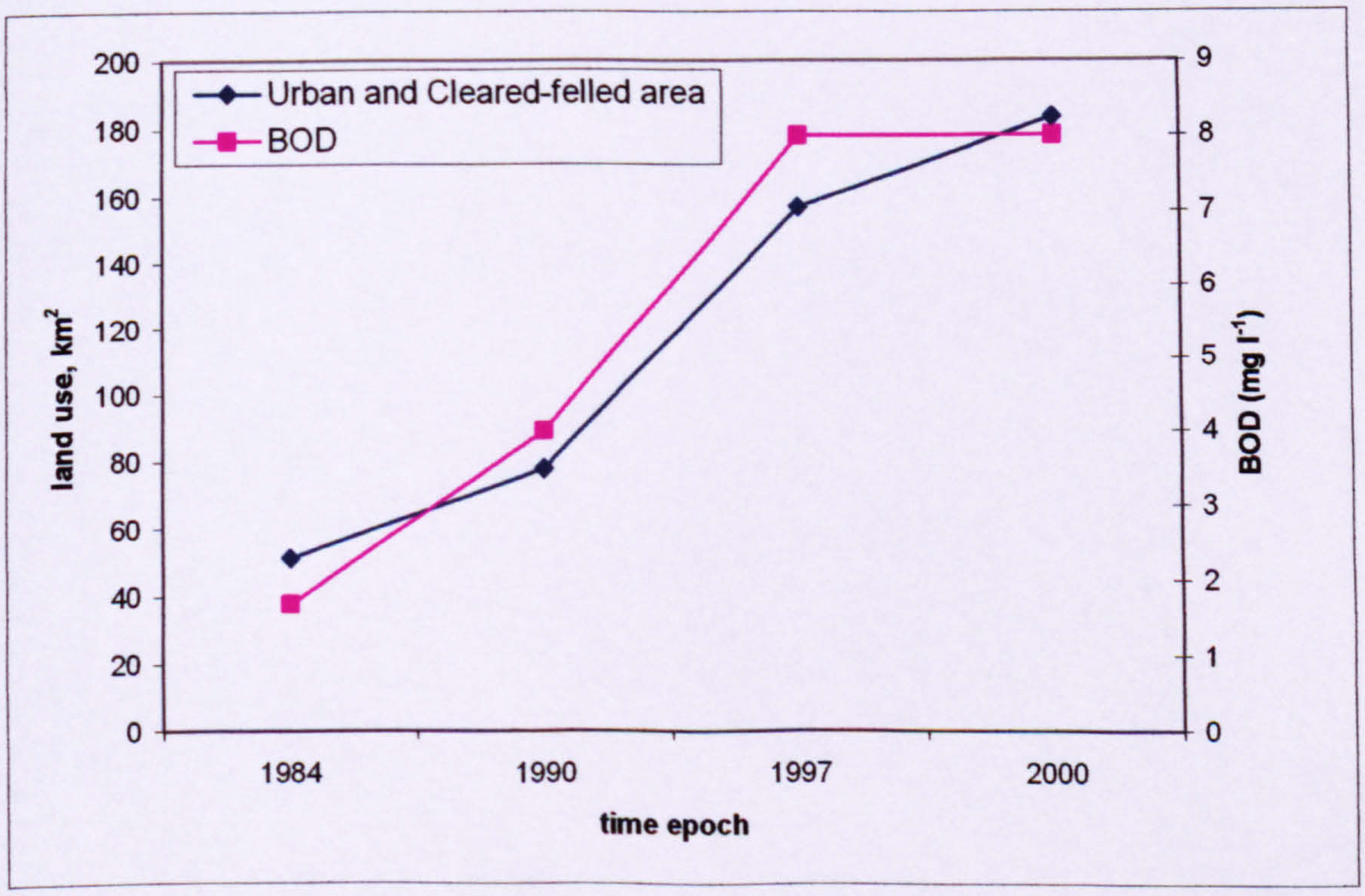


Figure 5.23: Langat –urban-cleared-felled areas and biological oxygen demand (BOD)

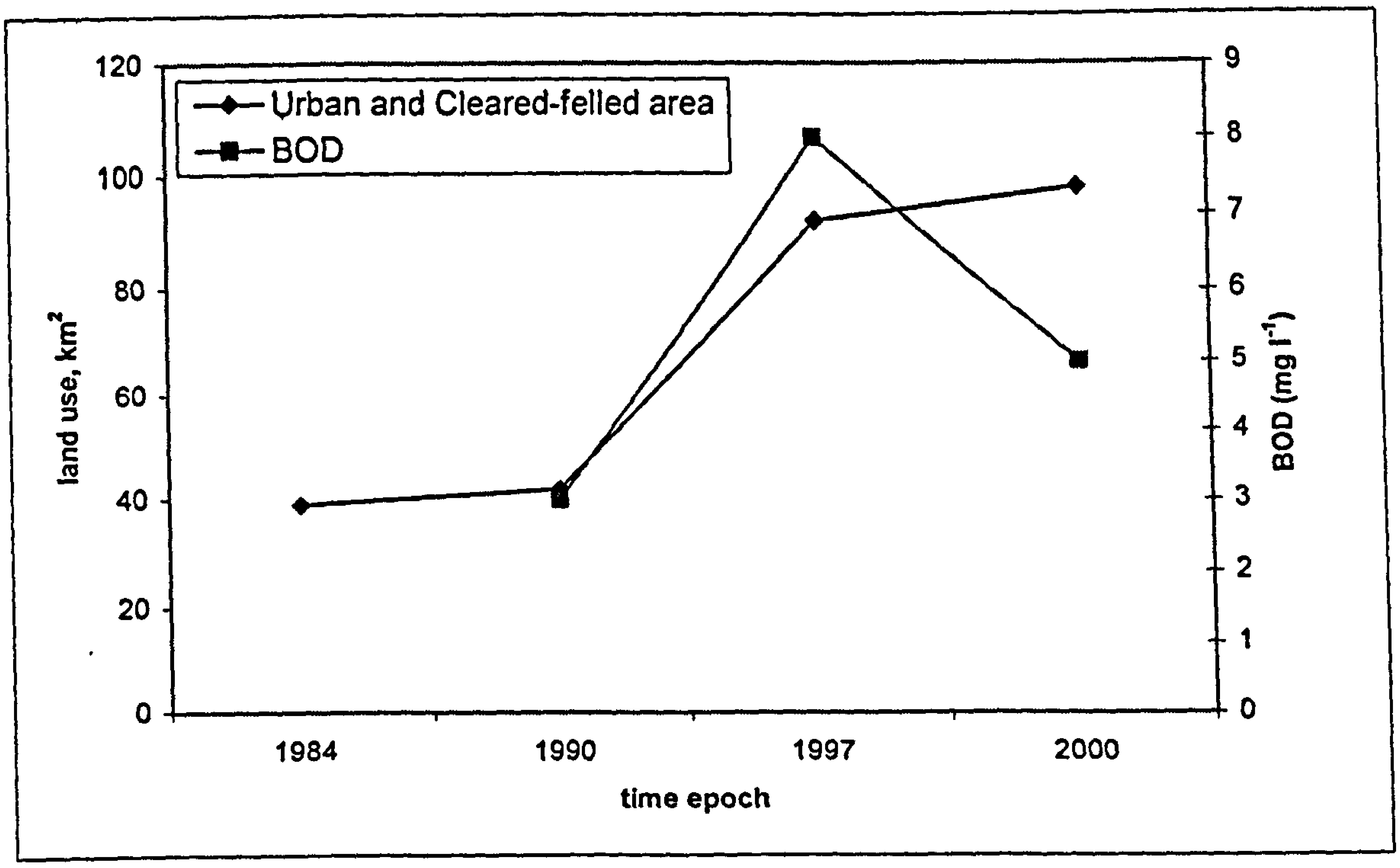


Figure 5.24: Linggi –urban-cleared-felled areas and biological oxygen demand (BOD)

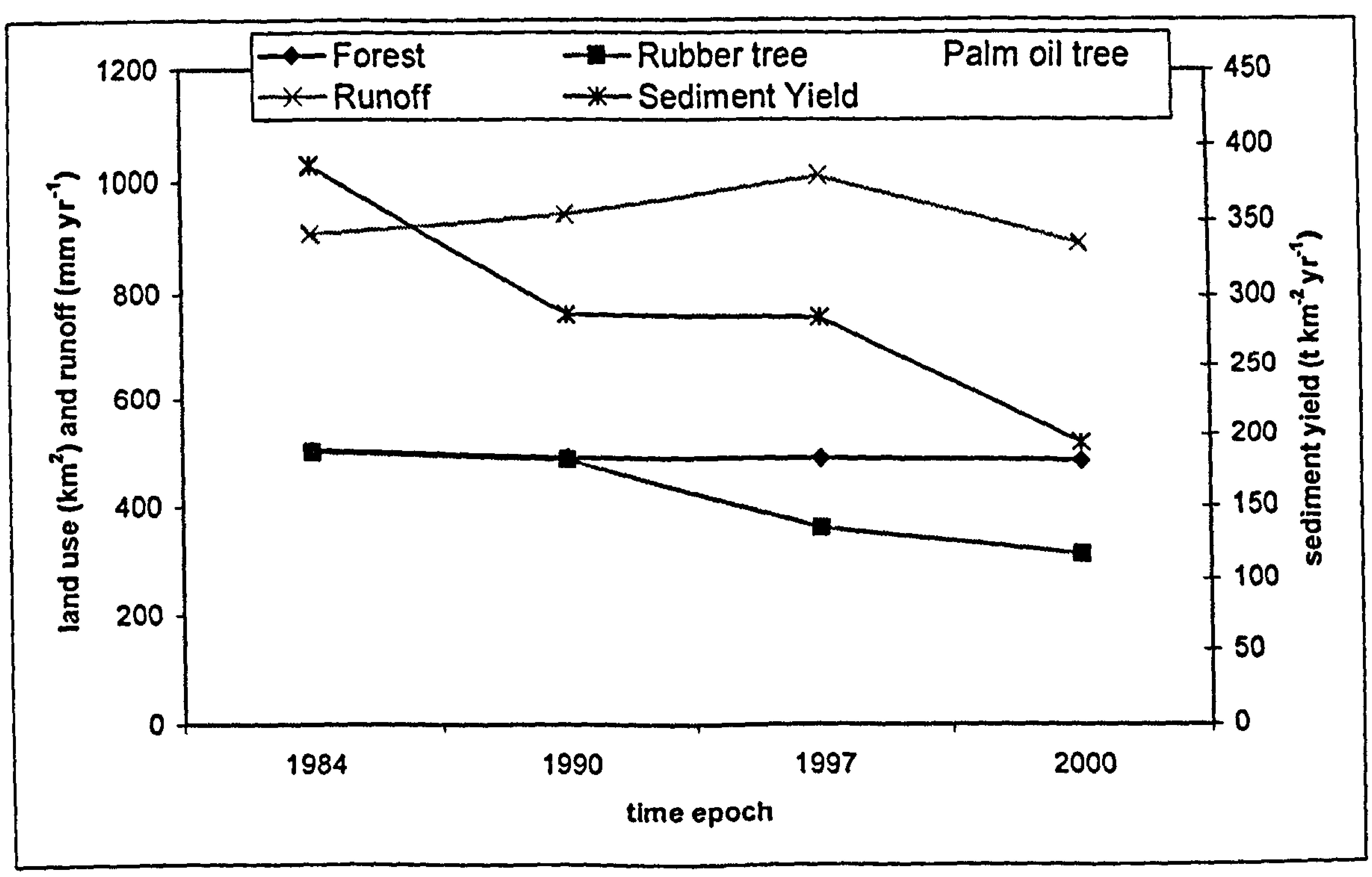


Figure 5.25: Langat – area of forest, rubber tree and palm oil tree and runoff and sediment yield

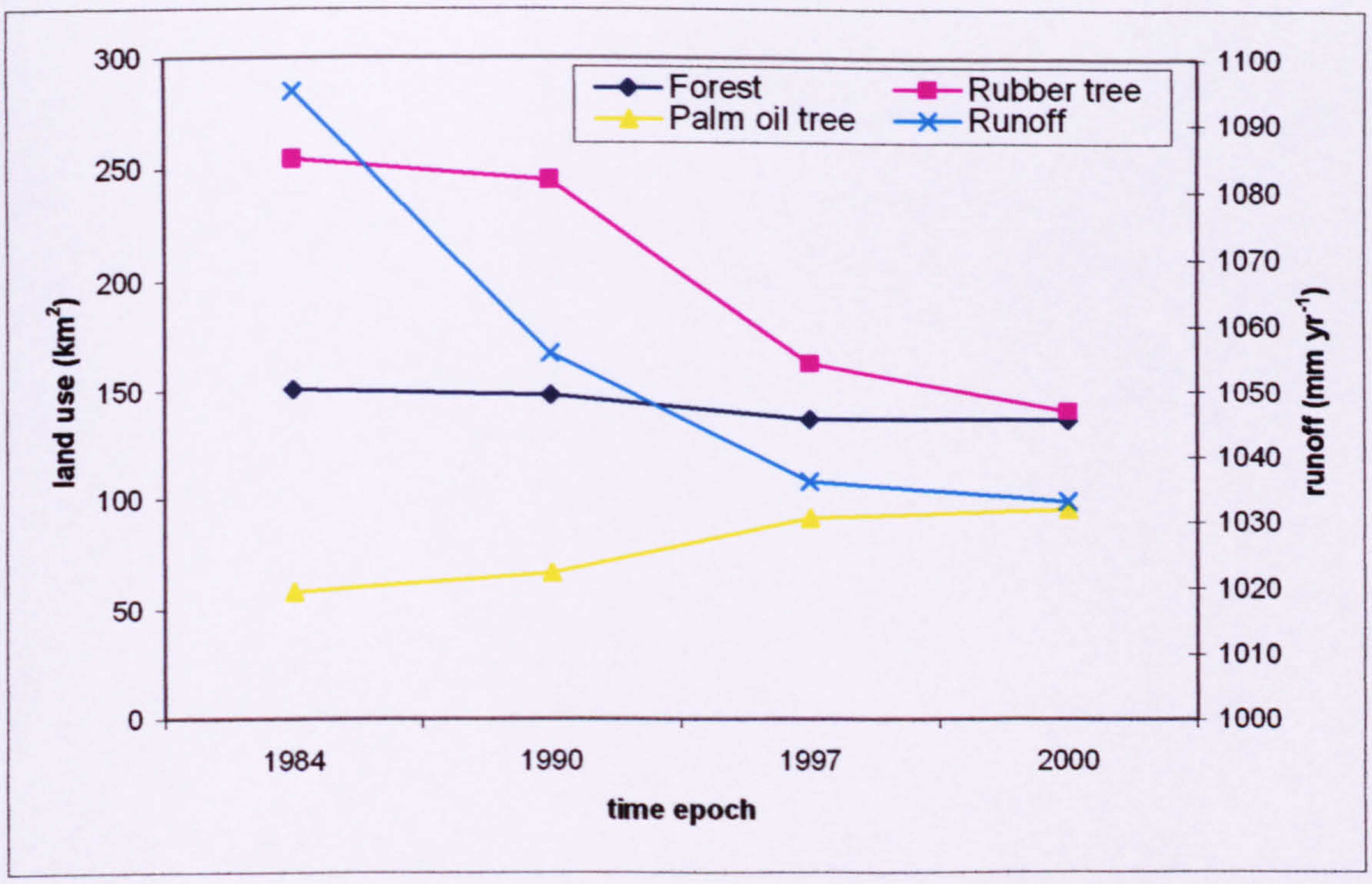


Figure 5.26: Linggi – area of forest, rubber tree and palm oil tree and runoff

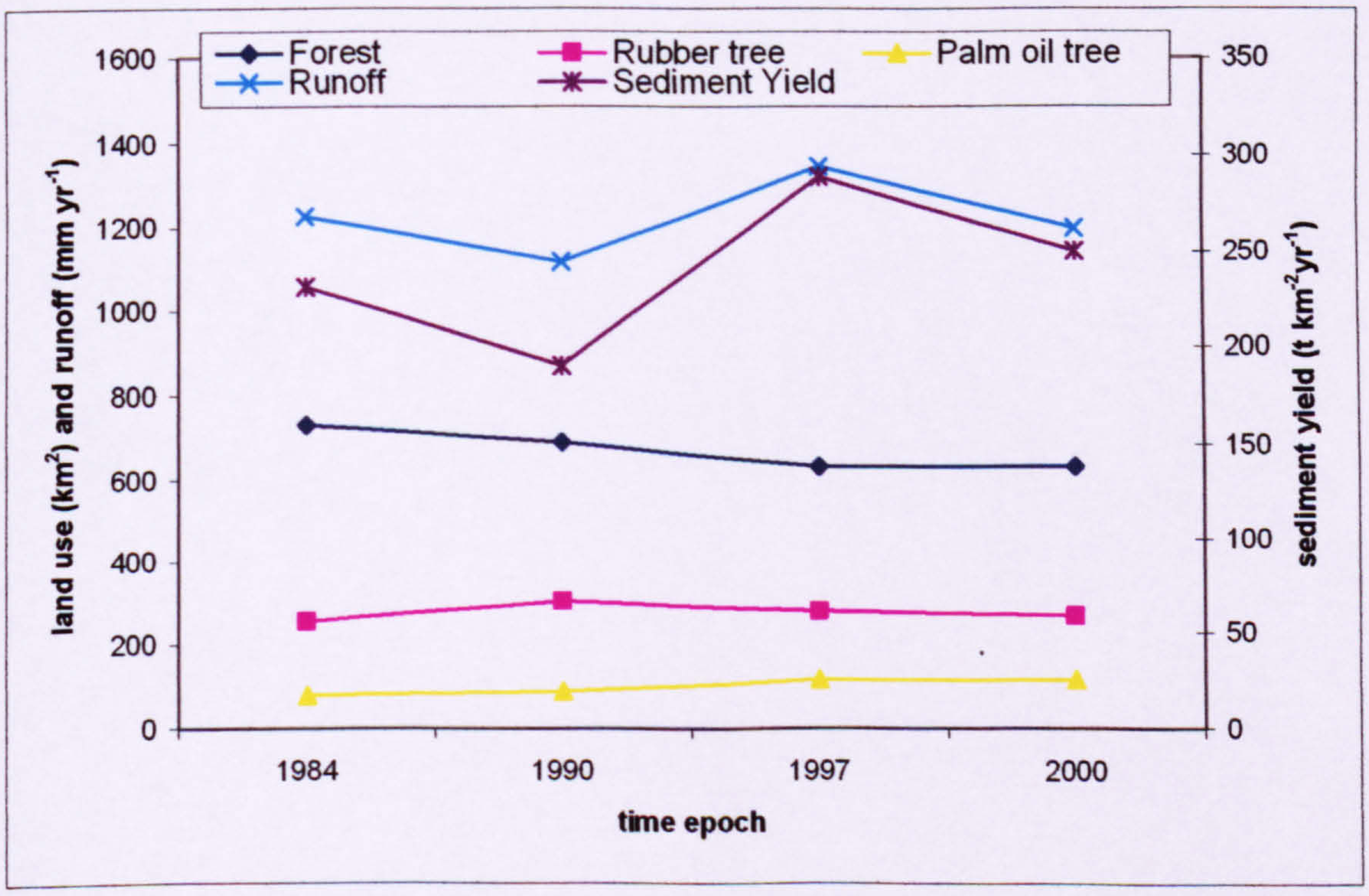


Figure 5.27: Bernam – area of forest, rubber tree and palm oil tree and runoff and sediment yield

CHAPTER SIX:
RAINFALL AND RUNOFF CHARACTERISTICS

6.1 Introduction

In this chapter, the general characteristics of monthly and annual point and area rainfall will be examined in order to understand the spatial and temporal trends and variations within and between study catchments. An analysis of the impact of El Nino and La Nina-related phenomena provides an insight into the cyclicity of rainfall excess and deficit relative to the long-term mean, a cyclicity that affects the availability of water resources being conveyed by the river system. The characteristics of runoff and the rainfall-runoff relation are evaluated in the context of land use change. This provides a set of indicators that assist recognition of the magnitude of the impact of land use change within study catchments through the period between 1960 and 2002.

The hydrological response of humid tropical catchments depends mainly on the character of the rainfall. The amount and intensity of rainfall plays a significant role in influencing runoff mechanisms, sediment yield and the quality of the water, particularly within disturbed catchments. Its variability contributes a significant source of uncertainty for hydrological studies, especially those related to water resources management (Niemczynowic, 1999; Ogden and Watson, 1999). For example, flash floods, especially within urbanized tropical catchments, have been related to intense, short-duration rainfall originating from the cores of intense convective thunderstorm (Smith *et al.*, 2001).

6.2 Rainfall depth – spatial and temporal characteristics

Rainfall in the humid tropics varies from place to place in the short-term (days) and this gives much variation at the local scale, depending on the movement and size of storm cells. Convective precipitation is an important component of the tropical weather system and it contributes to the spatial and seasonal variability of rainfall (Calder *et al.*, 1986; Desa and Niemczynowicz, 1996; Jetten, 1996). The dynamic properties of convective precipitation affect runoff response, while the spatial variability of rainfall is important in determining the volume and timing of rain transformed into runoff (Obled *et al.*, 1994).

In the study of hydrological responses of urbanized catchments, it is important to have detailed rainfall data covering both the long- and short-term. In this study, rainfall data have been analyzed in terms of temporal and spatial characteristics after deriving basic statistical properties. Discussion then focuses on the depth, intensity, return period, spottiness and temporal variation of areal rainfall for all three catchments.

6.2.1 Monthly rainfall

The monthly rainfall (short-term) inevitably tends to show more variability than annual rainfall. **Tables 6.1-6.3** show the statistical properties of monthly rainfall. The coefficient of variation (C_v) for all catchments lies between 0.3 and 0.4, except for January and February where the range is 0.4-0.7. The coefficient of variation for January and February for all catchments seems to be higher as a function of low rainfall but high spottiness. The range of 0.3-0.4 is similar to other areas reported in Malaysia. For example, the Kuala Lumpur area lies at 0.28-0.32 (Desa and Niemczynowiccz, 1996) and the Penang catchments lie between 0.4 and 0.8 (Ruslan, 1995). This variation of C_v values indicates the existence of strong variability in the rainfall of the study area (Dewar and Walis, 1999). This variability is corroborated by statistically significant differences (<0.001) for Langat-Bernam and Linggi-Bernam and (<0.05) for the Langat-Linggi relation. This effect is particularly crucial for interpreting the rainfall-runoff relation within this study, since the monthly record is a major data source.

Table 6.1: Langat– Average monthly areal rainfall characteristics (1950-2002)

Month	Season	Mean (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Error (mm)	Standard Deviation (mm)	Coeff. Var.	N
Jan	Dry 1	132	40	377	337	11	79	0.60	53
Feb	Dry 1	140	14	292	278	9	68	0.49	53
Mar	Wet 2	227	85	362	277	10	69	0.31	53
Apr	Wet 2	259	47	445	398	10	75	0.29	53
May	Wet 2	205	78	405	327	11	77	0.38	53
Jun	Dry 2	136	15	276	261	8	55	0.41	53
Jul	Dry 3	148	52	343	291	8	58	0.39	53
Aug	Dry 2	164	52	348	296	10	71	0.43	53
Sep	Wet 1	201	81	358	277	8	60	0.30	53
Oct	Wet 1	262	95	445	350	12	87	0.33	53
Nov	Wet 1	288	144	479	334	11	79	0.27	53
Dec	Wet 1	203	75	381	306	11	79	0.39	53

Table 6.2: Linggi - Average monthly areal rainfall characteristics (1951-2002)

Month	Season	Mean (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Error (mm)	Standard Deviation (mm)	Coeff. Var.	N
Jan	Dry 1	109	13	371	359	10	74	0.68	52
Feb	Dry 1	124	7	262	256	10	69	0.56	52
Mar	Wet 2	196	56	360	303	10	71	0.36	52
Apr	Wet 2	243	51	423	372	13	90	0.37	52
May	Wet 2	201	71	331	260	10	69	0.34	52
Jun	Dry 2	131	5	250	245	6	46	0.35	52
Jul	Dry 3	155	48	318	269	9	62	0.40	52
Aug	Dry 2	155	43	315	271	9	66	0.42	52
Sep	Wet 1	195	75	357	282	8	61	0.31	52
Oct	Wet 1	246	88	382	294	11	77	0.31	52
Nov	Wet 1	281	112	483	371	12	89	0.32	52
Dec	Wet 1	188	51	373	321	11	77	0.41	52

Table 6.3: Bernam – Average monthly areal rainfall characteristics (1948-2002)

Month	Season	Mean (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Error (mm)	Standard Deviation (mm)	Coeff. Var.	N
Jan	Dry 1	141	44	329	285	10	73	0.51	55
Feb	Dry 1	176	67	366	299	10	72	0.41	55
Mar	Wet 2	235	64	423	360	11	83	0.35	55
Apr	Wet 2	309	99	542	443	13	100	0.32	55
May	Wet 2	265	88	480	391	13	97	0.37	55
Jun	Dry 2	164	31	311	280	9	68	0.42	55
Jul	Dry 3	162	35	373	338	9	70	0.43	55
Aug	Dry 2	175	54	368	314	10	77	0.44	55
Sep	Wet 1	260	99	455	356	11	83	0.32	55
Oct	Wet 1	315	116	569	453	15	110	0.35	55
Nov	Wet 1	330	145	572	427	13	96	0.29	55
Dec	Wet 1	234	52	440	388	12	87	0.37	55

Figure 6.1 shows the temporal pattern of the long-term average monthly rainfall. For all catchments, November is the wettest month with 12.2 %, 12.6 % and 11.9 % of the average annual total for Langat, Linggi and Bernam, respectively (**Table 6.4**). April is the second wettest month where the percentage of monthly rainfall recorded by Langat, Linggi and Bernam are 11, 10.9 and 11.2%, of the average annual total, respectively. Meanwhile, January is the driest month with 5.6%, 4.9% and 5.1% of the average annual total for Langat, Linggi and Bernam, respectively. By ranking the mean monthly values, it is shown that the highest three values occur in the months of November, April and October. These months belong to inter-monsoon periods (April and October) and the beginning of the Northeast Monsoon season, which brings a lot of rain to Peninsular

Malaysia. This contrast with the early definition by the Malaysian Meteorological Services, which stated that the wet months are associated with monsoon.

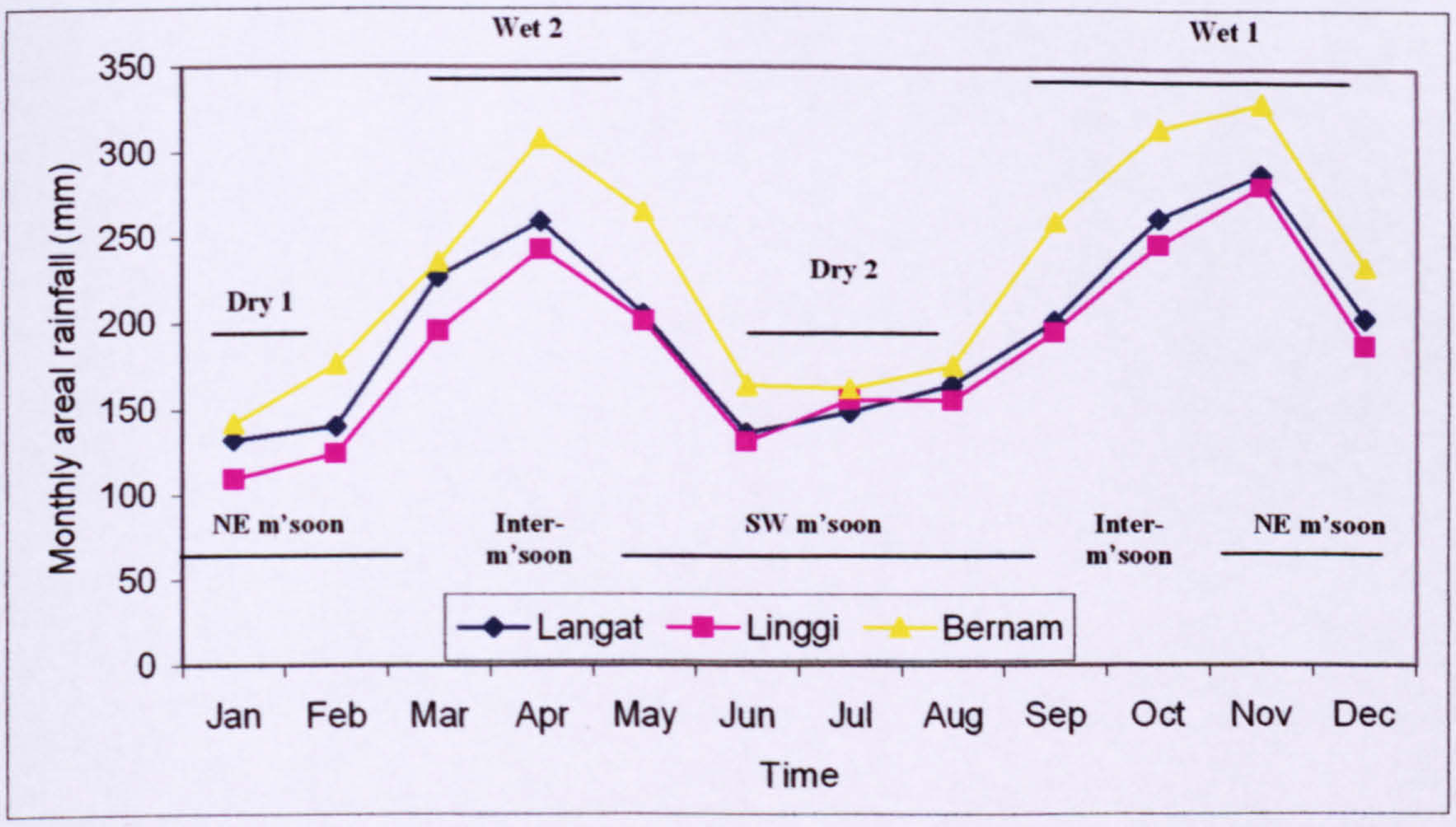


Figure 6.1: All catchments: Average monthly areal rainfall (1951-2002)

Table 6.4: Statistical properties of long-term monthly areal rainfall for all catchments 1951-2002

	Langat			Linggi			Bernam		
Month	Mean (mm)	% total rainfall	Rank	Mean (mm)	% total rainfall	Rank	Mean (mm)	% total rainfall	Rank
Jan	132	5.6	12	109	4.9	12	141	5.1	12
Feb	140	5.9	10	124	5.6	11	176	6.4	8
Mar	227	9.6	4	196	8.8	5	235	8.5	6
Apr	259	11.0	3	243	10.9	3	309	11.2	3
May	205	8.7	5	201	9.0	4	265	9.6	4
Jun	136	5.8	11	131	5.9	10	164	5.9	10
Jul	148	6.3	9	155	7.0	8	162	5.9	11
Aug	164	6.9	8	155	7.0	9	175	6.3	9
Sep	201	8.5	7	195	8.8	6	260	9.4	5
Oct	262	11.1	2	246	11.1	2	315	11.4	2
Nov	288	12.2	1	281	12.6	1	330	11.9	1
Dec	203	8.6	6	188	8.4	7	234	8.4	7
Total *	2366			2225			2766		
Mean (mm)	197			185			230		
Std dev.	54			53			66		
Coeff var	0.27			0.29			0.29		

*Slightly different compare to the mean areal rainfall due to difference in time span.

However, this circumstance would particularly be relevant for the east coast of the Malaysian Peninsula, which receives direct influence from the Northeast Monsoon. However, for the study area, the mountain range of Titiwangsa (backbone) plays a role in rainfall shading, while the mountain ranges on the island of Sumatra prevent the Southwest Monsoon from bringing significant rainfall. Therefore, in this study, the discussion about the effect of the rainfall on runoff characteristics will be based on the wet and dry month's definition. Even though the data shows that the Langat and Linggi are less wet than Bernam, this does not affect their function as an analogue, as the percentage long-term annual rainfall values are consistent between each dry and wet period. Here, it shows how strong the variation of rainfall spottiness is, even for catchments located in the same region. Despite this, we can expect a certain consistency of rainfall catch within each catchment, where the percentage long-term lies at 40%, 11%, 29% and 19% for Wet Period 1, Dry Period 1, Wet Period 2 and Dry Period 2, respectively.

Based on monsoon seasonal records, the Northeast Monsoon and Southwest Monsoon bring about 41% and 37%, respectively, of the annual rainfall for all catchments, whereas inter-monsoon seasons each contribute about 11% of the total rainfall (Table 6.5). All of the study areas received less rain in January and February due to shading from the backbone mountain range. Meanwhile, in July, August and September, the areas were in the shadow of the Sumatran Island mountain range.

Table 6.5: Statistical properties of long-term areal rainfall for each season in each catchment - May 1951 - April 2002

	Langat		Linggi		Bernam	
Season	Mean (mm)	% total rainfall	Mean (mm)	% total rainfall	Mean (mm)	% total rainfall
Southwest Monsoon (May-Sept)	857	36	839	38	1028	37
Inter-monsoon October	264	11	246	11	314	11
Northeast Monsoon (Nov-Mar)	982	42	890	40	1111	40
Inter-monsoon April	260	11	241	11	312	11
Total (51 cycles)	2364		2216		2765	
Mean	591		554		691	
Standard deviation	383		359		438	
Coefficient of variation	0.65		0.65		0.63	

There are two periods each of wet months and dry months (**Table 6.6**). The first group of wet months consists of the months of September, October, November and December, which receive about 40% of the total rainfall, whereas the second group receive about 29% and consists of the months of March, April and May. The first group of dry months consists of the months of January and February when only about 11% of the total annual rainfall is received. The second group consists of the months of June, July and August, which only receive about 18% of the total annual rainfall.

Table 6.6: The long-term rainfall average for months that contribute to each wet and dry period, separate from full-seasons influences (1951-2002)

		Langat		Linggi		Bernam	
Period	**Month**	**Mean (mm)**	**% total rainfall**	**Mean (mm)**	**% total rainfall**	**Mean (mm)**	**% total rainfall**
Wet Period 1	Sept	201		195		260	
	Oct	262		246		315	
	Nov	288		281		330	
	Dec	203		188		234	
	Total	955	40	910	41	1139	41
Dry Period 1	Jan	132		109		141	
	Feb	140		124		176	
	Total	272	12	233	10	318	11
Wet Period 2	Mar	227		196		235	
	Apr	259		243		309	
	May	205		201		265	
	Total	691	29	640	29	809	29
Dry Period 2	Jun	136		131		164	
	Jul	148		155		162	
	Aug	164		155		175	
	Total	449	19	442	20	501	18
	Annual total	2366		2225		2766	

6.2.2 Annual rainfall

In this study, rainfall over a catchment area has been estimated from point rainfall using the Thiessen polygon technique. All stations are located in flat-lowland areas where elevation is less than 50 m above sea level. **Tables 6.7, 6.8** and **6.9** show some properties of the long-term annual rainfall depth for all rain gauges available for areal estimation in the Langat, Linggi and Bernam catchments. The highest average annual areal rainfall was recorded in the Bernam with 2745 mm, followed by Langat and Linggi with 2401 mm and 2251 mm, respectively. The highest ranking of the Bernam arises because of its geographical location at the foot of Malaysian Main range and the orographic effect on precipitation. It has been classified as the second wettest place in the Malaysian Peninsula by the Meteorological Office. The rainfall for Langat and Linggi were lower than Bernam because they were situated in relatively low inland areas. However, despite its continuity with Linggi, Langat had slightly different rainfall due to spatial variability. The temporal variation between catchments (areal) and within catchments (point) is very small with a coefficient of variation (C_v) value of less than 0.2, equivalent to that recorded by other Malaysian studies (Desa and Niemczynowicz, 1996). The areal rainfall has a lower standard deviation than point rainfall as well as other statistical properties, owing to the averaging technique. The high variability between the highest and lowest values belonging to each point have been reduced and made proportional using each weighted area to represent a fairly consistent areal rainfall for the catchments.

Table 6.7: Langat – Annual point and areal rainfall characteristics (1950-2002)

Rain gauge	Mean (mm)	Standard Error (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Deviation (mm)	Coeff. Var.	N
Ampang	2576	49	1884	3521	1637	360	0.14	53
West Country	2345	35	1820	2796	976	251	0.11	53
Rinching	2391	37	1901	2912	1010	271	0.11	53
Lenggeng	2276	45	1542	2957	1415	326	0.14	53
Setul	2148	51	1353	2924	1571	369	0.17	53
Labu	2247	46	1288	2908	1620	332	0.15	53
Areal	**2401**	**34**	**1905**	**2869**	**965**	**246**	**0.10**	**53**

Table 6.8: Linggi – Annual point and areal rainfall characteristics (1951-2002)

Rain gauge	Mean (mm)	Standard Error (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Deviation (mm)	Coeff. Var.	N
Setul	2151	51	1353	2924	1571	371	0.17	52
Pantai	2188	42	1462	2689	1227	303	0.14	52
Seremban	2295	44	1539	2849	1310	319	0.14	52
Per. Tinggi	2304	46	1394	2773	1379	329	0.14	52
Sua Betong	2239	46	1533	2858	1325	334	0.15	52
Areal	**2251**	**40**	**1496**	**2697**	**1201**	**286**	**0.13**	**52**

Table 6.9: Bernam – Annual point and areal rainfall characteristics (1948-2002)

Rain gauge	Mean (mm)	Standard Error (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Deviation (mm)	Coeff. Var.	N
Hospital	2777	49	2024	3404	1380	361	0.13	55
Gumut	2953	53	2186	3752	1566	393	0.13	55
Trolak	2908	63	1910	3900	1990	467	0.16	55
Bedford	2582	56	1706	3682	1976	412	0.16	55
Behrang	3056	55	2307	4088	1781	408	0.13	55
Areal	**2875**	**42**	**2213**	**3496**	**1283**	**315**	**0.11**	**55**
Areal *	**2745**	**35**	**2213**	**3247**	**1053**	**261**	**0.10**	**55**

* value after application of correction factor for dataset from 1948-1973.

Figures 6.2, 6.3 and **6.4,** however, show the long-term average pattern of the annual areal rainfall. In Bernam, it is clearly demonstrated that the period of 1948-1973 had a higher rainfall catch than the later period of 1974-2002, with 9.4% (282 mm). It was found to be statistically significant at the 0.001 level (paired *t*-test). This was probably owing to a change in rainfall recorder from a 127-mm orifice to a 203-mm orifice in 1973 made by DID throughout Malaysia. Meanwhile, the Langat and Linggi show consistent trends during 1950-2002 and there are no significance shifts between the period before and that after 1973. According to DID, the latter recorder has a greater performance in rainfall catch. As the later period for Langat and Linggi show consistant patterns, and no evidence can be attributed to the changes in land use cover, it is believed that the earlier period in Bernam has been subjected to an error in rainfall catch. The higher rainfall will cause a higher runoff-rainfall ratio at the beginning, which contrasts with the assumption that the undeveloped catchment should have a low runoff-rainfall coefficient. Therefore, it is necessary to apply a correction factor for that period based on the ratio of the mean(s) of the later (2736 mm) and early (3018 mm) periods. After appling that correction factor (0.9) on the early period of data, the trend show consistency and the significance test reveals no different between those two periods (**Figure 6.5**). The later discussion on rainfall-runoff relation for the Bernam catchment is based on this new rainfall data.

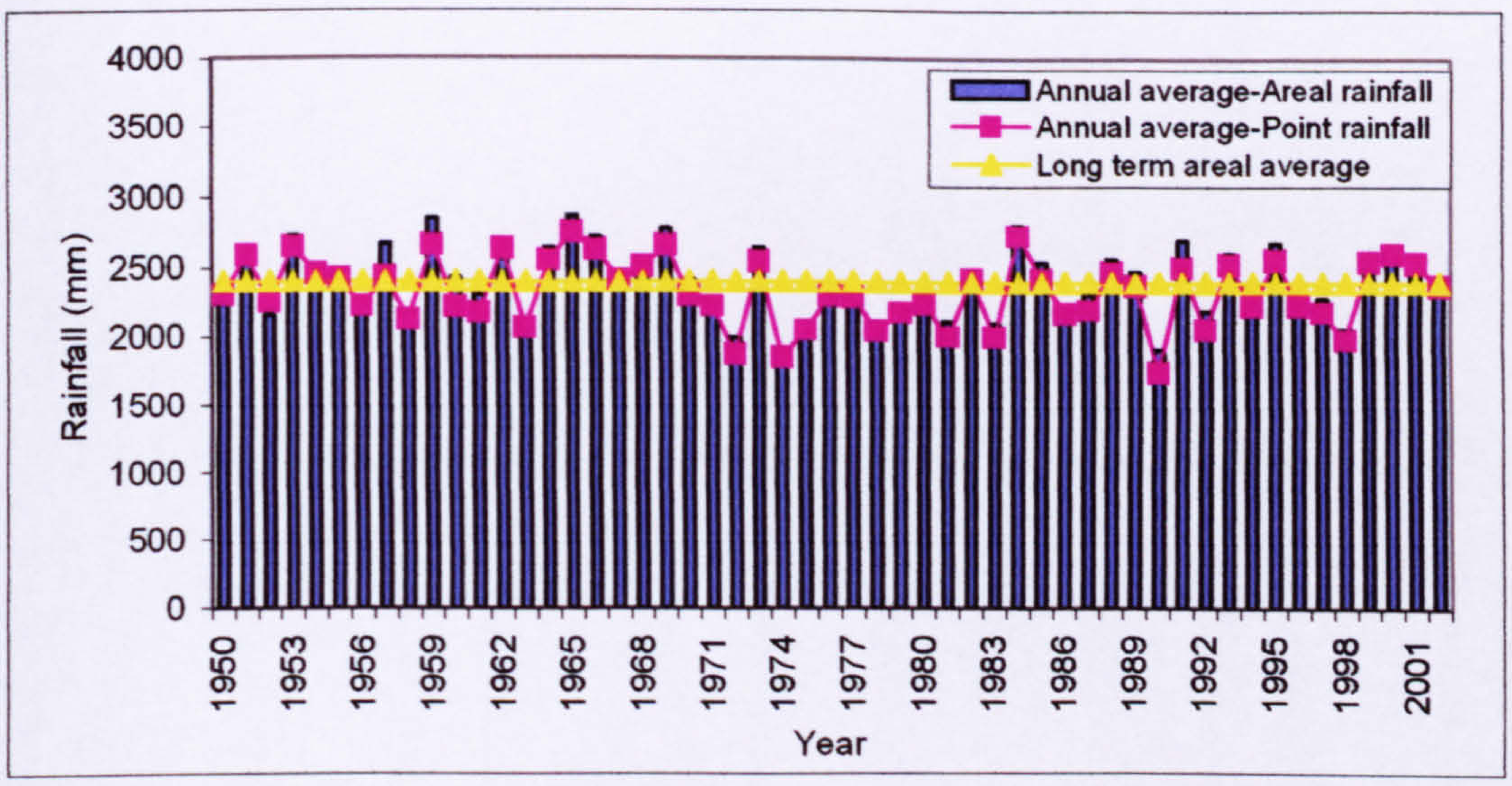


Figure 6.2: Langat – Annual rainfall pattern

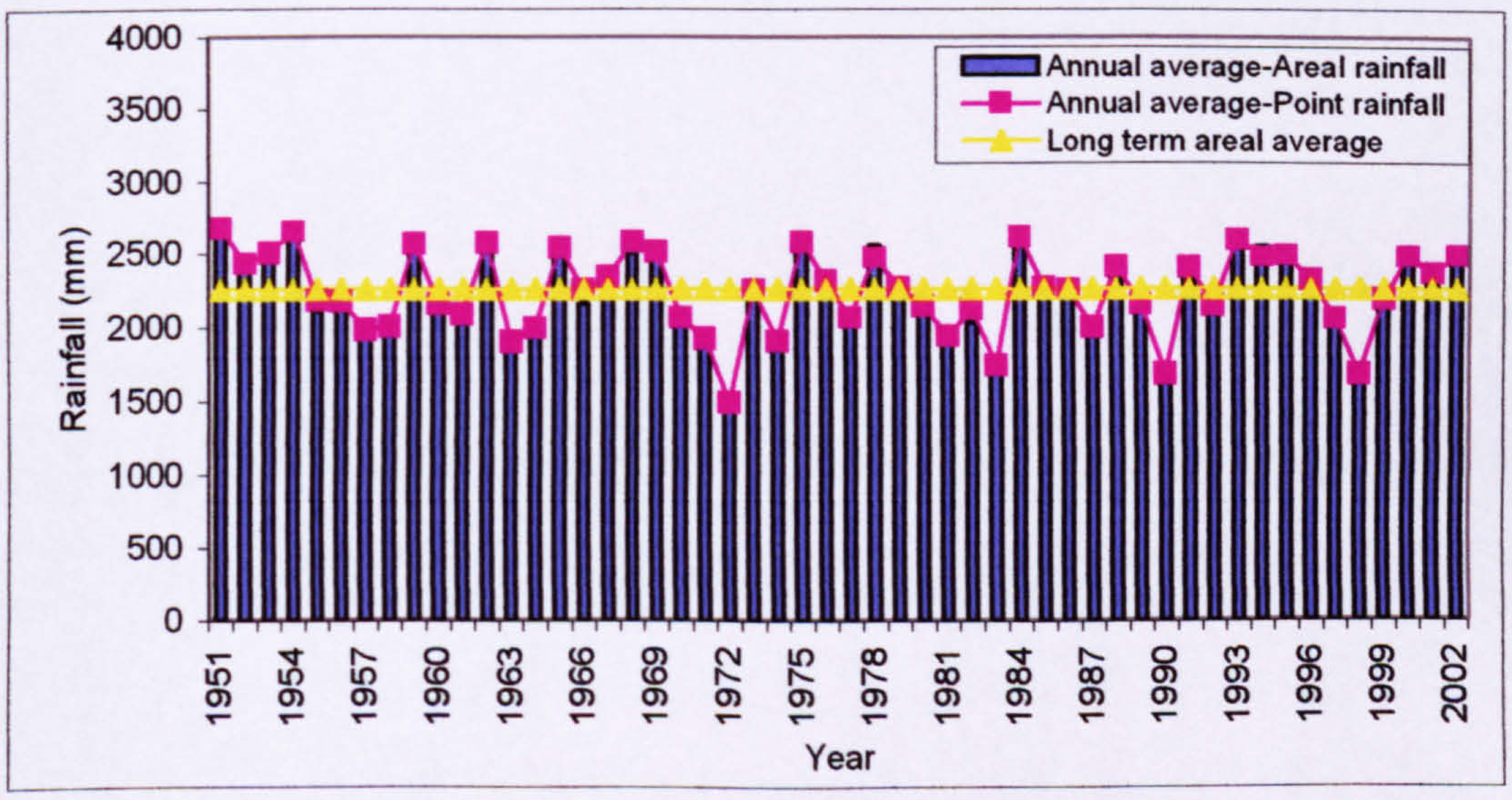


Figure 6.3: Linggi – Annual rainfall pattern

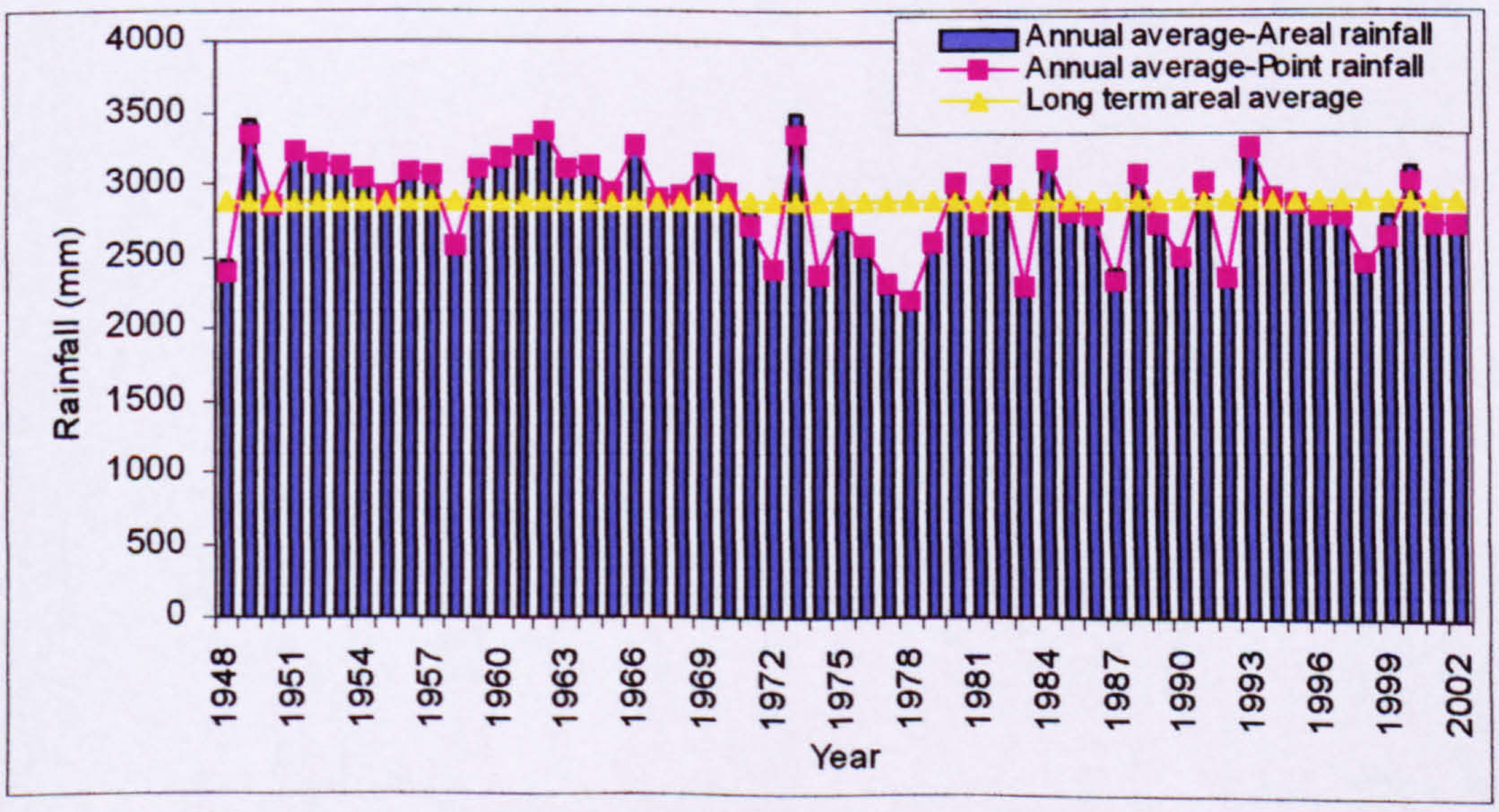


Figure 6.4: Bernam– Annual rainfall pattern

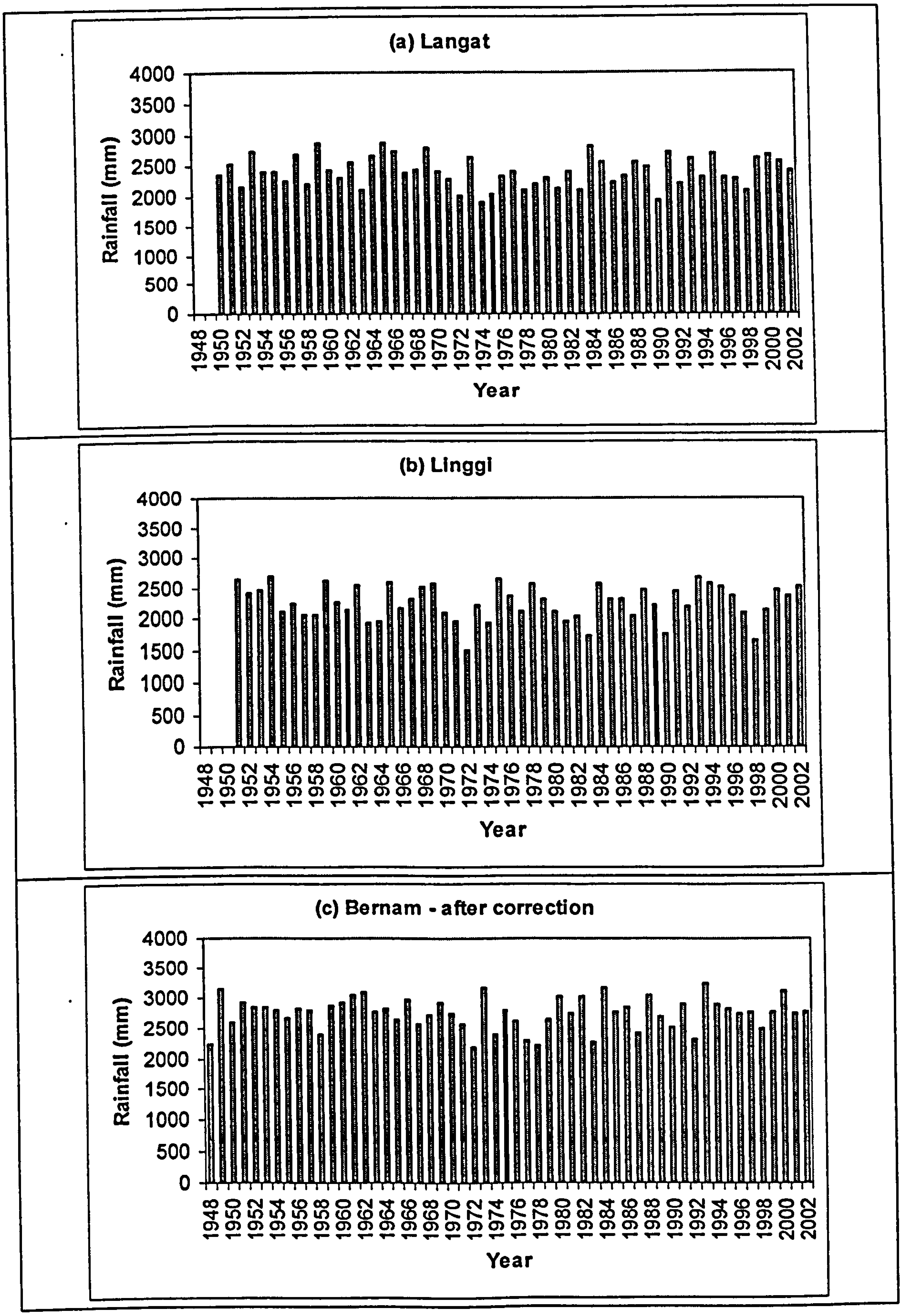


Figure 6.5: All three catchments – annual areal rainfall

The One-Way ANOVA reveals that the spatial variations of areal rainfall between catchments are significantly different at the 0.05 level, even for the neighbouring catchments Langat and Linggi. Bernam receives significantly higher rainfall than Langat and Linggi (**Figure 6.6**). The variations between some point rainfall records within catchments are also significant. In Langat, all gauges have a significantly different record from that recorded at Ampang, the distance between this site and other locations ranging between 24 and 52 km. Other significant differences include West Country and Setul (33 km, r^2 = 0.5) and Rinching and Setul (17 km, r^2 = 0.5). The correlation coefficient between Ampang and other gauges fell from 0.6 to 0.3 as distance increased. The amount of rainfall caught by Ampang is higher than other point gauges (**Figure 6.7**), which can be attributed to the more pronounced orographic effect since it close to the highland areas. In Bernam, point gauges between Hospital and Behrang are separated by 8 km (r^2 = 0.5); Gumut and Bedford are separated by 28 km (r^2 = 0.3); Trolak and Bedford are separated by 7 km (r^2 = 0.7) and Bedford and Behrang are separated by 13 km (r^2 = 0.2). The rainfall variation is greater in Bernam despite the closer distance between gauges. This is a function of the convective and orographic rainfall, but this is not the case for the Bedford station, since it receives less rainfall compared to the others (**Figure 6.8**). Surprisingly, all point gauges within the Linggi catchment have no significant differences among them, even though the distances between them range from 11-42 km. This would suggest that the Linggi rainfall has less variation, where, the correlation coefficient reveals a strong relation that ranges between 0.6 and 0.9 (**Figure 6.9**).

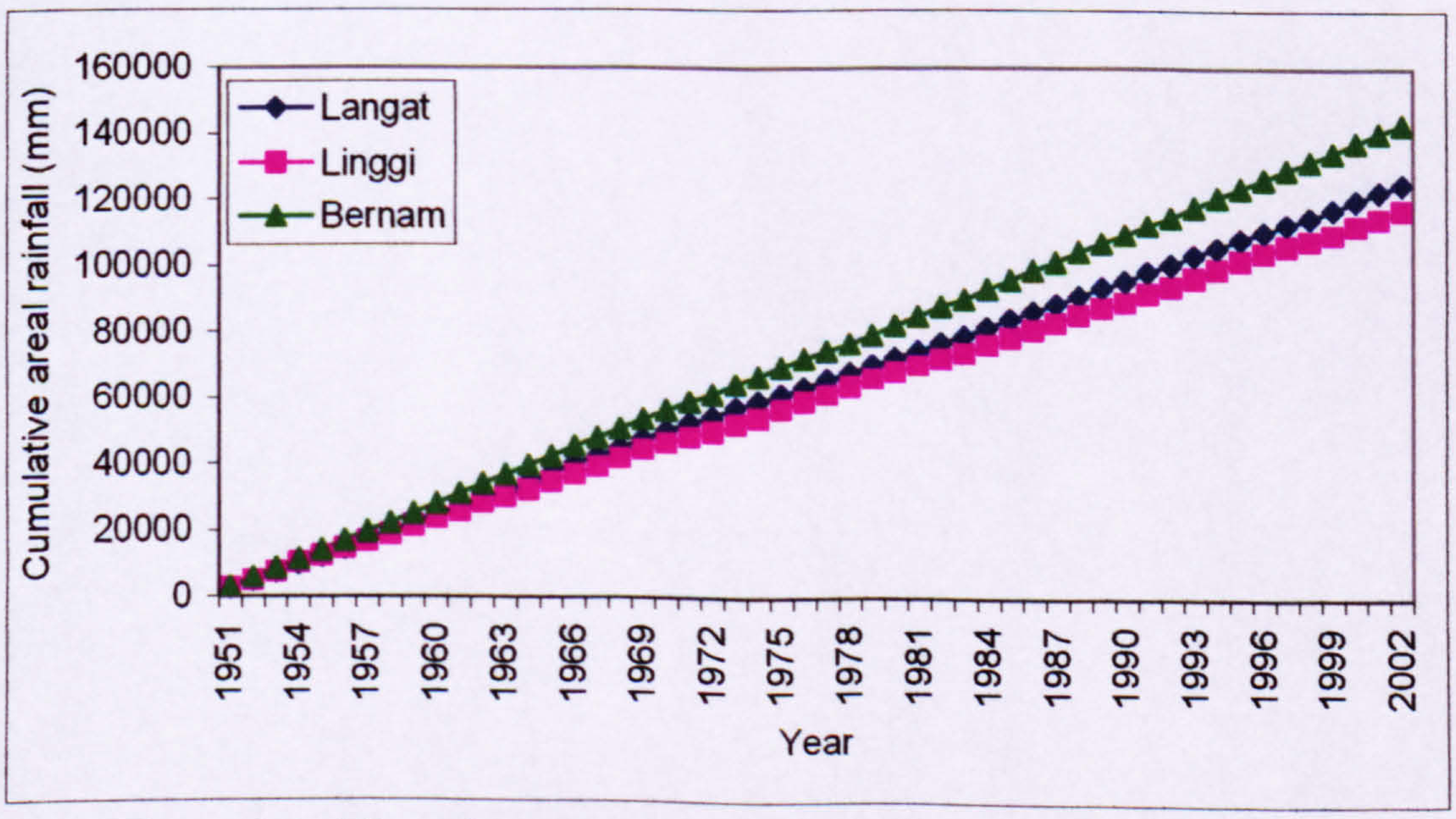


Figure 6.6: All catchments - Cumulative areal rainfall (1951-2002)

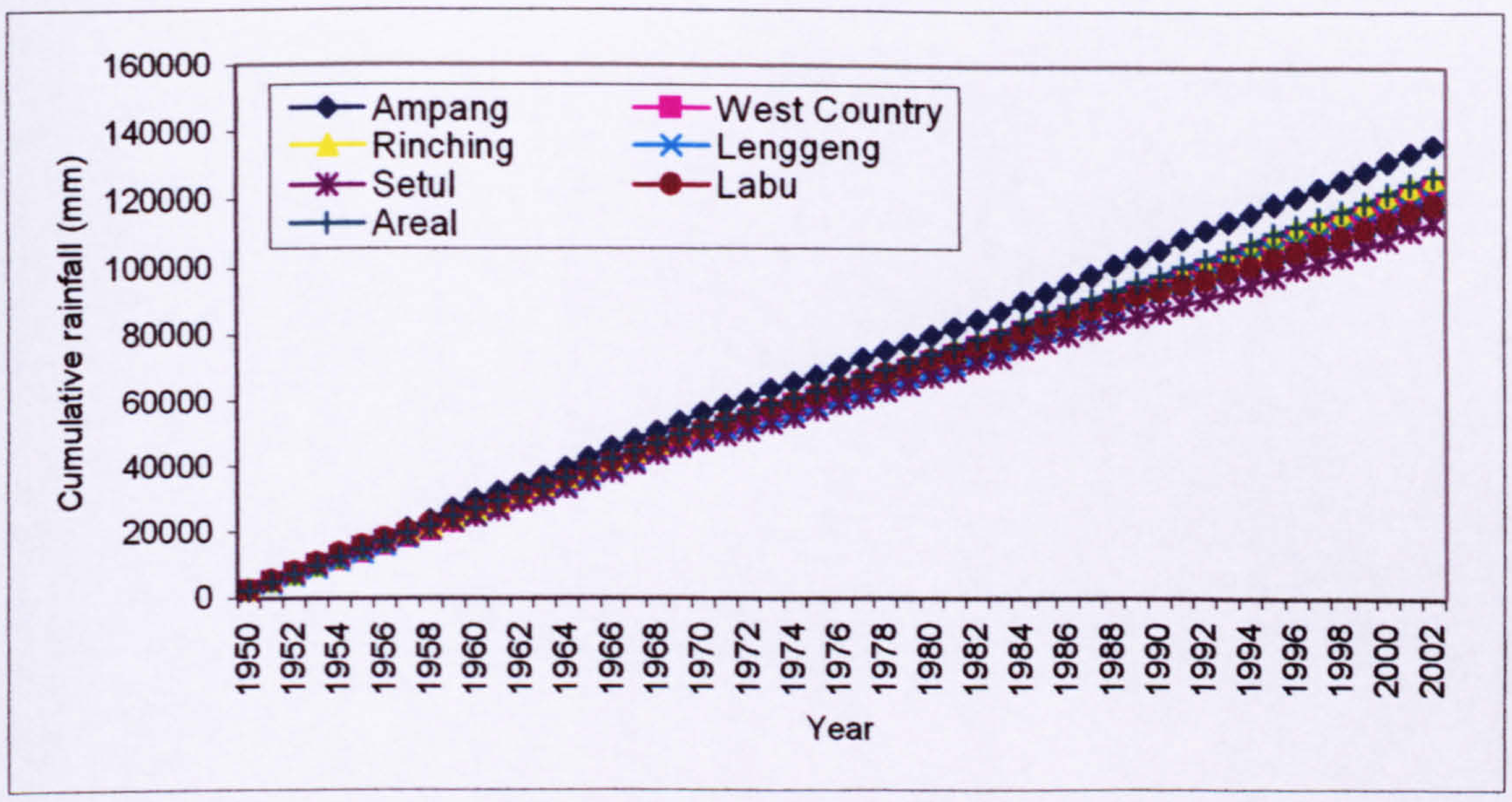


Figure 6.7: Langat – Cumulative rainfall

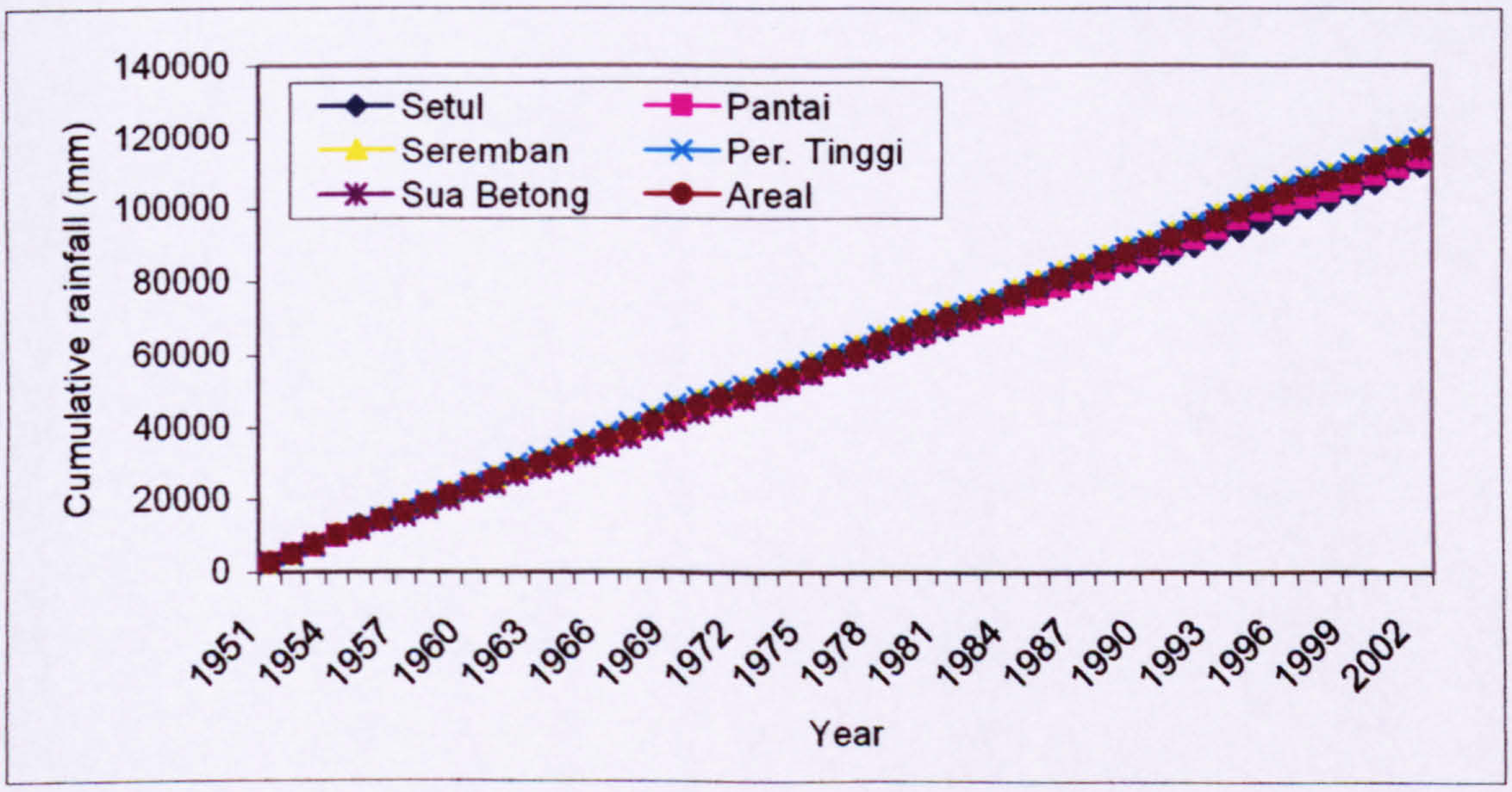


Figure 6.8: Linggi – Cumulative rainfall

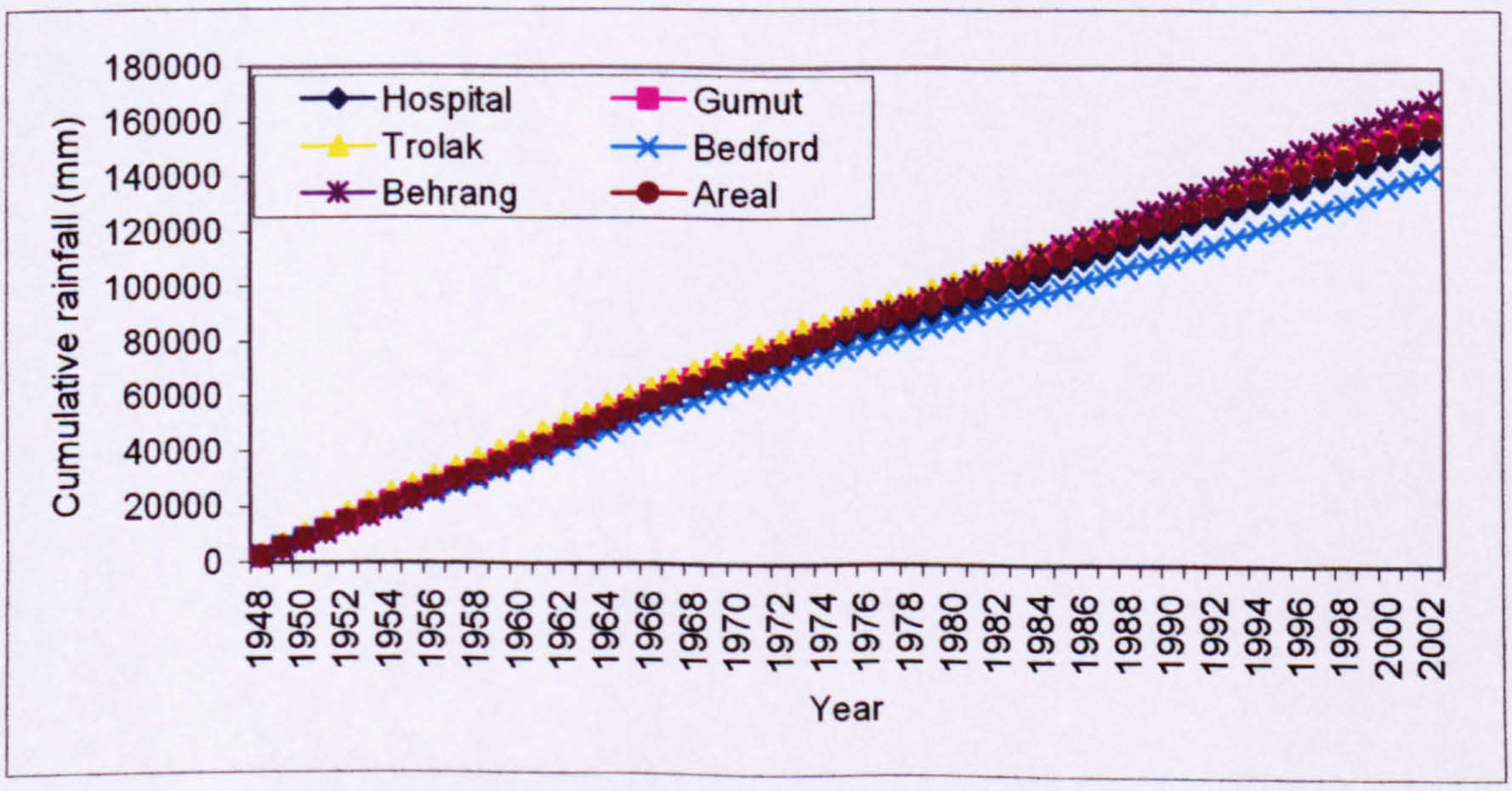


Figure 6.9: Bernam– Cumulative rainfall

In Langat and Bernam, the distances between point gauges ranges between 7 and 52 km, and 7 and 38 km, respectively. The correlation coefficient for point gauges in Langat and Bernam ranges between 0.3 and 0.8, and 0.2 and 0.7, respectively. The closest gauges in Langat, Linggi and Bernam are Setul and Lenggeng (7 km), Pantai and Setul (11 km) and Hospital and Gumut (7 km) with r^2 of 0.5, 0.6 and 0.7, respectively. The strength of relation is moderate, confirming the influence of the spatial variation in convective rainfall. Surprisingly, the variation in these study catchments is higher than arid regions, which are known to possess local variability of rainfall greater than temperate and humid areas of the world. For example, Sharon (1981) showed that the coefficients of correlation in the rainfall amounts recorded at different pairs of rainfall stations in Southern Israel and Jordan fell from 0.9 at a distance of 2 km to 0.6 at a distance of 5 km, and to 0.3 at a distance of 25 km. Similarly for Tanzania, Sharon (1974) and Jackson (1988) showed that correlation coefficients among pairs of rainfall stations declined rather sharply with distance. The cumulative point rainfall within catchments tends to decrease after 1973 as a function of the changes in equipment. The earlier period witnessed less precision in data gathering from a number of point gauges, owing to a higher rainfall at the beginning of the records. The cumulative rainfall in each catchment also decreases after the 1970s, which can be related with global climate changes associated with El Nino events that significantly affect rainfall, especially in the tropics (Goudie, 2006). Changes in precipitation would cause significant changes in a given runoff-rainfall relation (Najjar, 1999). There is a significant decrease in rain days since 1961 throughout Southeast Asia and western and central South Pacific (Manton *et al.*, 2001). The frequency and intensity of drought have been observed to increase in recent years in those regions in recent decades that are dominated by climate variability; i.e., ENSO – shift towards more warm events (Dore, 2005).

Figure 6.10 shows the inter-station correlation between point gauges within each study catchment. Not surprisingly, the greater the distance between point gauges, the lower the correlation (i.e., spatial variation). Langat and Linggi seem to follow a common trend where the correlation coefficients decrease as the distance increases. A similar trend also occurs in Bernam, but there are two pairs of stations - Behrang-Bedford (15 km) and Behrang-Gumut (13 km) - which have a very low r^2. Here, the correlation is far less dependant on actual distance. This reveals how important topography is in influencing spatial variability in rainfall. Buytaert *et al.* (2006) conducted a study in mountain areas in Ecuador, and found that a strong correlation (0.8-0.98) between gauges only occurs for distances less than 4 km. For corroboration, all point gauges were spatially correlated with the Meteorological Office gauge within each catchment, which was used to provide reference data. A similar trend was revealed (**Figure 6.11**). This rainfall spottiness reflects the characteristics of convective storms: well known in desert environments, but its presence here in the humid tropics is perhaps surprising.

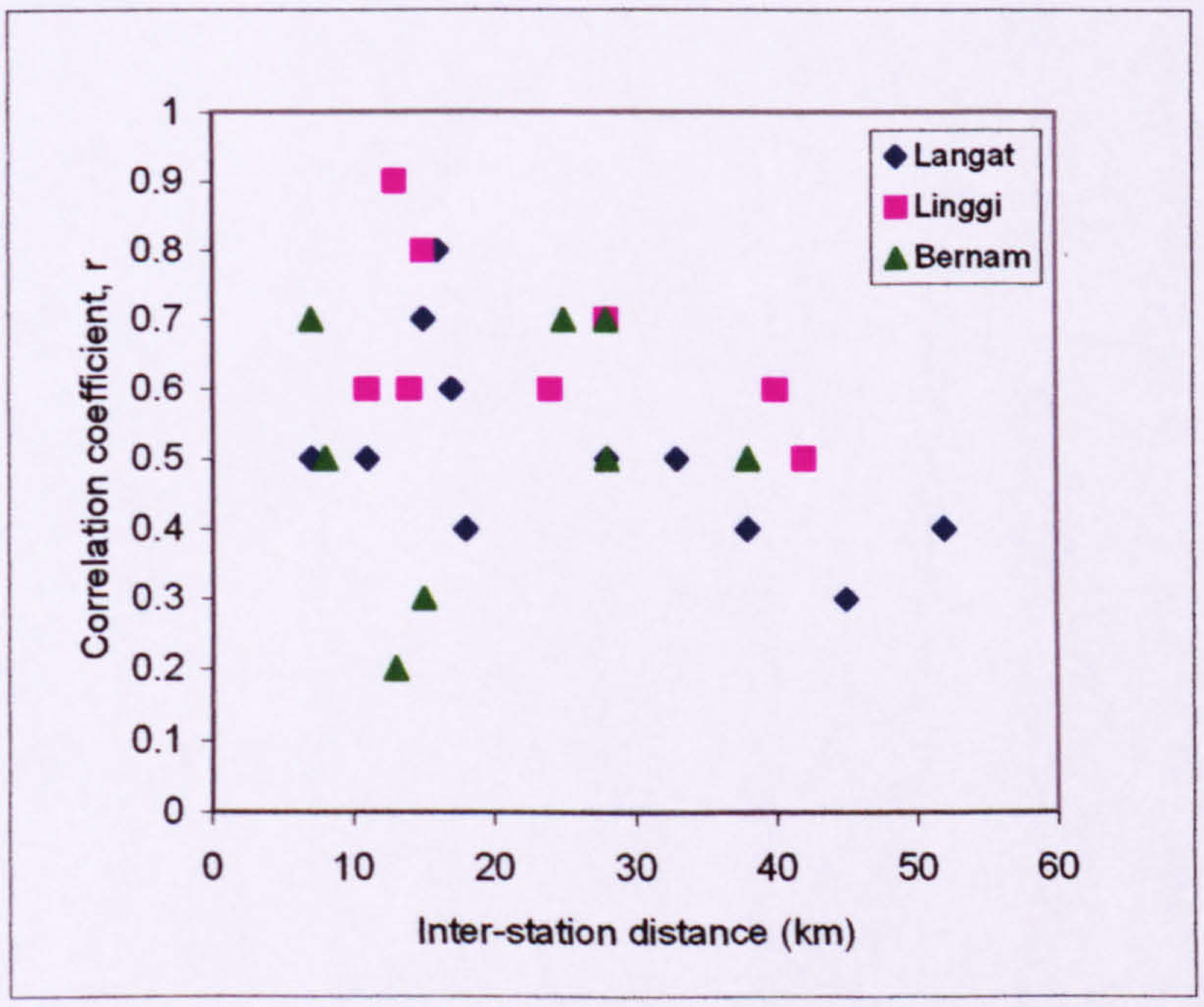


Figure 6.10: Correlogram of rainfall measured at gauges separated by specified distance

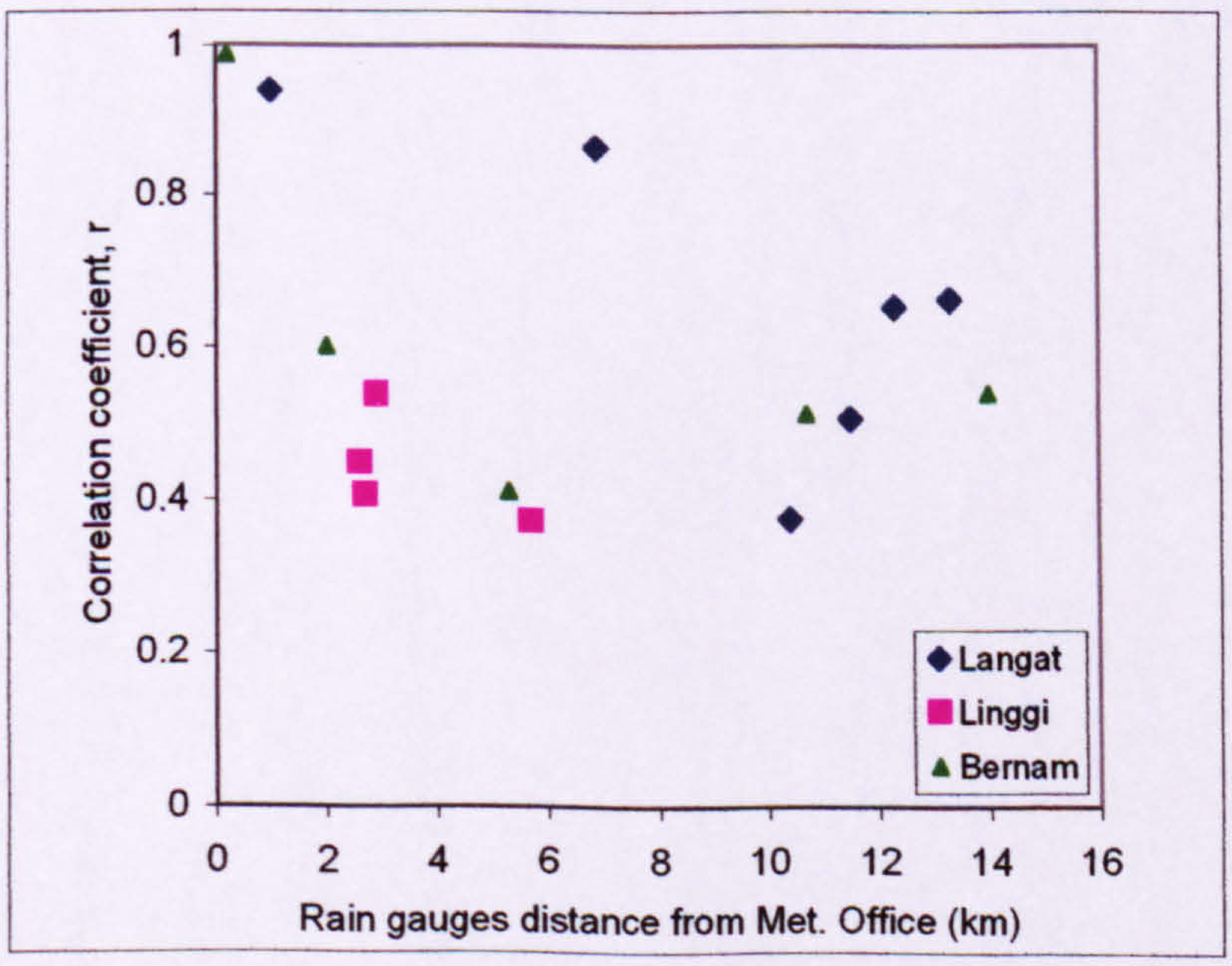


Figure 6.11: Correlogram of rainfall measured at gauges separated by specified distance from Met. Office gauge

In order to compare relative rainfall performance between catchments, Met. Office annual average rainfall for each of the three study catchments was rated against the areal average of the three. It clearly shows how spatial variation affects the amount of rainfall catch in each catchment. In Langat and Linggi, the amount of annual rainfall recorded is 6% (148.31 mm) and 8% (186.78 mm), respectively less than that recorded by the Meteorology Office for the region (**Figures 6.12** and **6.13**). However, moving further north, the wetter catchment Bernam receives 6% (157.60 mm) more than the regional average (**Figures 6.14**). This spatial variation is closely related to the typical characteristics of convective thunderstorms in these areas, which can move from one place to another and cause a great variation in precipitation, especially for the short-term record. For the long-term record (annual), the variation is less. In this tropical region, the weather can change suddenly. In bad weather conditions, thunderstorms form a line which normally moves inland from the coast producing strong winds with intense local rainfall (Desa and Niemczynowicz, 1996). Basically, the effect of full Northeast and Southwest Monsoon seasonal rain on the study areas are considerably smaller than expected, due to the rain shadow from the Main Range and Sumatra. However, as Bernam is located in the foothill of the Main Range, there is a strong orographic effect here, and, therefore, more rain is received.

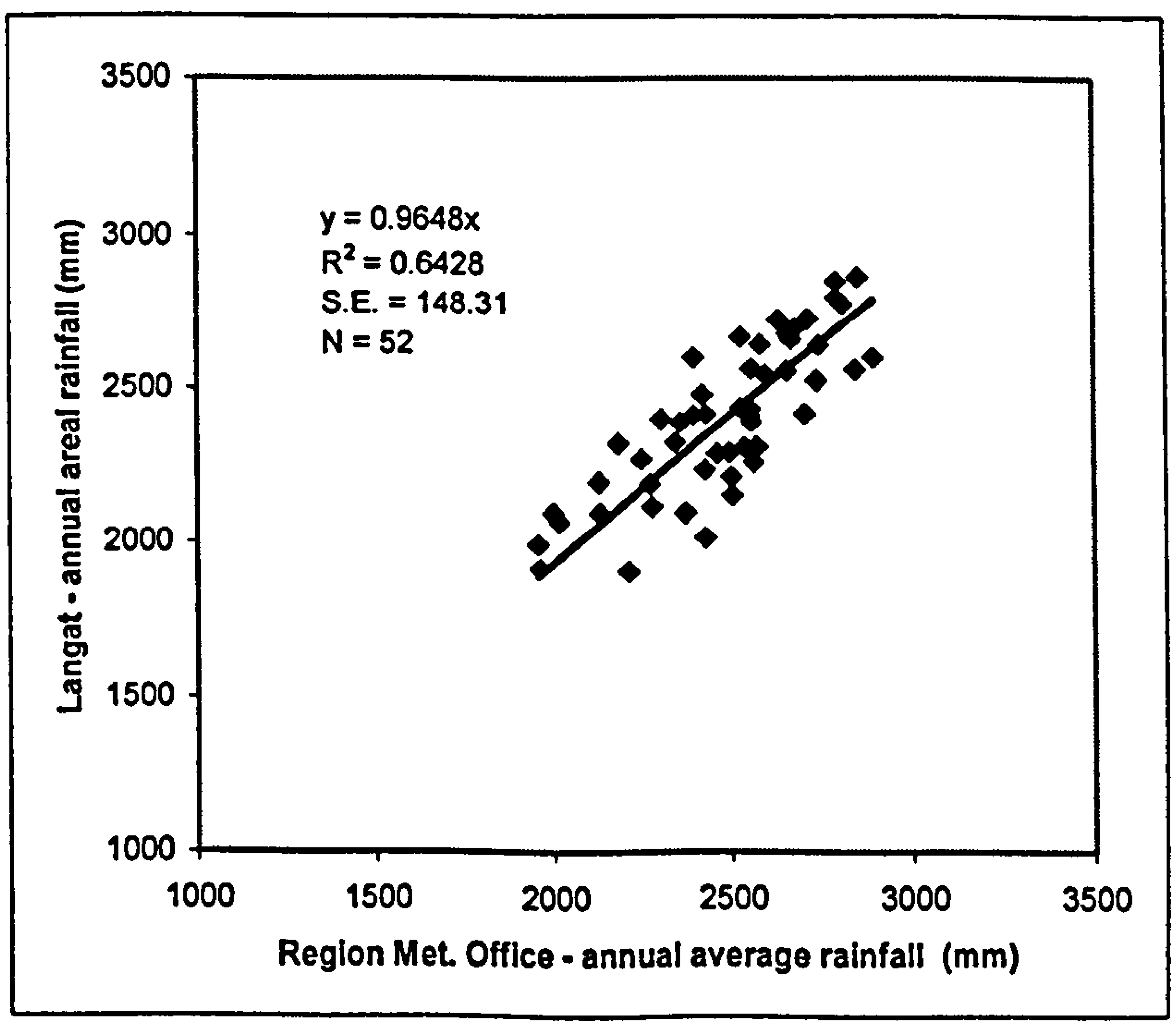


Figure 6.12: Areal Rainfall: Langat versus Region Met. Office, 1951-2002

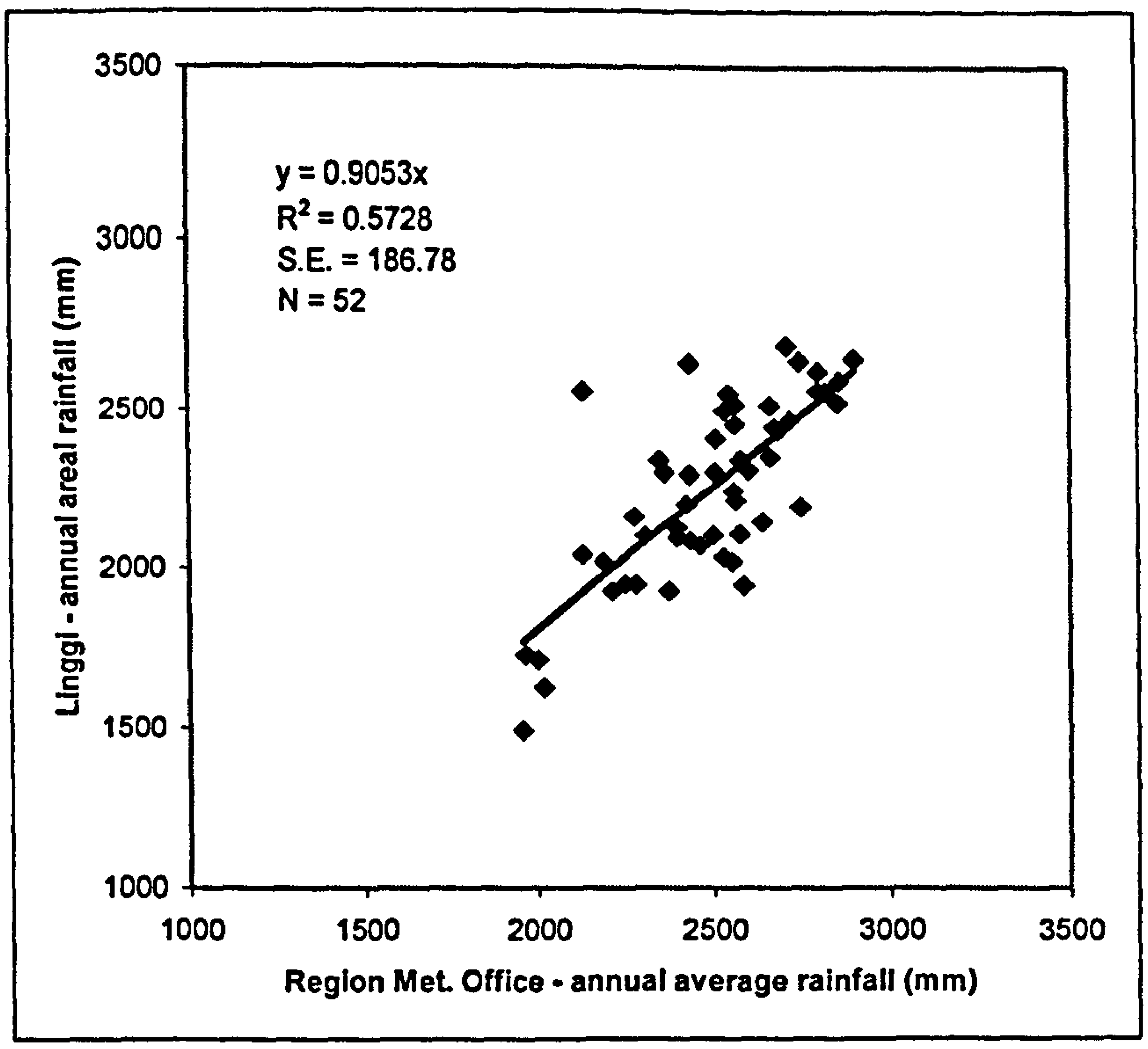


Figure 6.13: Areal Rainfall: Linggi versus Region Met. Office, 1951-2002

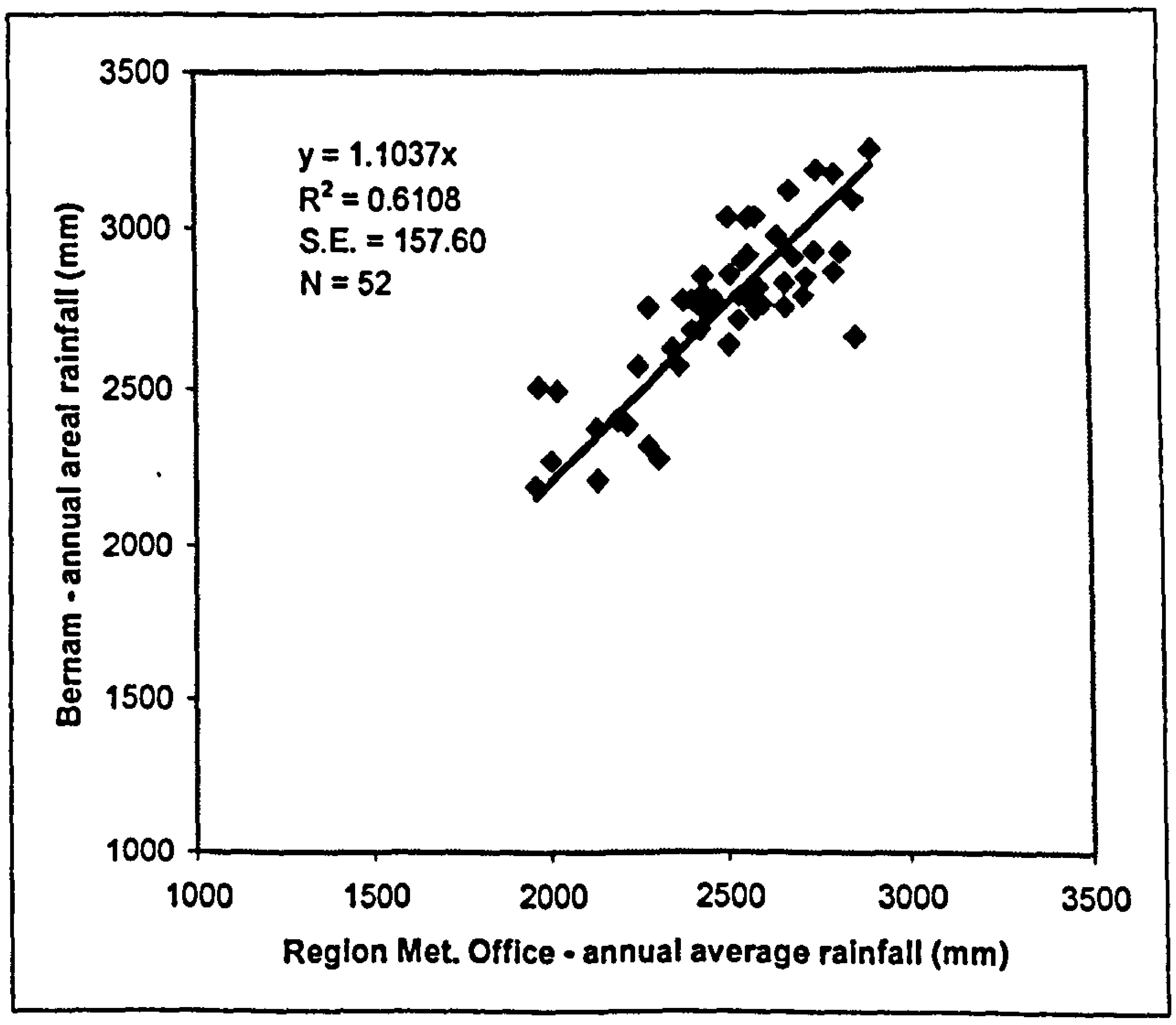


Figure 6.14: Areal Rainfall: Bernam versus Region Met. Office, 1951-2002

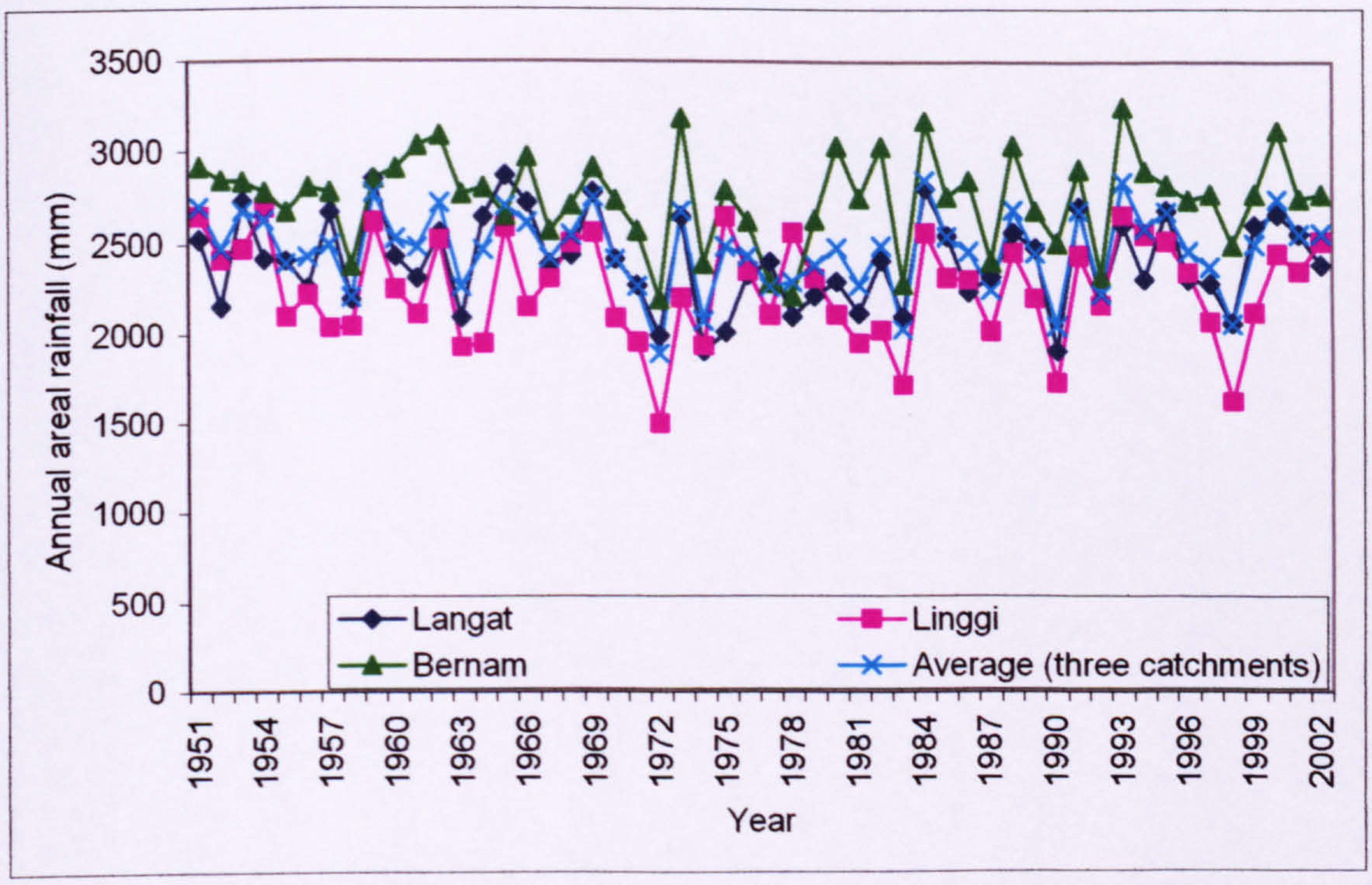


Figure 6.15: All catchments – Annual areal rainfall 1951-2002

Figure 6.15 shows the long-term annual areal rainfall of all three catchments. It demonstrates the general covariation of the Langat, Linggi and Bernam catchments. During the 52-year record, it reveals relatively wet and dry periods. Between 1972 and 1983, rainfall is slightly lower when compared with the decades before and after. But this does not apply for Bernam, which recorded higher rainfall in 1979-1982, related to variation in local rainfall. As corroboration, five-year running means are given in **Figure 6.16** to reduce the visual impact of annual variation. However, there is still exists a period from 1972-1974 in Linggi where the rainfall was high while it was not in Langat, again, reflecting the local spatial variation. The localized comparative dryness does not stand out, but the general reduction in annual values around the 1970s is noticeable, reinforcing the suspicion that data-gathering procedures changed affecting the data. Dryness could be related to changing global circulation and climate variation. Within the period 1972-2000 there occurred three moderate (1983, 1987 and 1998) and two strong El Nino (1972 and 1997) episodes (**Table 6.10**; Harger, 1995; Kane, 1999 and Severov, *et al.*, 2004). Locally, in addition, there were upland areas within the catchment planted with agricultural crops (palm oil trees and rubber trees) at the expense of natural forest during this period. However, there is no concrete evidence to relate the changes in the local precipitation regime to the changes in land cover type in this area given the geographical scale of Peninsula Malaysia is small. Huber and Iroume

(2001) did stress that the establishment of plantations initiates long-term changes at a bigger scale that could modify the distribution of the precipitation and some other elements such as the chemistry and water yield.

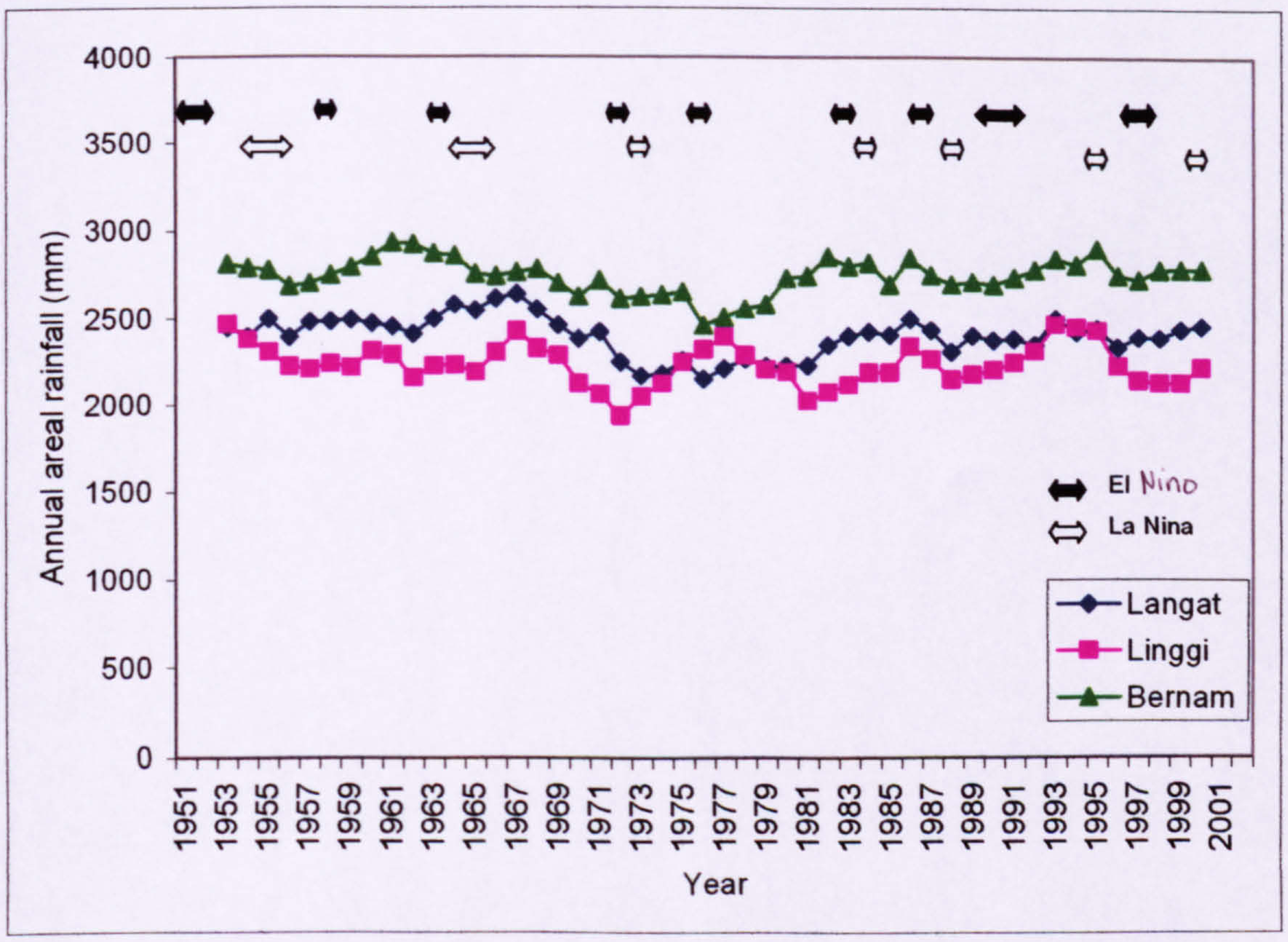


Figure 6.16a: All catchments annual areal rainfall: 5-year running mean (1951-2002)

The El Nino/Southern Oscillation (ENSO), which is related to the atmospheric-oceanic phenomenon, is a most significant factor, causing global hydro-climatic variability in the equatorial Pacific (Shrestha and Kostaschuk, 2005). The influence of global El Nino and La Nina events within the study area is noticeable. One-way ANOVA reveals a mean different between them at the 0.05 level. There has been no study reported by local meteorologists of the impact on water resources, but Kane (1999) reported that Southeast Asia suffered severe drought during the 1997 El Nino, causing widespread fires and damage. Coupled with prevailing winds, smoke haze was being diverted towards Peninsula Malaysia, reducing the amount of solar radiation. Through feedback mechanisms, convective cloud development was suppressed, thus reducing rainfall (Lim and Oii, 2004).

Within the 52-year rainfall record, there are 19 events that affect the amount of rainfall caught by the catchments (**Table 6.10** and **Figure 6.16a**). This is demonstrated by the values of the deviation from the long-term mean of areal rainfall from all study areas (**Figure 6.16b**). The long-term mean was chosen to represent the trend for the region. For all catchments, the annual areal rainfall fell significantly in the years 1958, 1972, 1983, 1990 and 1998, which all coincide with an El Nino event. Meanwhile, the La Nina event brought a relatively higher rainfall for all catchments during 1966, 1973, 1984, 1995 and 2000. Even though both El Nino and La Nina events made a contribution to the fluctuation of rainfall within catchments, there are a few events that cause an opposite effect for the region or have an impact a year after the event occurs. This could possibly relate to the variation of the global cycle or the circulation between one place and another. It is normally regarded that a stronger El Nino is associated with droughts. Surprisingly, though, this is not so (Kane, 1999). Floods occurred in some regions and droughts exist in others. This phenomenon has been reported by Bendix (2000) where there is a location in Peru that suffers huge storms and major floods during severe El Nino events in Southeast Asia. In support of this, it has been reported that during the El Nino in India and Sahel in 1983, 1986 and 1990, these areas received an excess of rainfall; while, during La Nina in 1971, 1973 and 1989, they experienced droughts (Kane, 1999). Since rainfall in the tropics is extremely variable in both space and time, identifying the precise cause of fluctuations remains problematic (Nieuwolt, 1977; Manton and Bonell, 1993).

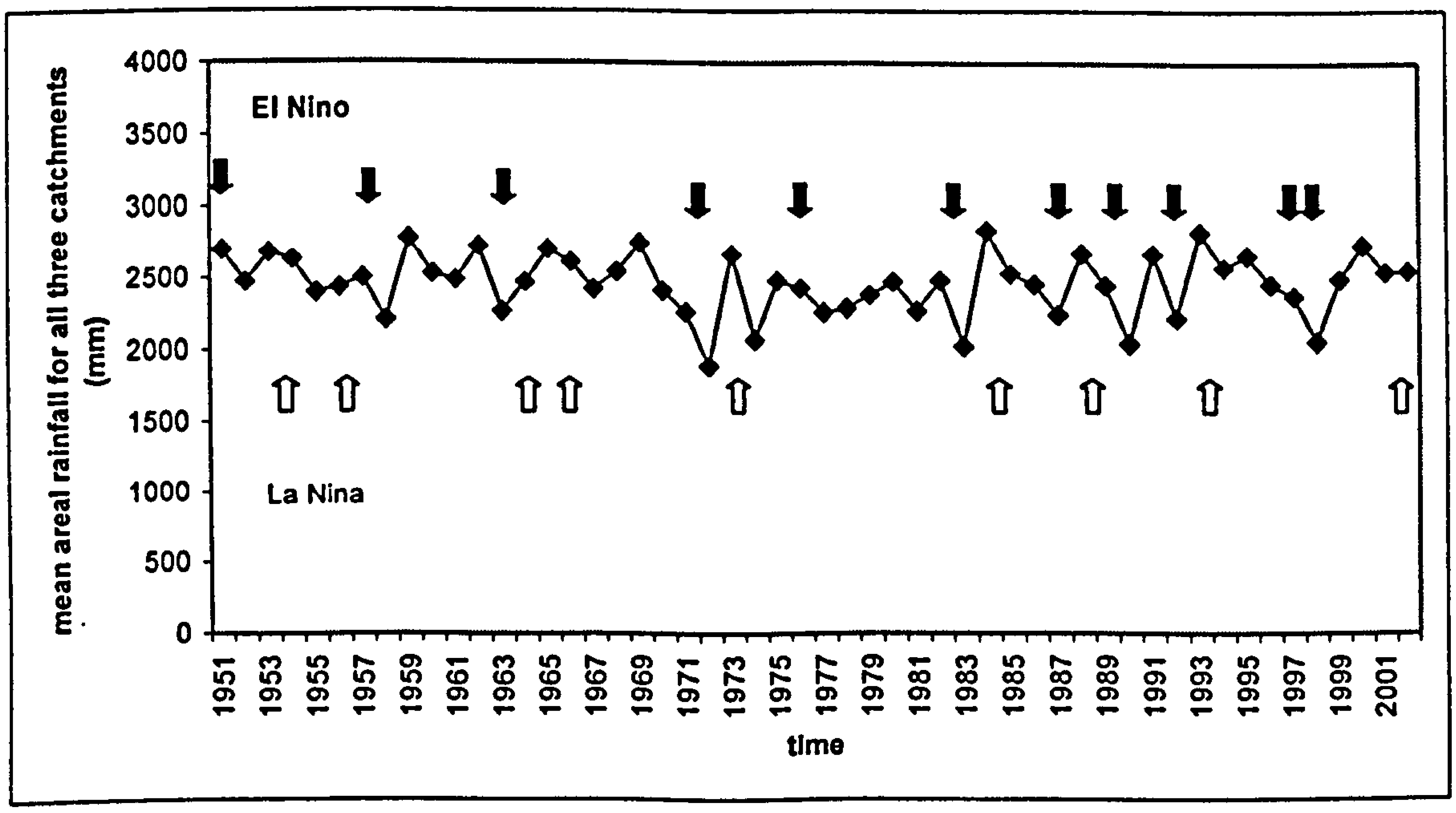


Figure 6.16b: The El Nino and La Nina event based on average annual areal rainfall for all catchments, 1951-2002

Table 6.10: Annual average of areal rainfall for all catchments: The most coincident year with El Nino and La Nina event, based on deviation of rainfall from long term mean (2468 mm)

Year	Event	Index*	Average annual rainfall (mm)	Average annual rainfall: Deviation from long term mean (1951-2002)
1954	La Nina	1	2632	164
1956	La Nina	0.5	2430	-38
1958	El Nino	1	2208	-260
1963	El Nino	1	2267	-201
1964	La Nina	1	2469	1
1966	La Nina	1	2615	147
1972	El Nino	1.5	1894	-574
1973	La Nina	1.5	2676	208
1976	El Nino	0.5	2431	-37
1983	El Nino	1	2031	-437
1984	La Nina	0.5	2844	376
1987	El Nino	1	2249	-219
1988	La Nina	1.5	2685	217
1990	El Nino	0.5	2052	-416
1992	El Nino	0.5	2228	-240
1995	La Nina	0.5	2674	206
1997	El Nino	1.5	2379	-89
1998	El Nino	1	2065	-403
2000	La Nina	1	2744	276

* Kaplan index is based on Sea Surface Temperature (SST); 0.5 - weak; 1 – moderate; 1.5 – strong (Harger, 1995; Kane, 1999 and Severov, *et al.*, 2004).

Note: The Kaplan index is based on analyses of global monthly sea surface temperature (SST) anomalies from 1856 to 1991; the SST is one of the important indicators used to detect any climate variability. This index is based on the application of a number of statistical methods i.e. optimal smoothing (OS), Kalman filter (KF), and optimal interpolation (OI) accompanied by estimates of the error covariance of the data fields being analyzed. Theoretically, all these methods are optimal linear estimates which provide best estimates using observational information at the present time (OI), or at present and past times (KF), or at all times, past, present and future (OS) (Kaplan *et al.*, 1998).

6.3 Runoff – general characteristics

In order to understand a change in any of the factors that could possibly affect the stream-flow response, such as rainfall input, land use and catchment characteristics, a detailed study of discharge records is required. However, all of the study catchments are far from having a complete monthly discharge record over the length of time needed to detect the impact of any changes in land use. Even some of the annual records are based only on a few monthly average values within a year. This raises the problem of how to generate a worthwhile dataset. Despite this, a rainfall-runoff analysis was carried out based on both the complete 12-month discharge data and data where there are partially complete months only.

Both the Langat and Linggi catchments have only 21 complete years out of the 42 years of records, whereas Bernam is much better documented with 37 years of completed and only 5 years worth of partial records (**Table 6.11**). Partial records means there is a missing value in daily runoff data. Therefore, the monthly average could only be calculated based on available data for that particular month. The issue of how representative the findings of rainfall-runoff response in relation to land use changes, especially from the late 1980s onward for both Langat and Linggi, which underwent rapid development, is debatable, since many of the runoff records are not complete. It would be expected that the partial records slightly underestimate the runoff volume, which could contribute to lower runoff-coefficient values, as they are only based on available daily discharge data during conversion to runoff. Therefore, the 5-year interval for the runoff running mean was used in the hope of providing a general indicator of the rainfall-runoff response.

Table 6.11: All catchments: status of monthly runoff record (1961-2002)

Year	Status monthly runoff record					
	Langat	**% missing**	**Linggi**	**% missing**	**Bernam**	**% missing**
1961	Complete	-	Complete	-	Partial	57
1962	Complete	-	Complete	-	Complete	-
1963	Complete	-	Complete	-	Complete	-
1964	Partial	4	Partial	17	Complete	-
1965	Complete	-	Partial	8	Complete	-
1966	Complete	-	Partial	33	Complete	-
1967	Complete	-	Partial	25	Complete	-
1968	Complete	-	Partial	24	Complete	-
1969	Partial	10	Partial	16	Complete	-
1970	Partial	13	Partial	10	Complete	-
1971	Partial	5	Partial	8	Partial	
1972	Complete	-	Partial	22	Complete	-
1973	Complete	-	Partial	8	Complete	-
1974	Complete	-	Partial	16	Complete	-
1975	Partial	20	Partial	15	Partial	44
1976	Partial	22	Complete	-	Partial	16
1977	Partial	30	Complete	-	Partial	25
1978	Partial	9	Complete	-	Complete	-
1979	Complete	-	Complete	-	Complete	-
1980	Complete	-	Complete	-	Complete	-
1981	Complete	-	Complete	-	Complete	-
1982	Partial	50	Complete	-	Complete	-
1983	Complete	-	Partial	14	Complete	-
1984	Complete	-	Partial	8	Complete	-
1985	Complete	-	Complete	-	Complete	-
1986	Complete	-	Complete	-	Complete	-
1987	Complete	-	Complete	-	Complete	-
1988	Partial	27	Complete	-	Complete	-
1989	Partial	32	Complete	-	Complete	-
1990	Partial	27	Complete	-	Complete	-
1991	Partial	43	Partial	35	Complete	-
1992	Partial	33	Partial	27	Complete	-
1993	Partial	15	Partial	17	Complete	-
1994	Complete	-	Complete	-	Complete	-
1995	Partial	20	Complete	-	Complete	-
1996	Complete	-	Complete	-	Complete	-
1997	Partial	14	Partial	18	Complete	-
1998	Partial	25	Partial	34	Complete	-
1999	Partial	63	Complete	-	Complete	-
2000	Partial	25	Complete	-	Complete	-
2001	Partial	57	Partial	16	Complete	-
2002	Complete	-	Partial	8	Complete	-

Table 6.12: Annual runoff characteristics, 1960-2002

Catchment	Mean (mm)	Standard Error (mm)	Minimum (mm)	Maximum (mm)	Range (mm)	Standard Deviation (mm)	Coeff var	N
Langat	926	30.6	625	1419	793	200.9	0.22	43
Linggi	1146	31.0	688	1632	943	203.1	0.18	43
Bernam	1275	30.8	800	1604	804	201.8	0.16	43

Table 6.12 shows some basic properties of annual runoff for all catchments. The long-term annual average reveals that the Bernam catchment has a higher runoff volume, since it received more rainfall than Langat and Linggi. Bernam had 1275 mm yr^{-1}, followed by 1146 mm and 926 mm for Linggi and Langat, respectively. One-Way ANOVA reveals that the mean difference is significant at the 0.05 level. Linggi seems to have a considerably higher runoff due to its smaller catchment size and its rapid development since the late 1980s. A simple runoff-rainfall ratio based on the long-term average (1960-2002), shows that the Bernam catchment has a higher percentage of water flowing out of the catchment [about 50%], followed by Linggi and Langat with 51% and 36%, respectively. At this site, the relative performance of the Bernam is counterintuitive, since it has yet to be urbanised when compared with Langat, which has already been developed. This would be related to the higher rainfall received by Bernam. The runoff ratios reported for small experimental studies on forest conversion in the tropics lie between 17 and 40%, depending on rainfall intensity, magnitude of changes, type of conversion, catchment size and also physical aspect of the study area (Baharuddin, 1988; Abdul Rahim; 1988; Bruijnzeel, 1990; Lal, 1993).

All three catchments show a complex long-term pattern of runoff with up and down fluctuations (**Figure 6.17**). There is no clear trend of increase in runoff dover the period 1960-2002 for all catchments, which can be related to changes in land use. But, it is clearly showing the reflection from the 'extreme' rainfall event due to El Nino as the runoff significantly decreases in 1972, 1983, 1990 and 1998. The effect from La Nina was only observed in 1973, 1984 and 1994. Despite the separation between the drainage basins being no more than 200 km, there are some periods where the trend in Bernam does not follow the Langat and Linggi records. In this case, it is likely to be owing to the spatial variation in rainfall events as a function of spottiness and orographic effects. A running mean with a five-year interval has been superimposed over the data in order to distil several trends (**Figure 6.18**). The five-year interval is considered a suitable period to detect any changes related to major land development. In the period from 1960 to 1975, all catchments were subjected to the early conversion of forest to rubber plantation and mining activity as a major foundation for the development of the economy soon after independence. There may be some indication that some of the unsteadiness could be related to the phase of the agricultural land development carried out under government directives during several periods between 1960 and 2002. Surprisingly, there is no significant increase in runoff trends. Starting from the 1980s, both Langat and Linggi underwent a very rapid development through urbanisation and industrialisation, which could contribute an increment to the runoff volume every year. Again, there is no significant trend observed. In the late 1980s and late 1990s when an economic crisis struck the Southeast Asian region, there was a reduction in land development, which seems to have reduced runoff volume. However, it is more likely to reflect the El Nino events during those periods. For Bernam, the initial stage of land clearances for urbanisation began just before the crisis in 1997 and was continued after the year 2000.

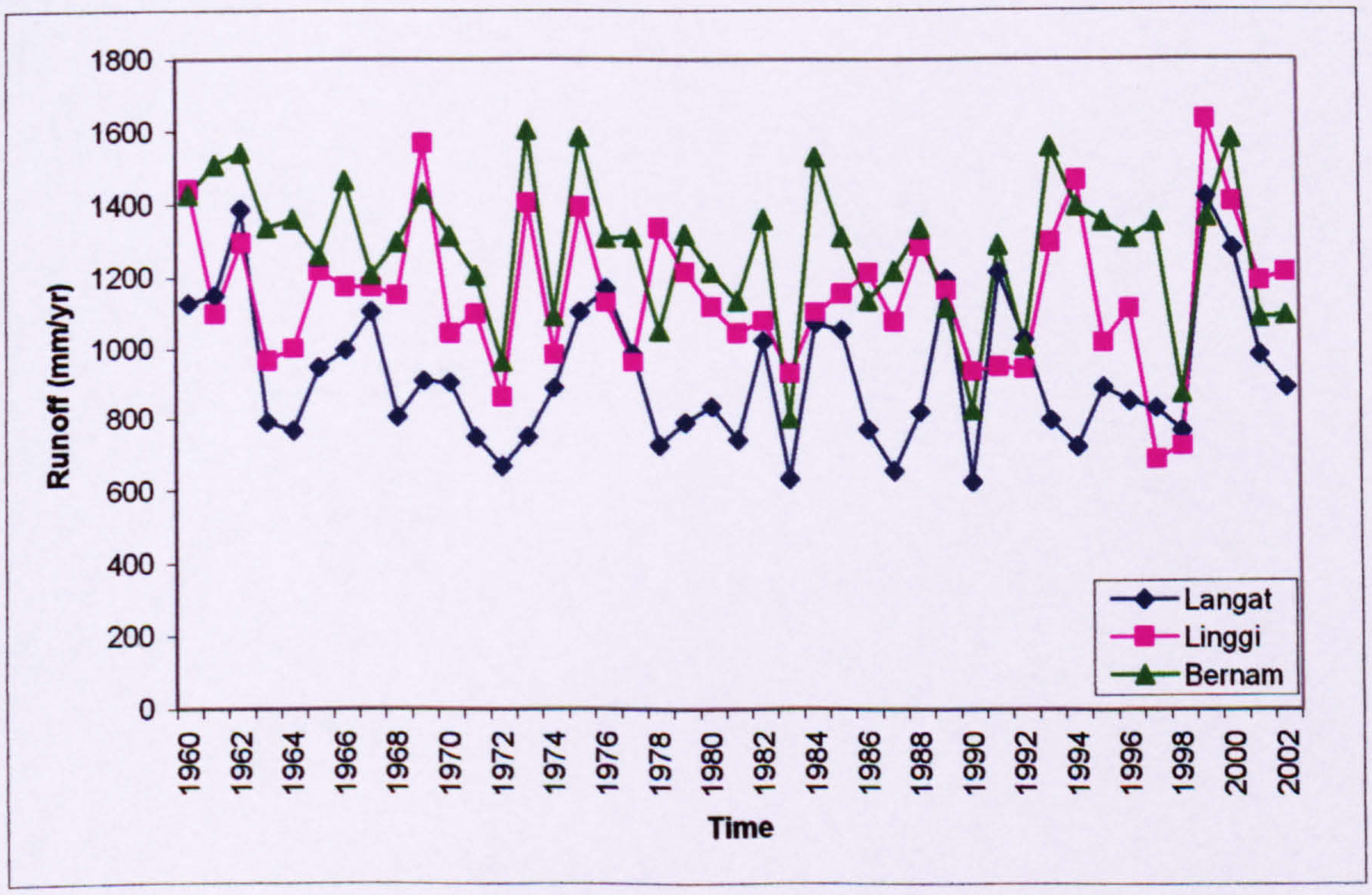


Figure 6.17: Mean annual runoff (1960-2002)

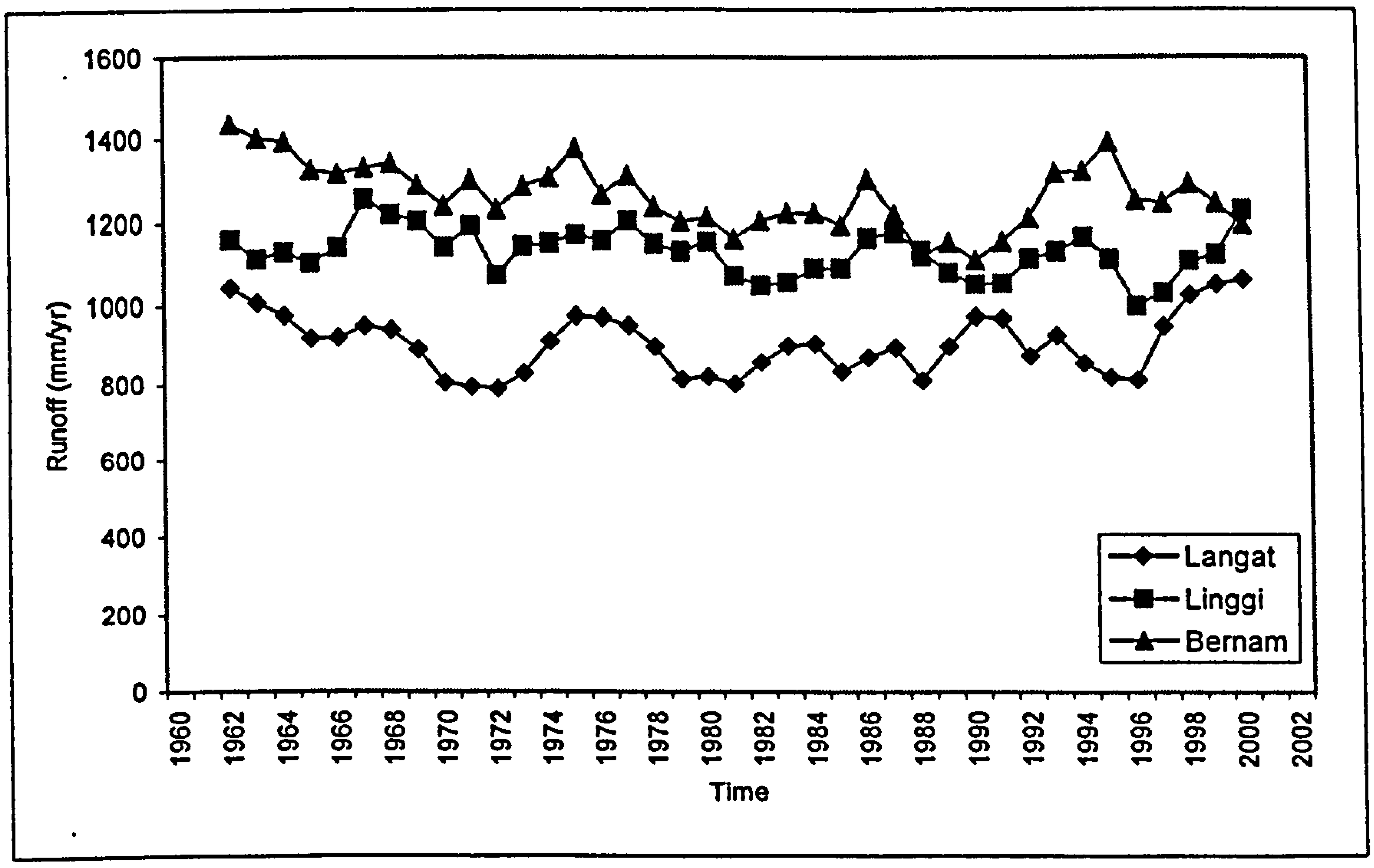


Figure 6.18: Mean annual runoff – 5-year running mean (1960-2002)

As corroboration, a double mass curve analysis (complete monthly-discrete and annual records) also demonstrates no significant increase in runoff for all catchments (**Figures 6.19** and **6.20**). However, there is a clear shift in slope before and after 1973 which reflects the changes in equipment to measure rainfall. There is a trend in Linggi (monthly data) especially during 1994 and 1999, but it is difficult to relate to land use change, as the dataset is not continuous. This is because there is a gap in the data between 1990 and 1994, while the trend in 1999 is affected by El Nino events in 1997 and 1998. Therefore, there is a shift in the double mass curve as a function of lower and higher rainfall during those years. As the runoff-rainfall relation (**Figure 6.19**) is based on discontinuous data, the cumulative values are significantly different between catchments, and it is impossible to directly compare the cumulative values. The long-term pattern of monthly and annual rainfall and runoff are shown in **Figures 6.21** and **6.22** for all catchments. As there is no significant increase in runoff, the trend generally reflects rainfall. The annual data clearly demonstrates this, as a longer data set contains less variation, especially due to seasonal rainfall effects. The irregularity shown by the sequence of monthly average runoff during the wet months (March – May and September – December) are indicative of a catchment responding rapidly to rainfall and producing a sharp recession in runoff in the dry months (January-February and June-August). This relates to a lack of storage in the drainage basin.

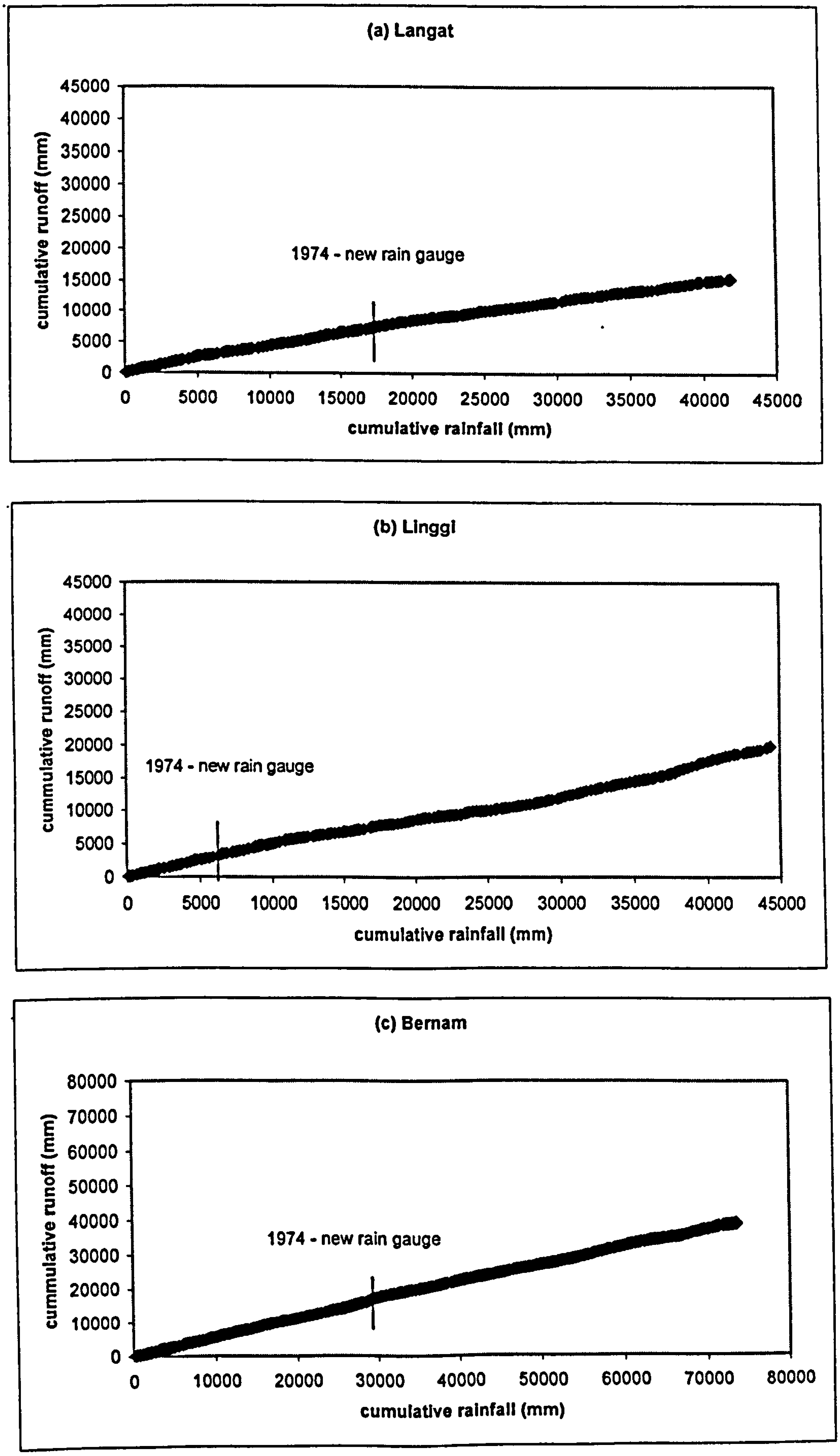


Figure 6.19: All three catchments: cumulative rainfall-runoff-monthly data (1960-2002)

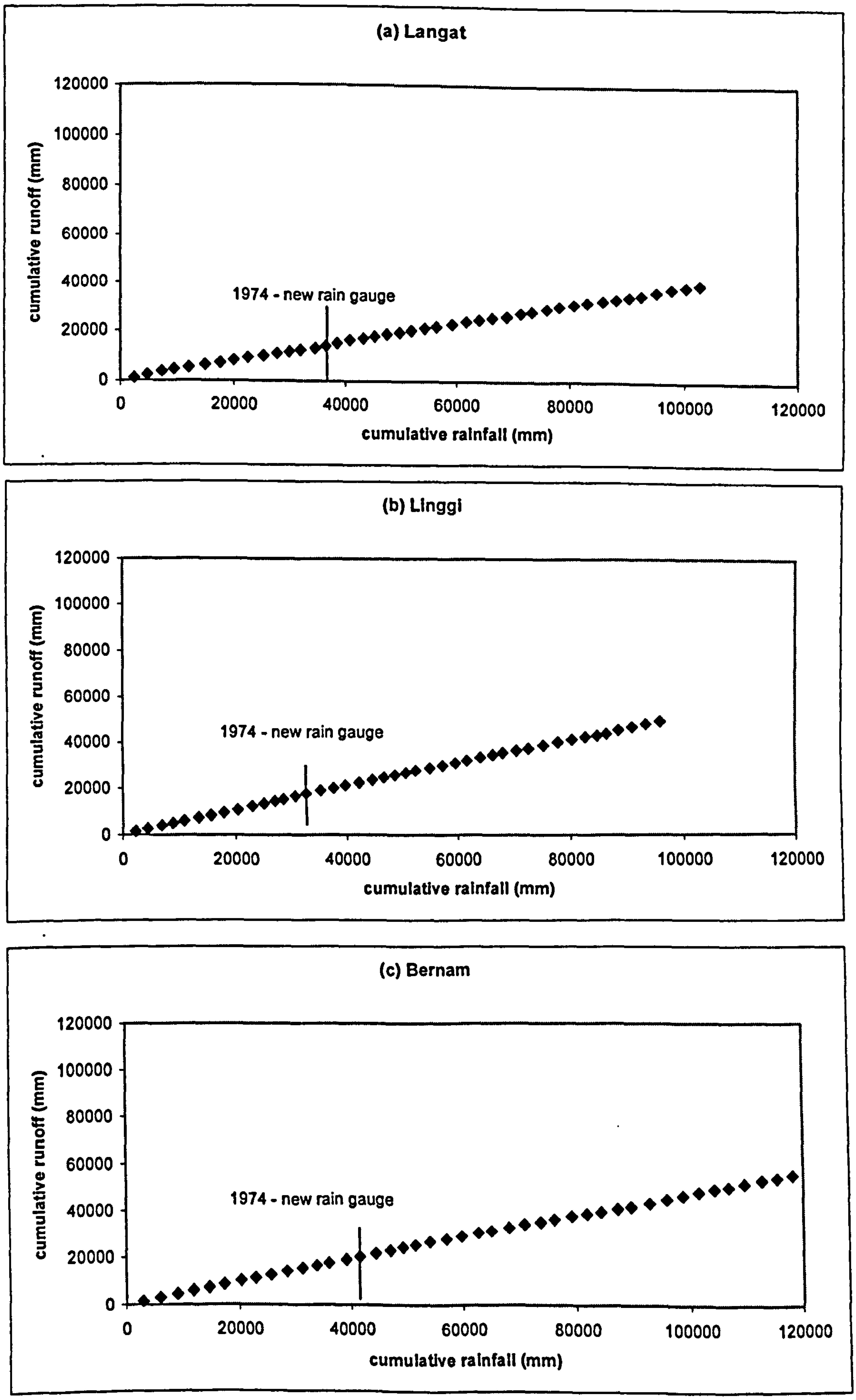
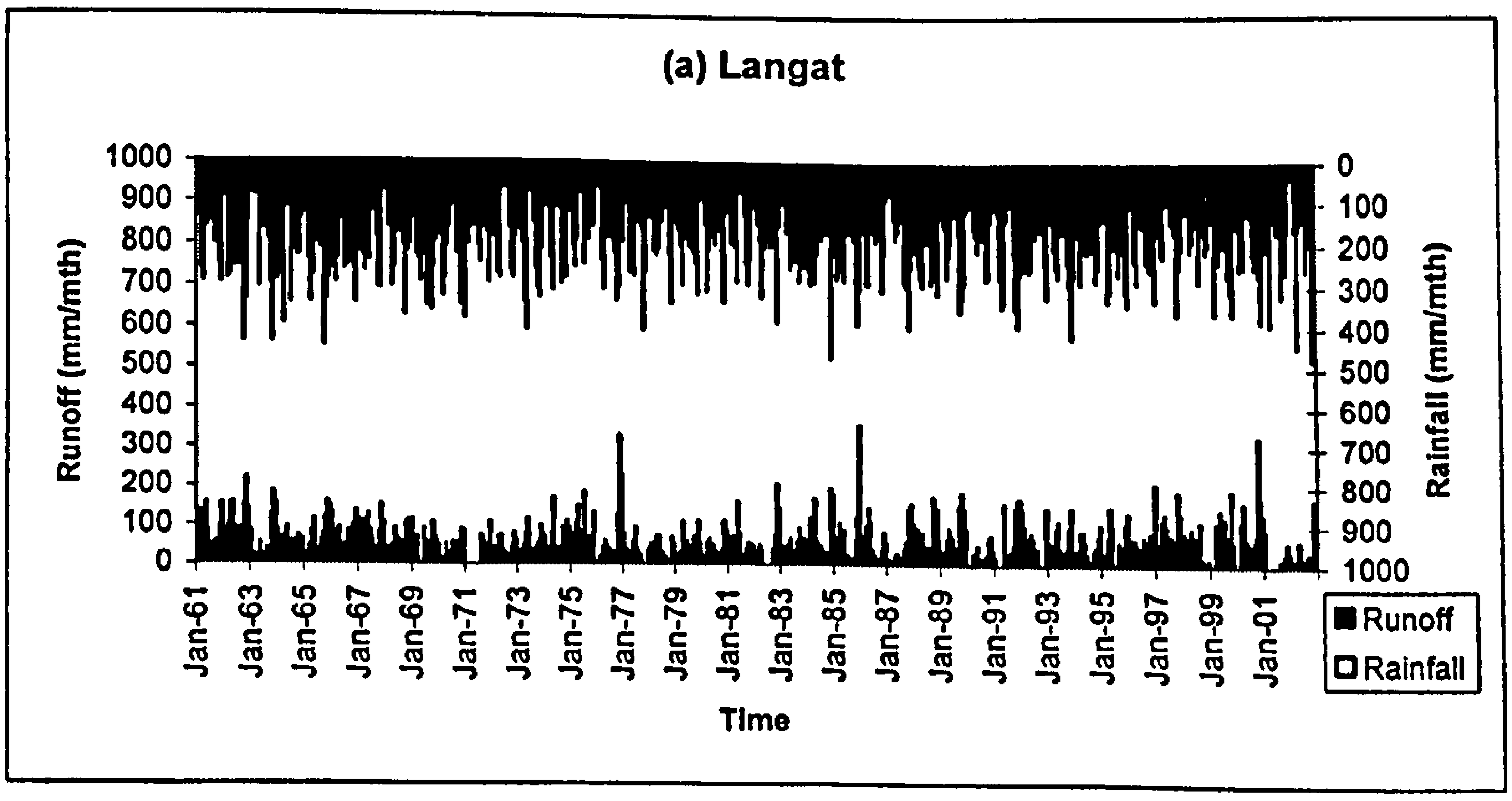
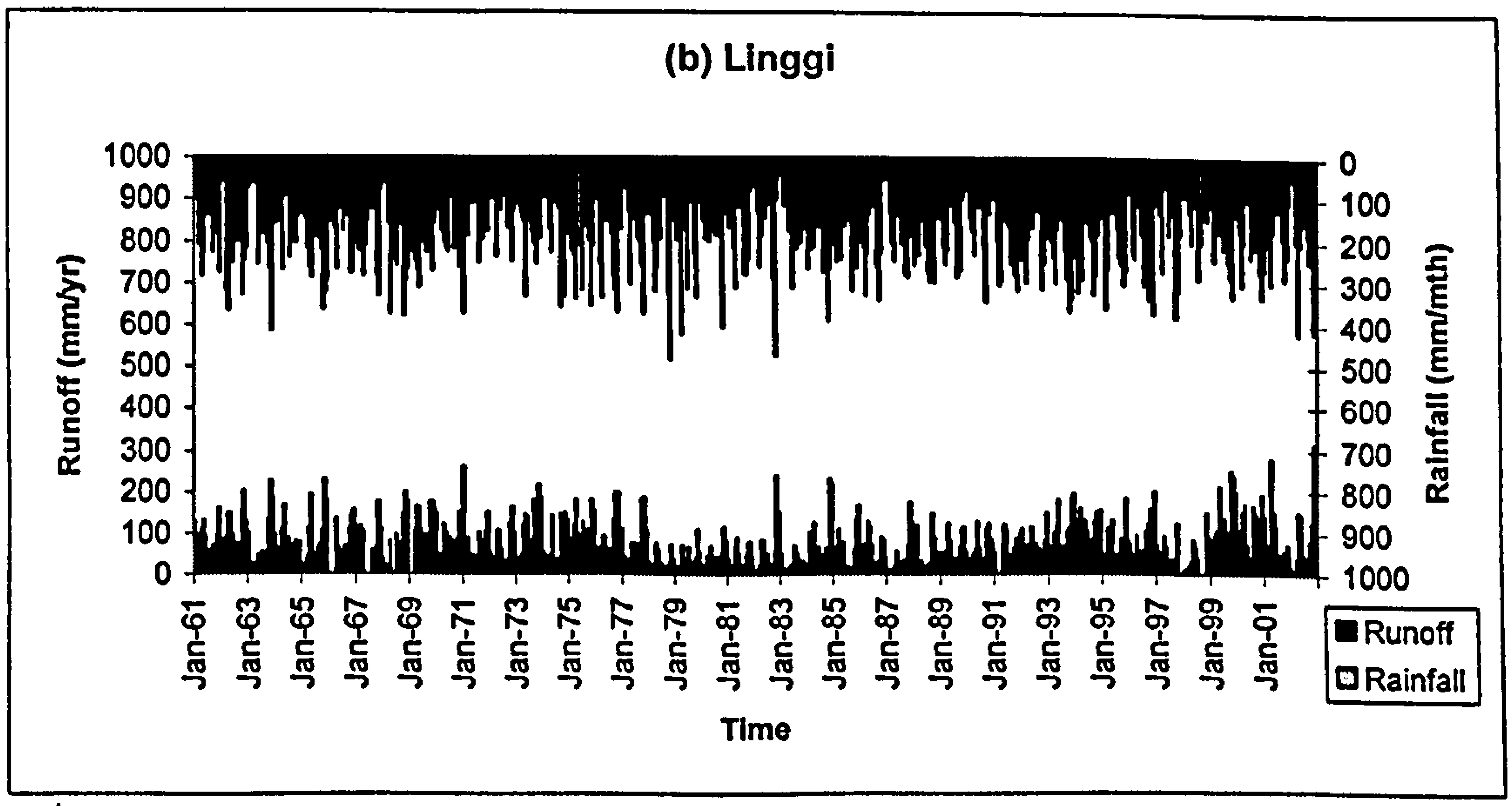


Figure 6.20: All three catchments: cumulative rainfall-runoff-annual data (1960-2002)





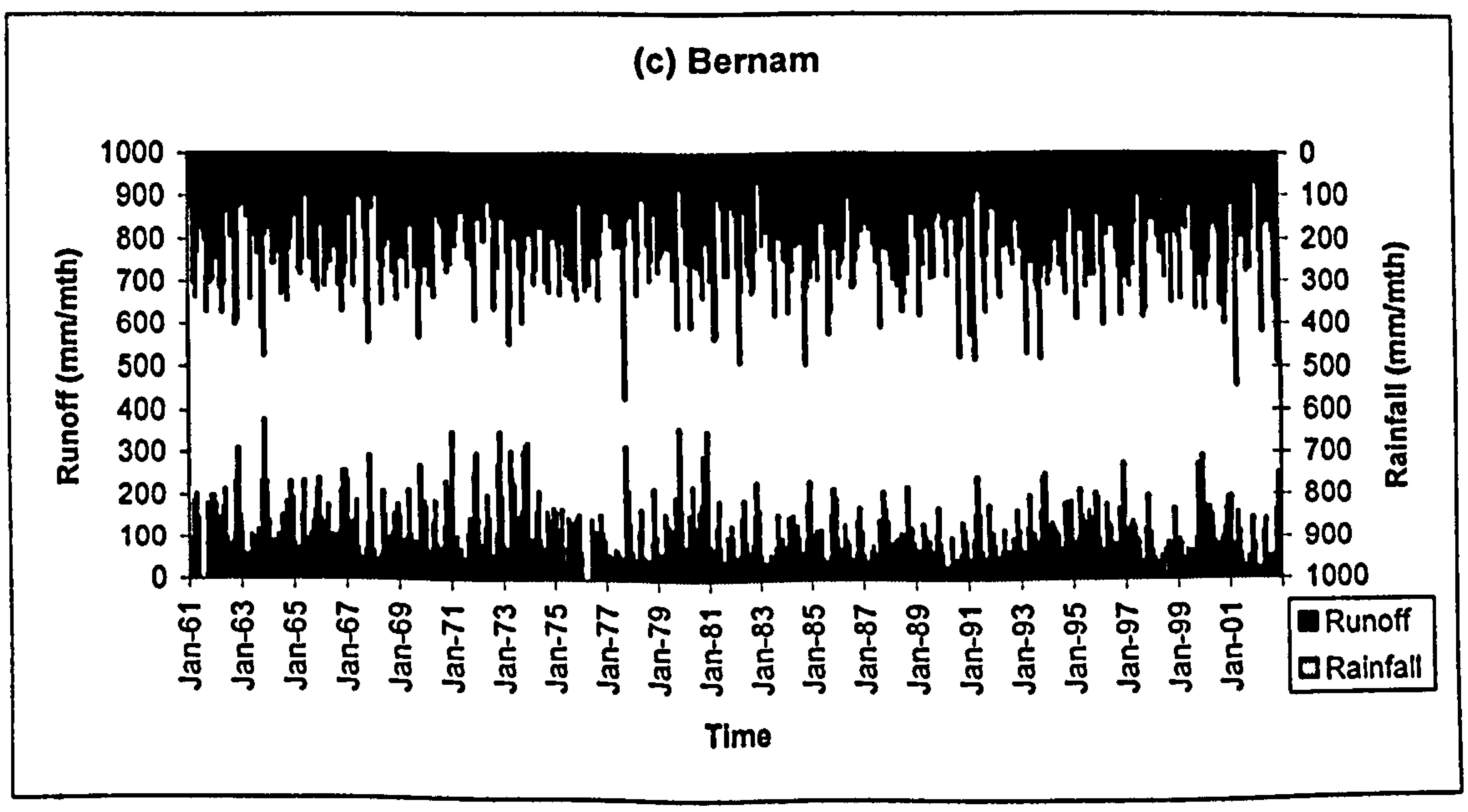


Figure 6.21: Rainfall and runoff long-term trend (monthly data), 1961-2002

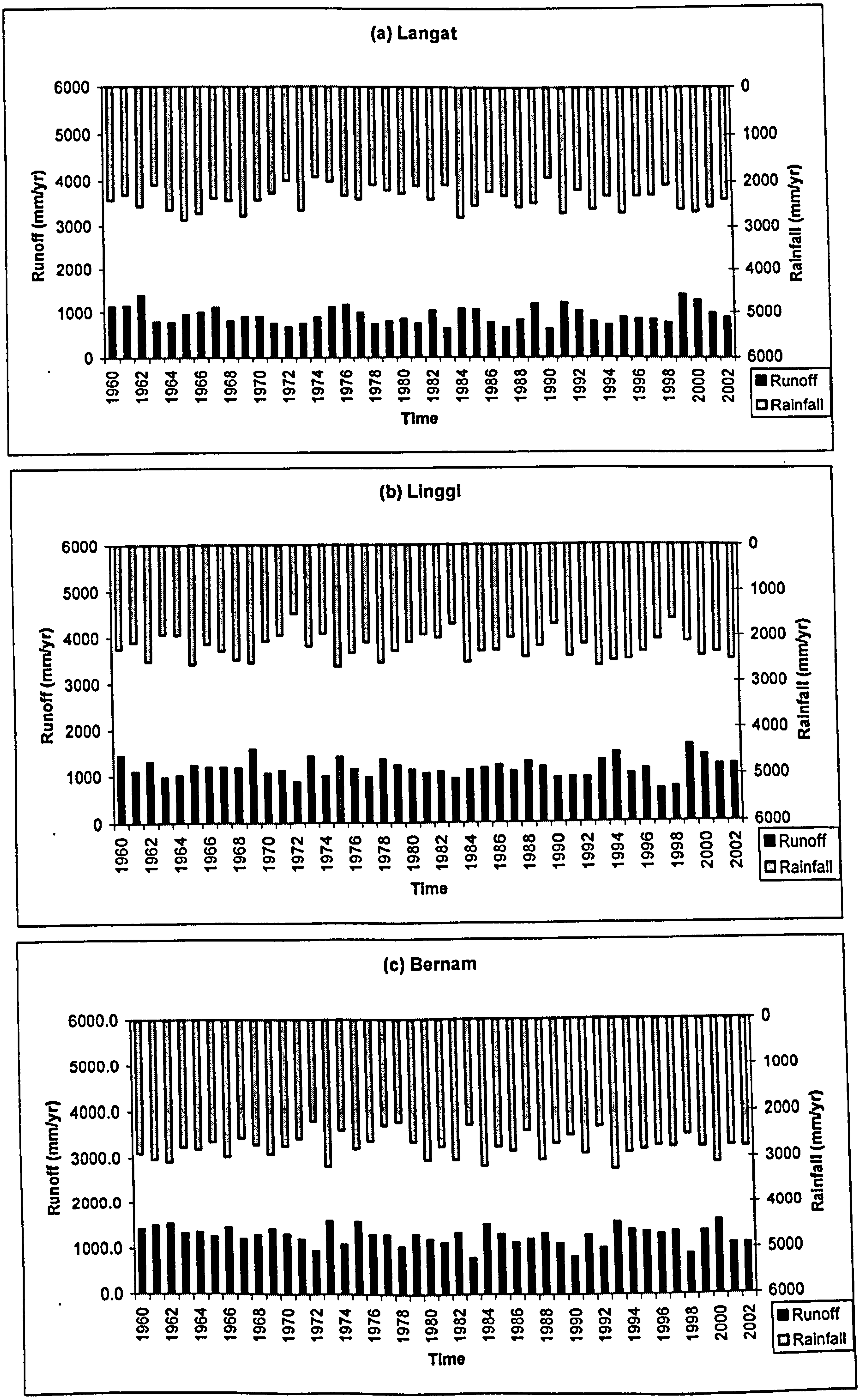


Figure 6.22: Rainfall and runoff long-term trend (annual data), 1961-2002

In terms of the relation between the runoff volumes received by each catchment outlet, Langat recorded only 60% of the runoff received by Bernam, reflecting lower rainfall in Langat. Linggi recorded almost the same amount of runoff as Langat (97%), though its response was quicker due to its smaller size (**Figure 6.23**). In terms of the relation between the outlet and upstream, Langat and Linggi nearly have a 1:1 relation where all of the runoff from upstream flowed out the catchment. This shows that there is no sign of water abstraction/transferral via a pipe to supply areas outside/inside the catchment, which could cause a lower base-flow and affect the quality of the water (**Figure 6.24**).

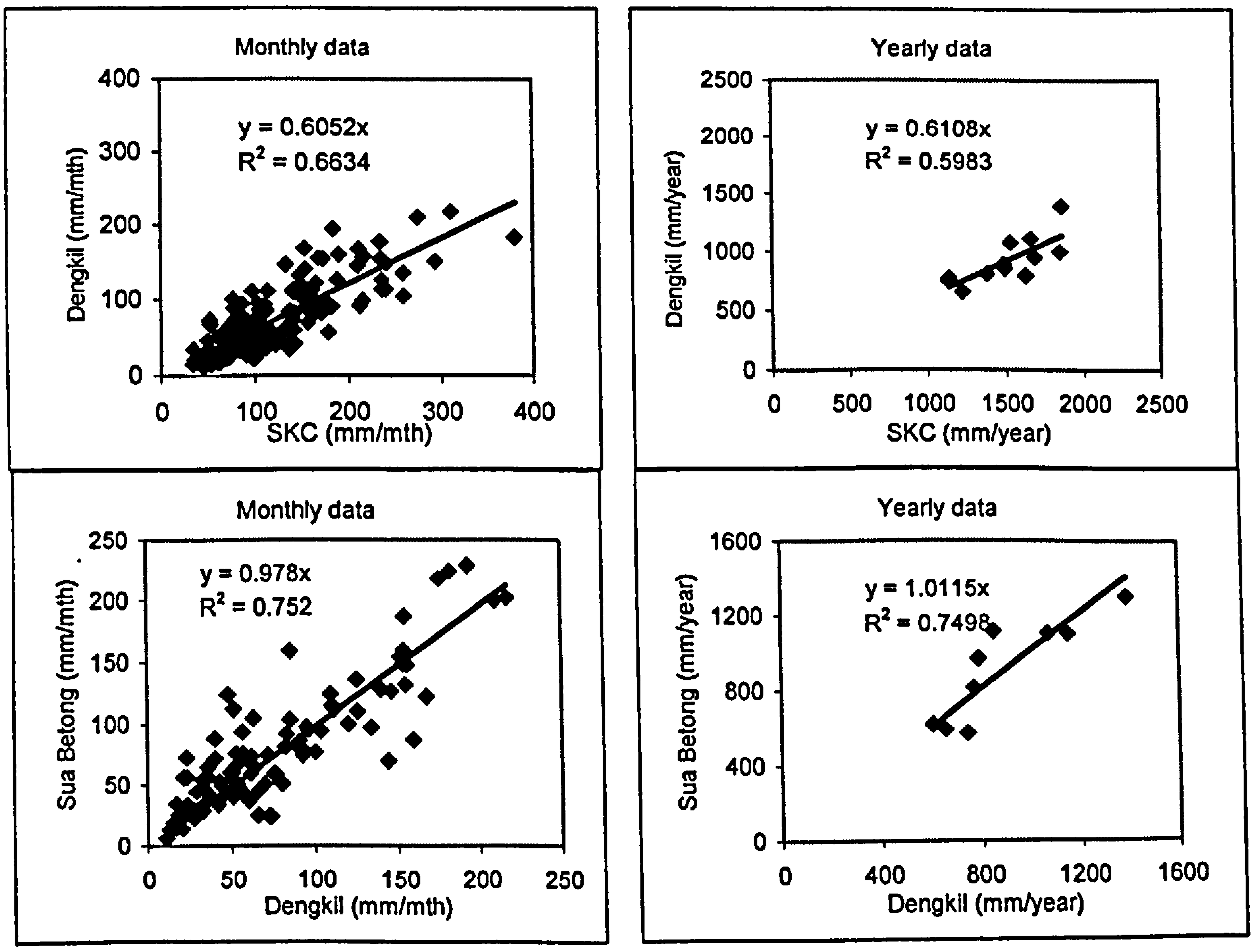


Figure 6.23: Runoff relation between all three catchment discharges, 1961-2002 (selected years – with complete monthly and yearly data only)

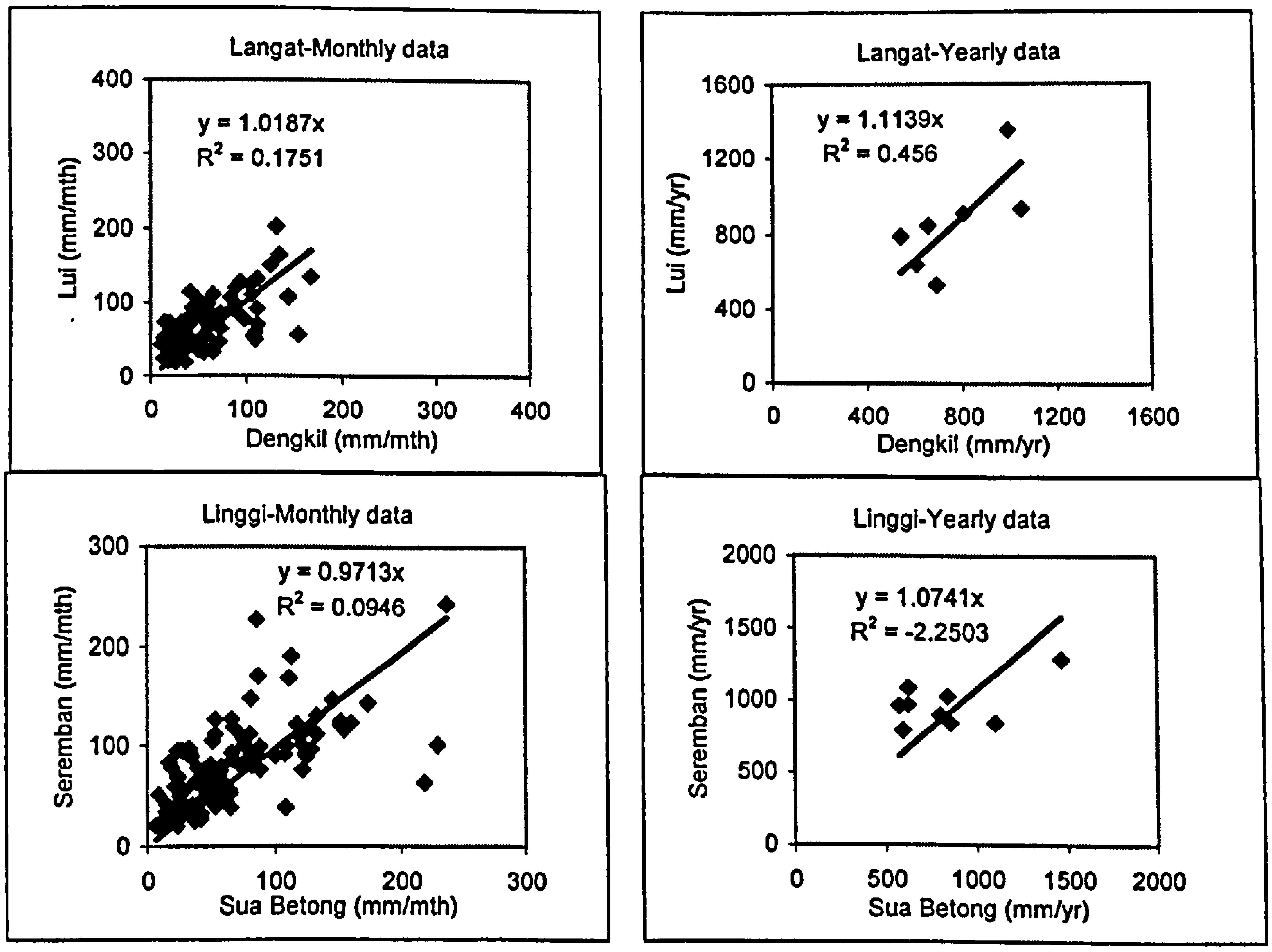


Figure 6.24: Langat and Linggi: Outlet-upstream runoff relation, 1961-2002 (selected years – with complete monthly and yearly data only)

In the Bernam catchment, there are some difficulties in understanding the runoff response recorded at the SKC outlet, since it has a major trunk river (Bernam) and a large tributary (Slim) that join just before SKC. Both of the rivers will play a significant similar stream close order (7 and 6), which could bring a similar amount of runoff. The difficulty is about how to get a possible discharge/runoff for the right trunk (Bernam). In this case it is based on the simple differentiation between the data at SKC and Slim (left tributary) for the same period of record. The problem was that the Slim records are very sparse, so it would not be possible to calculate reasonable discharge data for the right trunk. This is important since the right trunk will be involved in many development plans near the city of Tanjong Malim. As the SKC recorded discharge data for both trunks, it might not be able to give a close estimate of the land development impact from this area. However, from the limited data, it appears that the discharge record from the right trunk is relatively higher than the Slim tributary with 62% or a 60:40 ratio (**Figure 6.25**). This could give some clue as to understanding the rainfall-runoff response from the Bernam river.

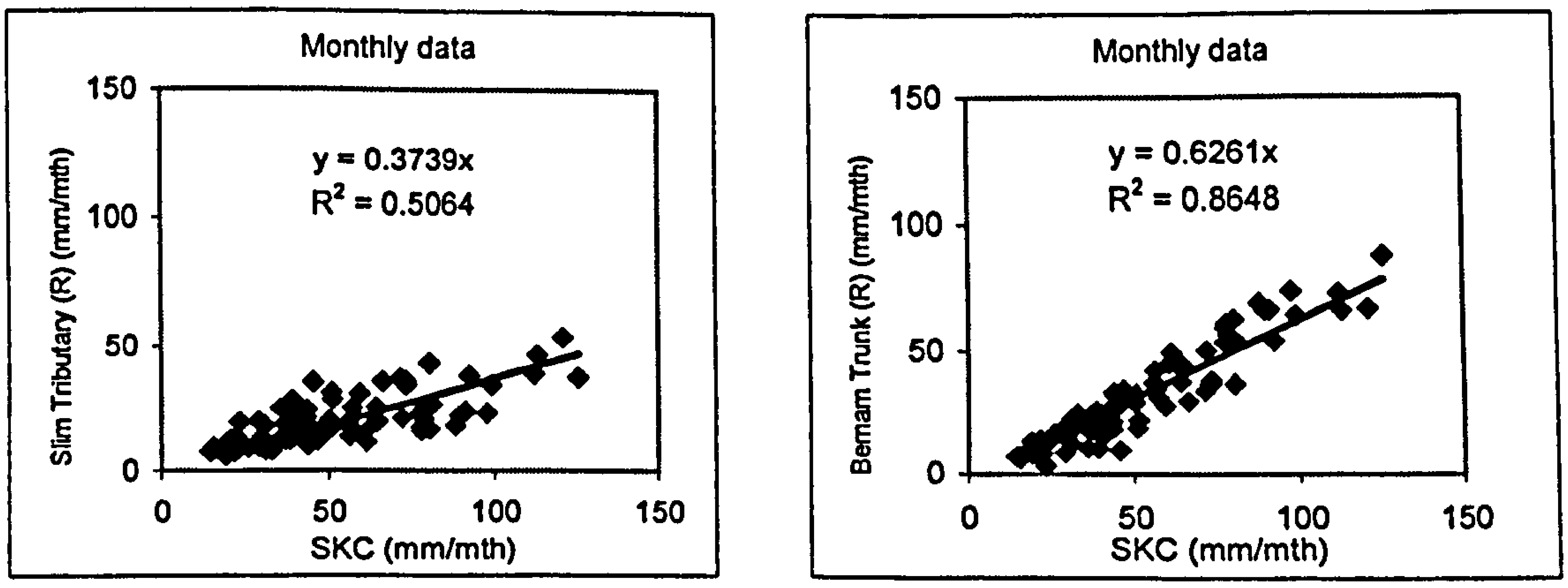


Figure 6.25: Bernam: Discharge volume received at SKC from two main trunks, based on Slim data availability (only 1967, 1969, 1970, 1981 and 1985)

6.4 Rainfall-Runoff relation

The establishment of relations between rainfall and runoff depends on the availability of the discharge record. In many developing countries, such as Malaysia, there are usually plenty of rainfall records, but continuous long-term discharge data is often limited. This becomes a fundamental problem for hydrologists studying water resources. Estimating runoff from available rainfall data depends on the timescale being considered (Shaw, 1994). Normally, for short duration records (hours), the rainfall and runoff relation will be confused and complicated to understand. As the interval in the record lengthens (monthly or annually), the relation becomes simpler (less influence from lag and seasonal factors) and a linear regression may be obtained.

However, this relation depends on hydrological factors, such as distribution of the rainfall, evaporation, infiltration and groundwater, and also physical characteristics of the catchments, such as catchment size and shape, geology and soil characteristics. The bigger the catchment, the more complex is the rainfall-runoff relation. As the nature of the data obtained from DID would not allow for hydrograph separation of quick-return flow (from the effective rainfall after the surfaces and soils are saturated) and base-flow (contribution from groundwater), both were included as lumped runoff for the study. This is expected to cause complications in the rainfall-runoff relation, especially where base-flow maintains the runoff level in months with low rainfall.

6.4.1 Data distribution test

Prior to the rainfall-runoff analysis, the dataset underwent a test for data normality using the Kolgomorov-Smirnov test statistic. From the test output, all monthly data for all catchments were not normally distributed, having a right-skewed distribution, but the annual data were normally distributed (**Table 6.13**). Since data transformation is common in hydrological studies, the monthly data were transformed using base-10 logarithms. However, the output from the normality test revealed that only the runoff data had become normally distributed, not the rainfall. This again shows that the monthly rainfall data was exposed to spatial and temporal variation, which in this case can be attributed to the effect of the monsoon seasons. Based on analysis for short transformed data, there is no indication of an improved relation. Therefore, for the rest of the rainfall-runoff analysis, the original data (without transformation) have been used, even though the transformation data could normally improve the relation between the two measured variables.

Table 6.13: All catchments: the statistical properties of the normal distribution test for monthly and yearly rainfall and runoff data

Station/	Variable	Data	Period	Transformation	Test of Normality (Kolgomorov-Smirnov)			
Catchment					Statistic	df	*Sig.	Normality
Dengkil	Runoff	Monthly	1961-2002	No	0.122	215	0.000	Not normal
(Langat)	Rainfall	Monthly	1961-2002	No	0.063	215	0.037	Not normal
	Runoff	Yearly	1961-2002	No	0.103	21	0.200	Normal
	Rainfall	Yearly	1961-2002	No	0.091	21	0.200	Normal
	Runoff	Monthly	1961-2002	Log base 10	0.043	215	0.200	Normal
	Rainfall	Monthly	1961-2002	Log base 10	0.084	215	0.001	Not normal
Sua Betong	Runoff	Monthly	1961-2002	No	0.112	276	0.000	Not normal
(Linggi)	Rainfall	Monthly	1961-2002	No	0.057	276	0.032	Not normal
	Runoff	Yearly	1961-2002	No	0.075	21	0.200	Normal
	Rainfall	Yearly	1961-2002	No	0.104	21	0.200	Normal
	Runoff	Monthly	1961-2002	Log base 10	0.049	276	0.200	Normal
	Rainfall	Monthly	1961-2002	Log base 10	0.079	276	0.000	Not normal
SKC	Runoff	Monthly	1961-2002	No	0.102	324	0.000	Not normal
(Bernam)	Rainfall	Monthly	1961-2002	No	0.065	324	0.002	Not normal
	Runoff	Yearly	1961-2002	No	0.075	37	0.200	Normal
	Rainfall	Yearly	1961-2002	No	0.104	37	0.200	Normal
	Runoff	Monthly	1961-2002	Log base 10	0.128	324	0.200	Normal
	Rainfall	Monthly	1961-2002	Log base 10	0.141	324	0.182	Normal

* Significance value of more than 0.05 indicates normality

6.4.2 Seasonal factors

The effect of the wet and dry seasons is significant, affecting the rainfall-runoff relation in a non-linear fashion. At the beginning of the wet season, the first storm is normally going to wet the soil to restore soil moisture storage, apart from some interception due to the soil's very high permeability, thus causing less water flow out of the river system. In addition, convective rainfall often occurs in the afternoon with high intensity, but is localised. It rarely extends over the entire catchment and rarely exceeds one hour in duration (Desa *et al.,* 2001). This condition will cause a lot of variation in the rainfall data and the hydrograph response also differs from one storm to another. The area of the catchment contributing runoff may vary even in a small river. Sometimes, it will be the upper part of the catchment produces more runoff, at other times the lower part or one side of the catchment. The data distribution shows considerable scatter, and includes cases where the runoff is greater than the rainfall in a month. This influences the value of the regression coefficient. This may be a function of several reasons, such as delayed runoff (lag) and urbanisation.

In order to understand the problem, a small sub-catchment, with an outlet at Seremban, in the Linggi catchment, was chosen (**Figure 6.26**). The figure demonstrates the nature of the dataset where there is some points lie far from the regression line. The envelope A shows - where runoff values was greater than rainfall – is likely to reflect lag/delayed runoff flow arising from ground water storage and base-flow from the previous wet month. This happens at the end of wet months, i.e. November and December or April and May. Runoff-rainfall ratio for wet month of November and December is 20%, slightly lower than dry month of January-February with ratio of 28%, showing the influence from lag runoff. However, the amount of runoff contribute from January-February month is significant different (<0.001) (paired *t*-test) from November-December as a function of less rain receive. In this study, there is no evidence to relate with contribution of base-flow during dry months from the continual output of urban waste water discharge from households in the urbanised catchment.

In Envelope B, there are some data points that belong to very wet months, normally November and May, when the soil was saturated and caused a very high flow. As all of the related data points belong to those months in 1980-1982, there is no clear indication that the high flow was caused by the land development/urbanisation programme - where infiltration was lower due to soil compaction and development of low permeability surfaces - can cause an increase in quick-return flow. Envelope **C** suggests that some of the rainfall occurs in a dry month (June) and in the first month (September) of a wet period where infiltration into the soil is high due to a prolonged preceding dry period and the level of evaporation on hot days is also high. Finally, Envelope **D** reflects typical dry months with less rain and with runoff volume attributed to base-flow. However, by including the data points from Envelopes **A** and **B** (wet months), the runoff-rainfall ratio does not change, remaining at 27%, but the R^2 increases to 0.45, with standard error of 26.10 mm/mth.

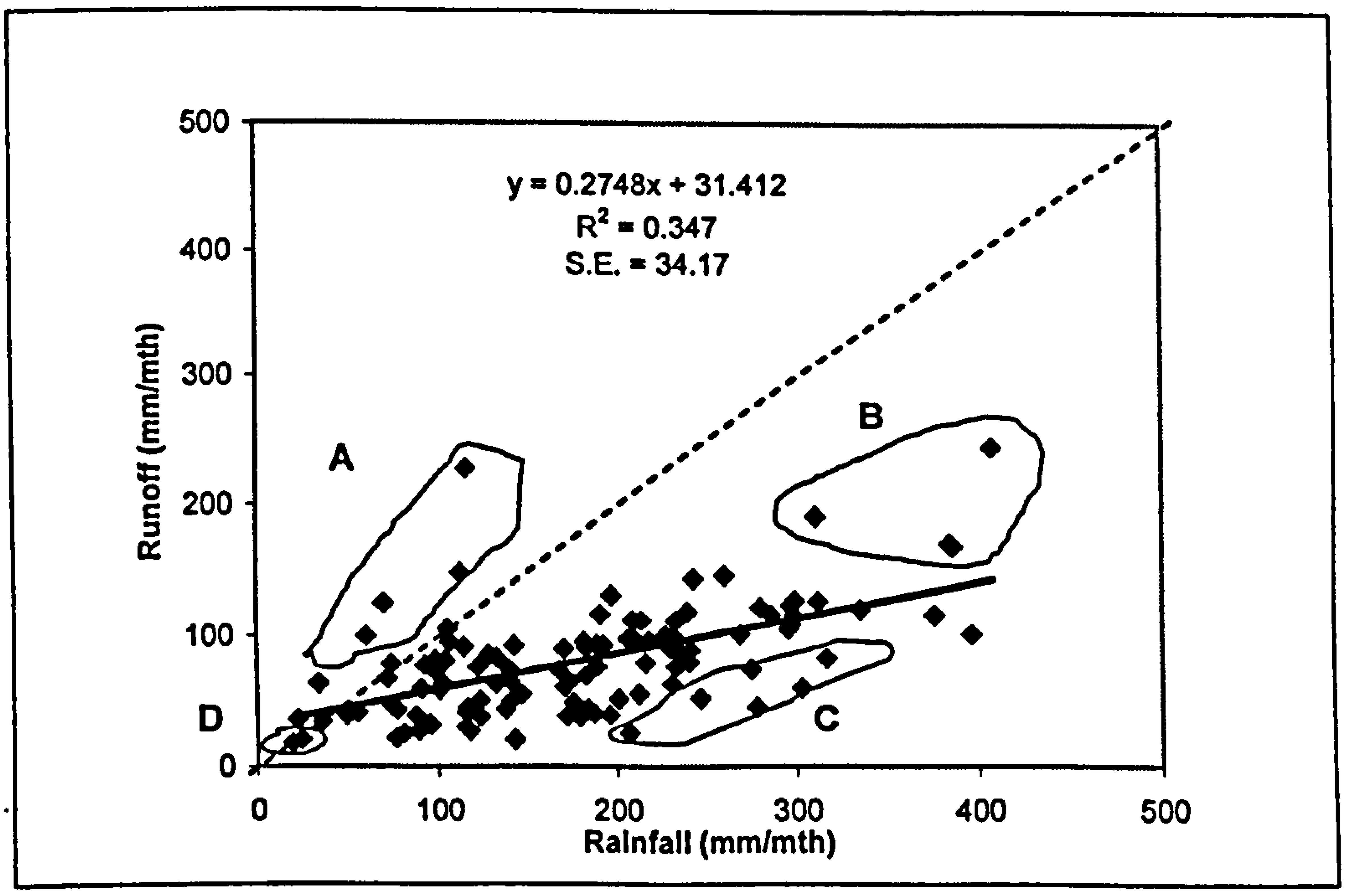


Figure 6.26: Sub-catchment Seremban (Linggi): monthly rainfall-runoff relation (1980-1994) due to various seasonal effect – all months
(See text for explanation of Envelopes A, B, C and D)

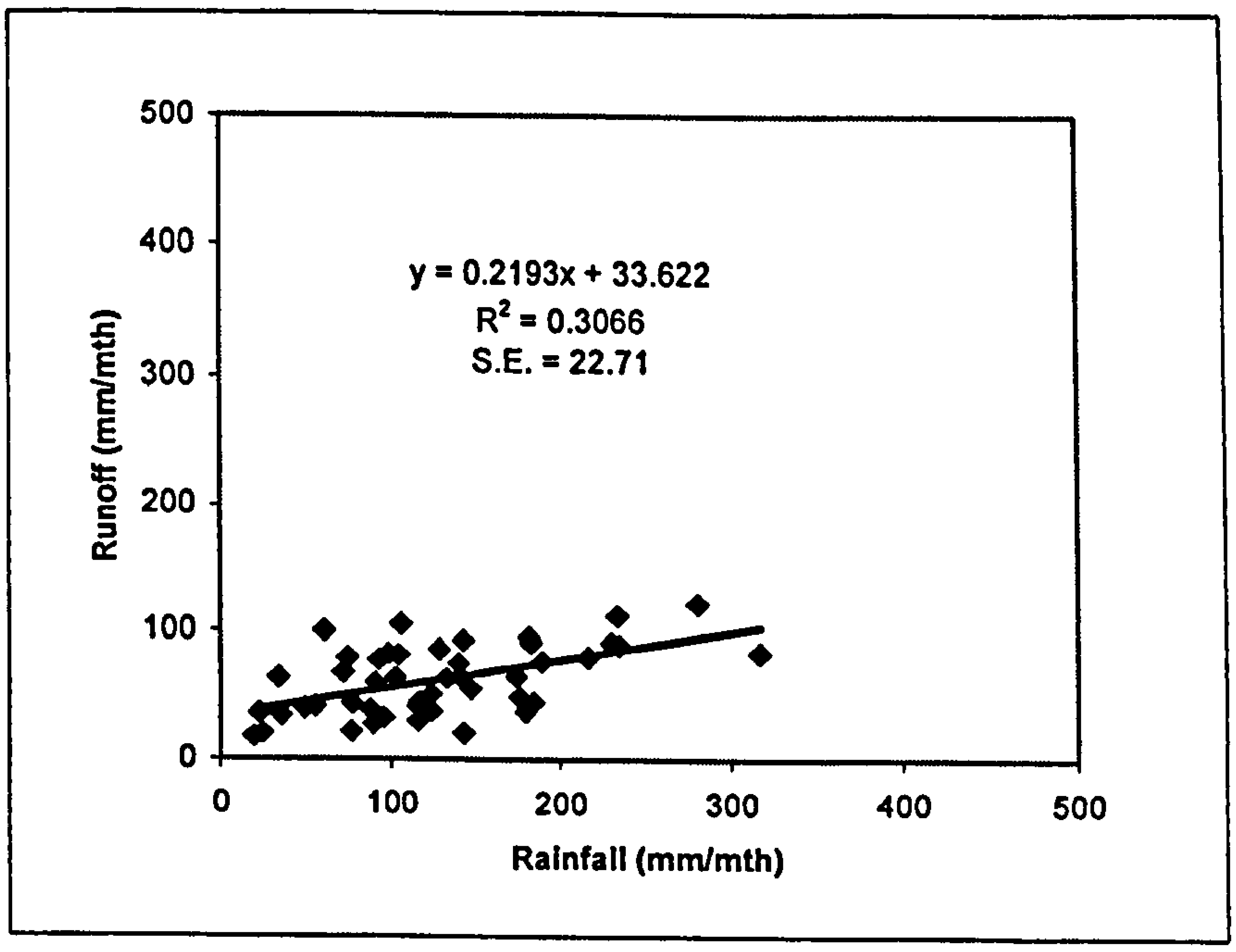


Figure 6.27: Sub-catchment Seremban (Linggi): monthly rainfall-runoff relation (1980-1994) due to dry months effect

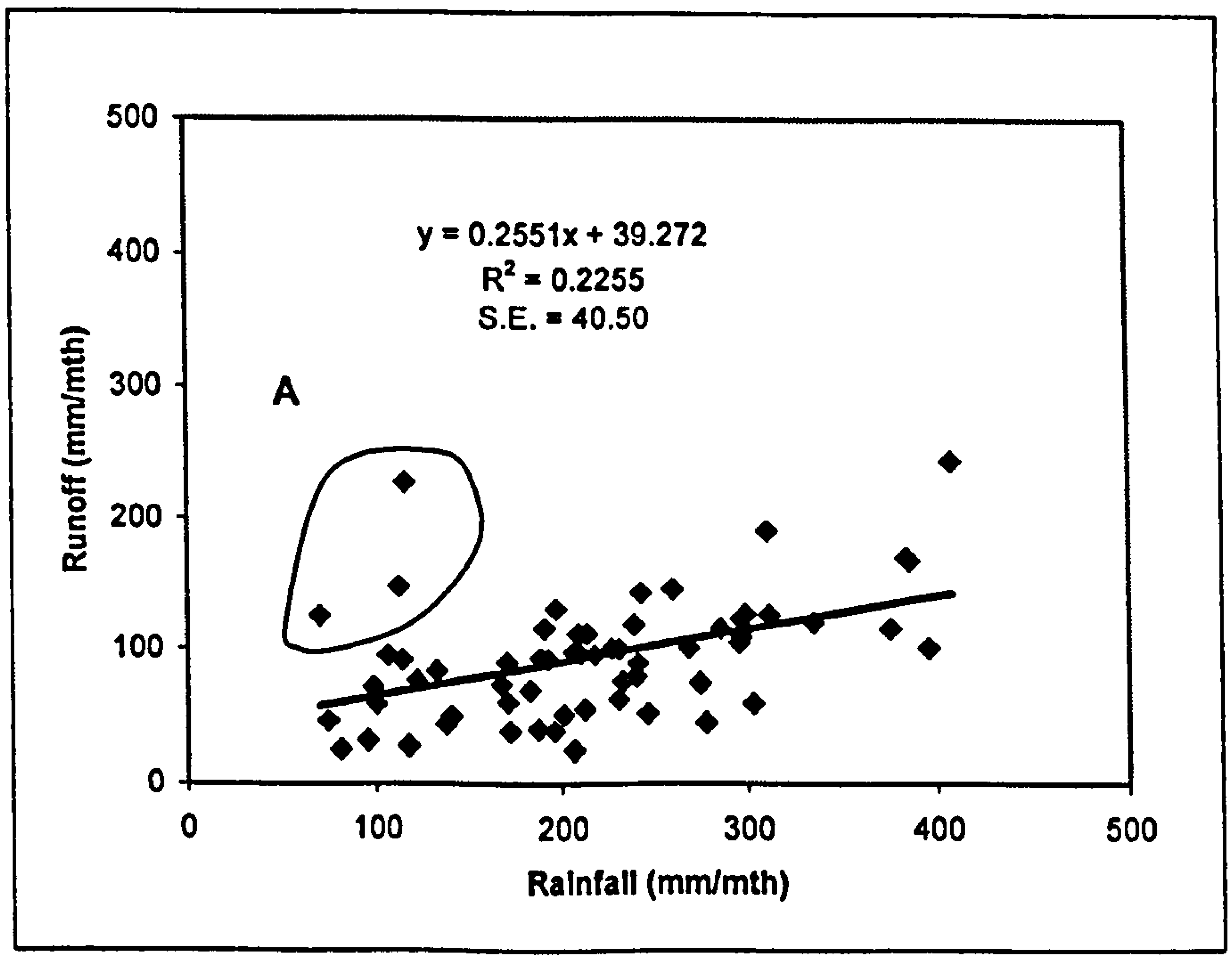


Figure 6.28: Sub-catchment Seremban (Linggi): monthly rainfall-runoff relation (1980-1994) due to wet months effect

The variation in rainfall between seasons clearly affects the scatter of the data, which causes the runoff-rainfall ratio to remain low, but remains within a typical range for tropical areas. The separation between dry months and wet months shows less scatter for the dry months (**Figure 6.27**), but there still is an impact of lag runoff from

November and December for the analysis of the wet months (**Figure 6.28**). If the data points within Envelope A are left out, the coefficient (25 %) will increase to 34% with $R^2 = 0.45$. As the wet and dry seasons prevail twice within a year, the differences in rainfall catch are obvious, but it is difficult to define the dry months in term of runoff. This is because the influence of heavy-rainfall months in the wet seasons produces an elevated water flow in the next month. Although the scatergraphs for dry months is less scattered, it is still affected by the higher runoff from the previous wet month. Ruslan (1995), in his study in Penang's catchments, also found that the high rainfall-runoff ratio - even with a low rainfall - is due to carry-over base-flow from the previous rainy month. The initial analysis, based on the daily runoff data, shows that the lag is about a day for the study catchment and less than a day for the small sub-catchments Lui in Langat with an area of 73 km^2 (**Figure 6.29**).

In the case of monthly data, the higher base-flow that extends beyond the original rainy month will cause an abundant runoff in the later month where it prolongs recession. It would suggest that, without hydrograph separation, the use of monthly rainfall-runoff data could not provide much information on the actual response, as the data is exposed to large a variation. Despite that, the ratio has not much change between all data and wet and dry data for that period of study. Therefore, the monthly data could also provide additional information for annual data in order to detect the changes in the runoff ratio due to land development.

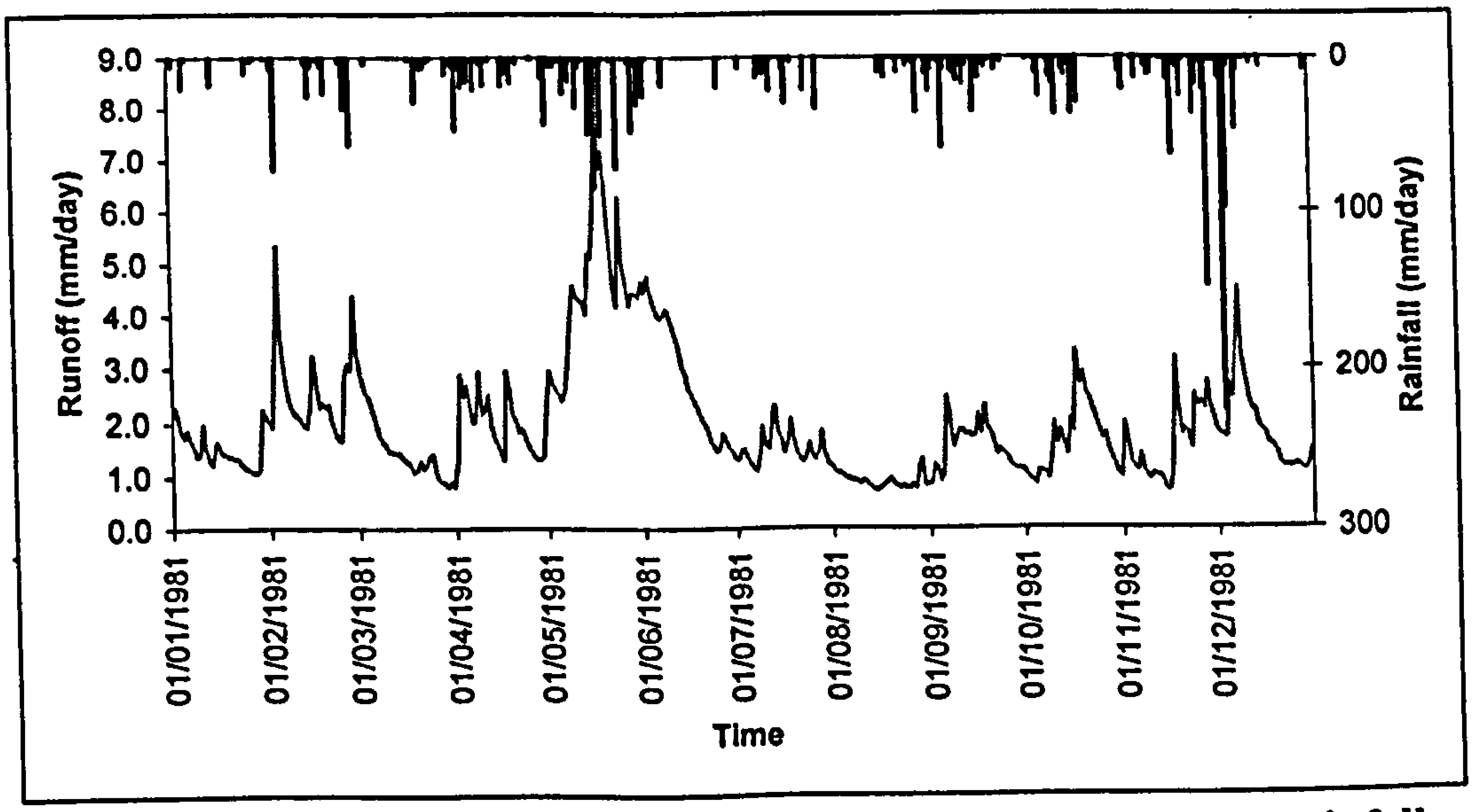


Figure 6.29: Sub-catchment Lui (Langat): relation between daily rainfall and runoff data 1981 for lag detection

All these factors indicate the difficulties faced in understanding the nature of the data and provide reasons for variation of the rainfall-runoff coefficient. There is a clear indication that rainfall-runoff can be tackled for gross-time intervals of 12 months using annual data. By adopting a coarse time interval all season/conditions within a year are represented, but it reduces the prospect of fine-tuning the rainfall-runoff analysis to reveal impacts from land use change. A straightforward linear relation is expected with less scatter around the regression line. All these data were then used to establish the rainfall-runoff coefficient based on the development period, which will be used in further investigations into the effects of changes in land use. The level of confidence will be increased when the longer data time spans are used. This is an attempt to understand the processes acting within the system through simplification. The rainfall-runoff relations based on monthly data were not discarded. Despite limitations, it can provide some basic general long-term ratio, which can be used to recognise the impact of land use on runoff within study catchments.

6.4.3 Rainfall-Runoff ratios for complete and partial data

Figures 6.30-6.32 show the annual rainfall-runoff coefficients for complete and partial runoff records for all catchments. The partial runoff records seem to have a considerably higher coefficient of rainfall-runoff than the complete record. There is a significant difference (paired *t*-test) between them for Langat (p = 0.004), but not for Linggi (p = 0.263). This is due to the influence from available datasets within a year that contain much data from wet months. It is also possible that it contains a record within a dry month but received runoff carried forward from rainfall in a previous wet month. Partial records also could give a lower ratio when the available data only contains data from a dry month. Within a complete record, there are few years where the runoff-rainfall ratio is subject to 'data complication' and is treated as an outlier. For example, in Langat (**Figure 6.30a**), the La Nina prevails in 1973 and 1984, but the ratio did not reflect either event (remaining at a low value), but higher rainfall is observed in 1984. In 1972, the low ratio is due to the influence from El Nino. In Linggi and Bernam, the opposite situation occurs, where the higher ratio in 1963 and 1999 did not reflect the El Nino event which prevails during 1963 and 1997-1998 (**Figures 6.31a** and **6.32a**). The lowest ratios for Linggi in 1978 (13%) and 1979 (16%) are due to extremely low runoff values, which fall below the long-term mean of 84 mm/mth. The ratio increases after severe 1997-1998 El Nino periods is counter to expectation that the rainfall event - especially in wet months - should wet the soil and restore the water-table level after long droughts, therefore reducing the runoff coefficient. As the complete record did not cover most of the development period in Langat and Linggi, the partial record will be examined if it can provide some indicator.

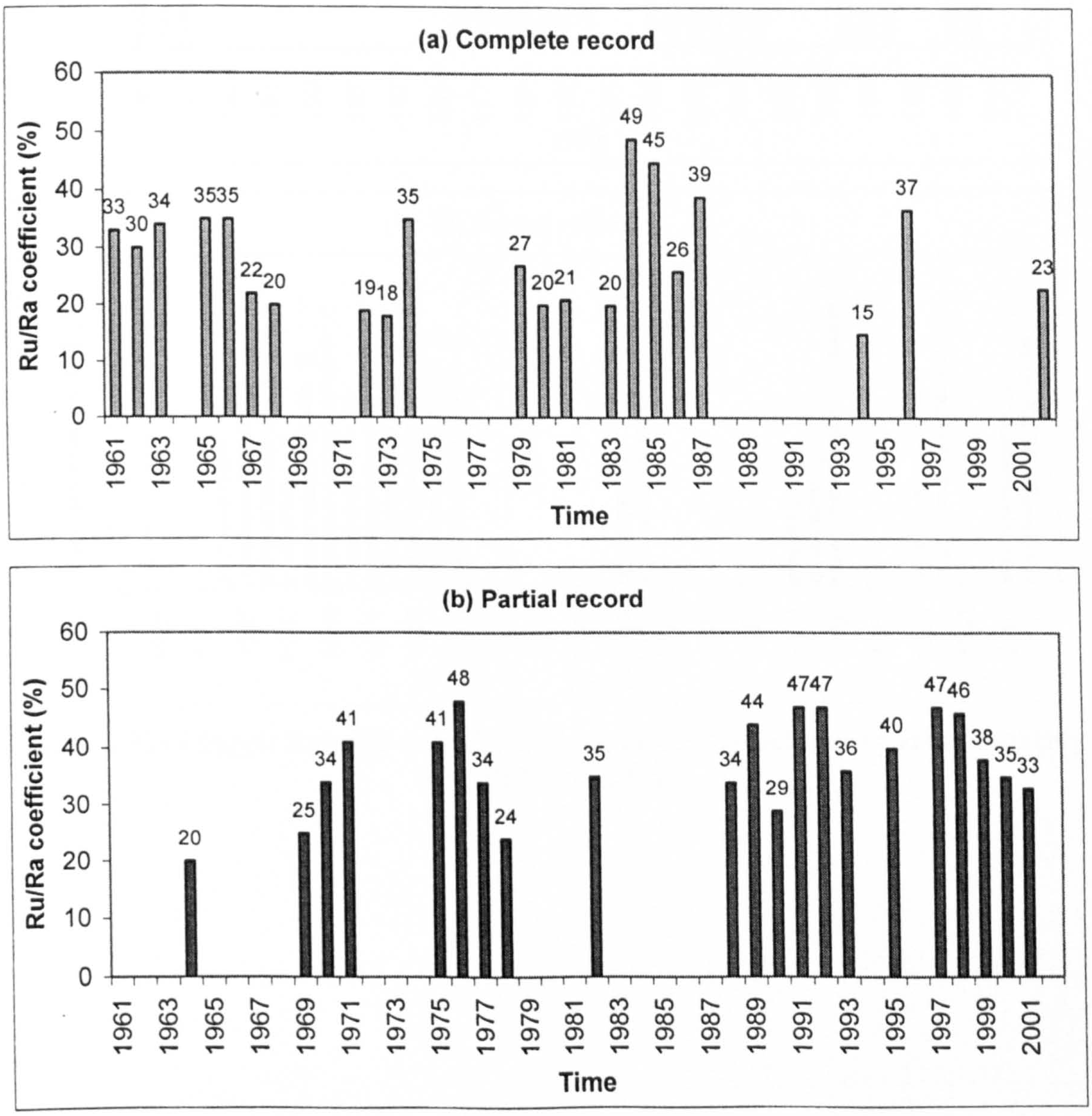


Figure 6.30: Langat: Rainfall-runoff coefficient for complete and partial monthly records (1961-2002)

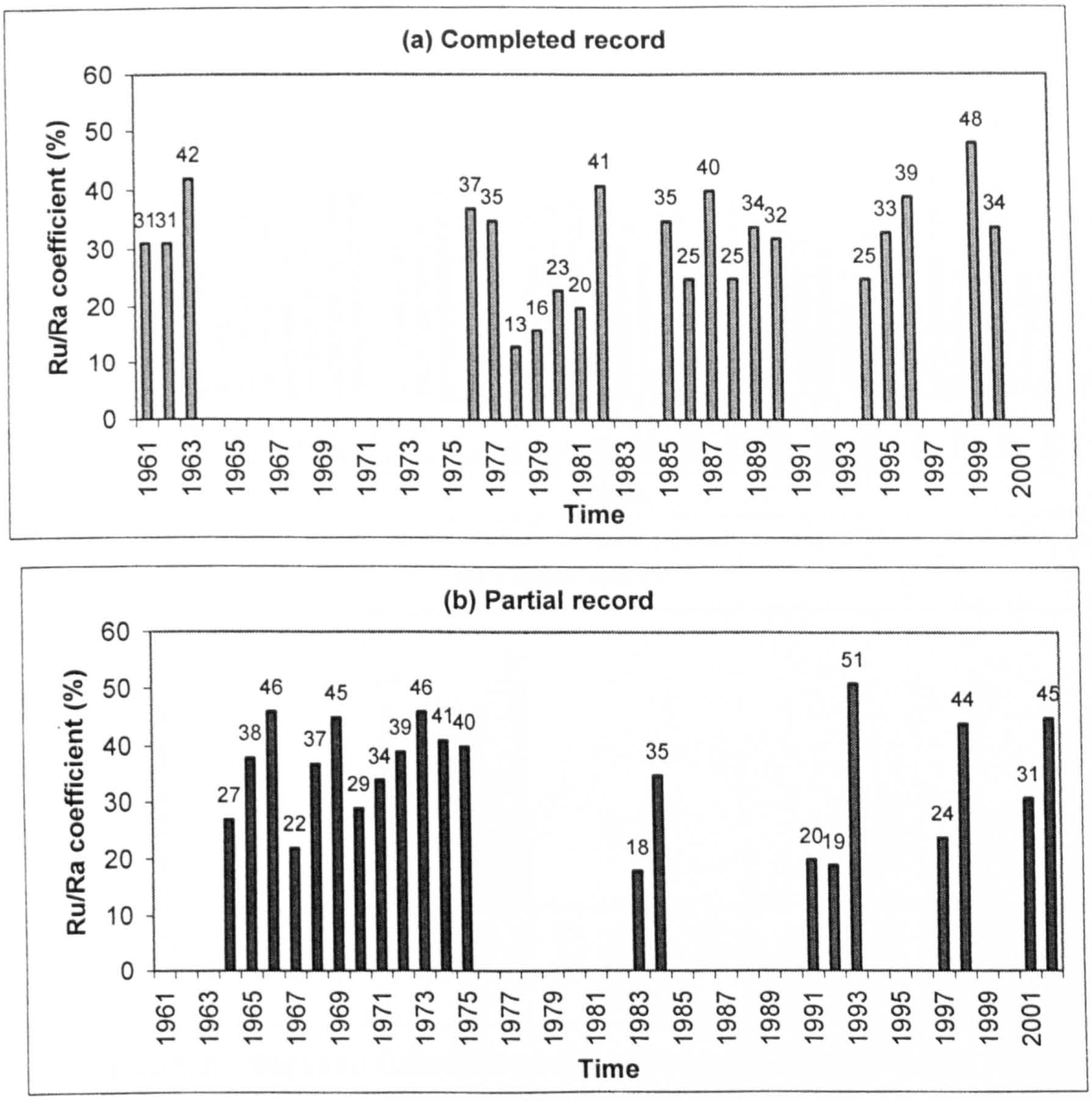


Figure 6.31: Linggi: Rainfall-runoff coefficient for complete and partial monthly records (1961-2002)

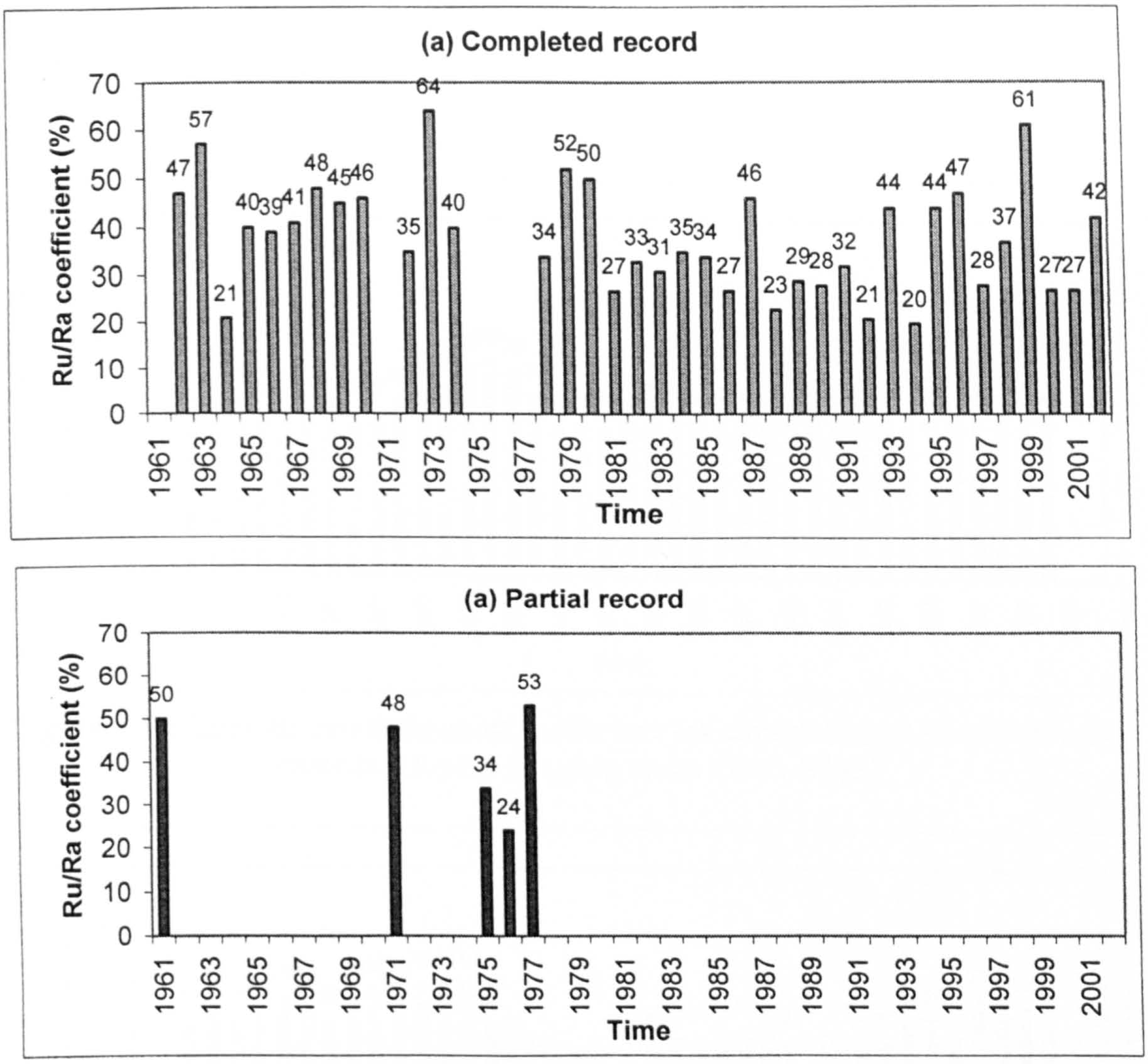


Figure 6.32: Bernam: Rainfall-runoff coefficient for complete and partial monthly records (1961-2002)

In order to compensate for the non-availability of data, a five-year interval running mean analysis was carried out in order to provide some information about the effects on the rainfall-runoff ratio (**Figures 6.33-6.35**). It is hoped that this five-year interval will help cope with any extreme values that arise from partial or complete records, and that the impact of major land development could be detected. Both Langat and Linggi have a uniform long-term rainfall-runoff ratio. A paired *t*-test reveals that there is significant difference in the mean ratio ($p = 0.910$). The higher ratio for the period of 1975-1977, 1989-1993 and 1997-2000 in Langat and 1964-1975 in Linggi is still caused by the higher ratio from the partial record. Meanwhile, the lower ratio during 1977-1981 is caused by lower runoff data in 1978-1979. In Bernam, the higher ratio between 1963 and 1975 is genuinely due to a higher rainfall catch before the equipment change in

1974. The lower runoff between 1987 and 1993 is due to larger variations in the rainfall and runoff dataset, as there is no significant indicator from land use change.

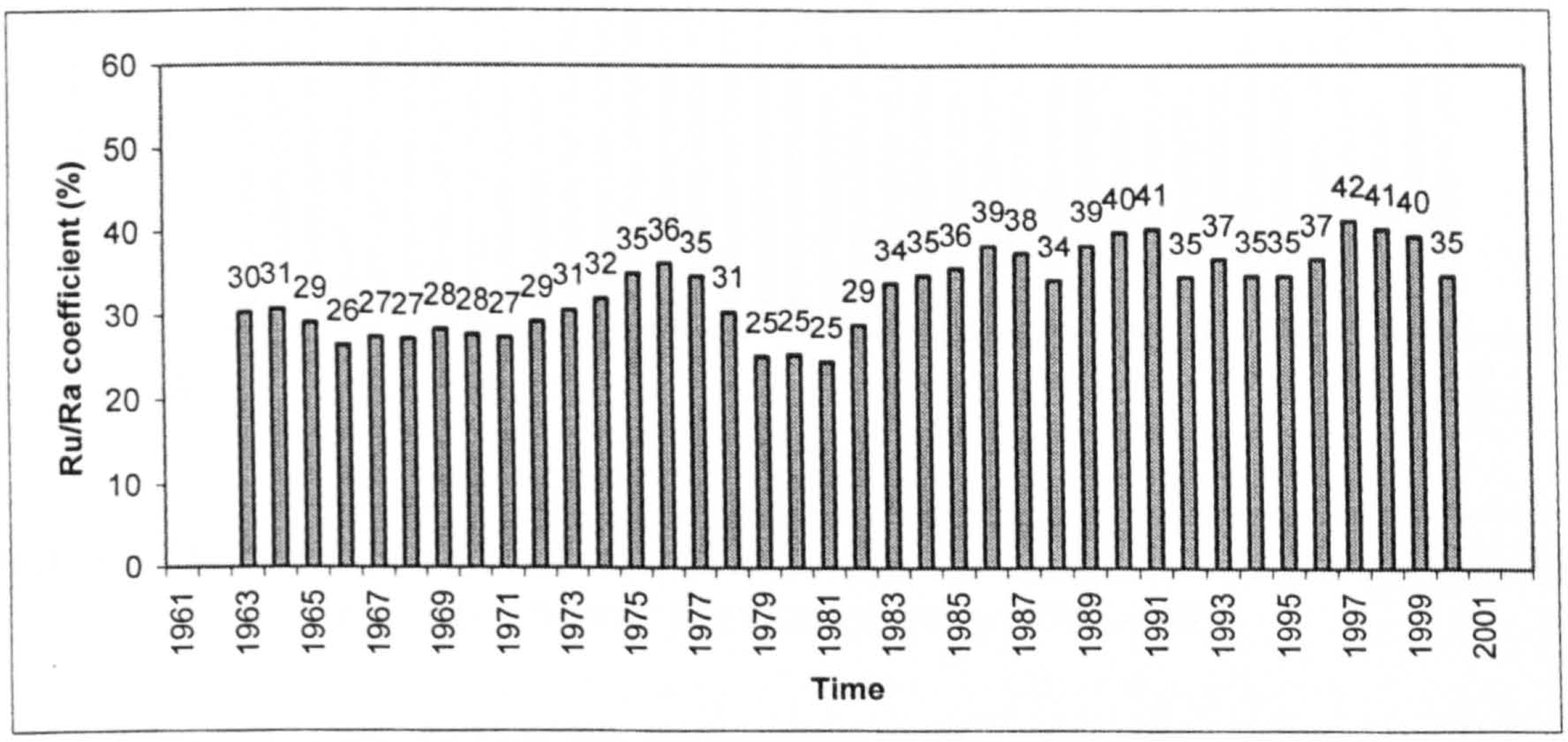


Figure 6.33: Langat: rainfall-runoff coefficient for complete and partial monthly records – 5-year running mean (1961-2002)

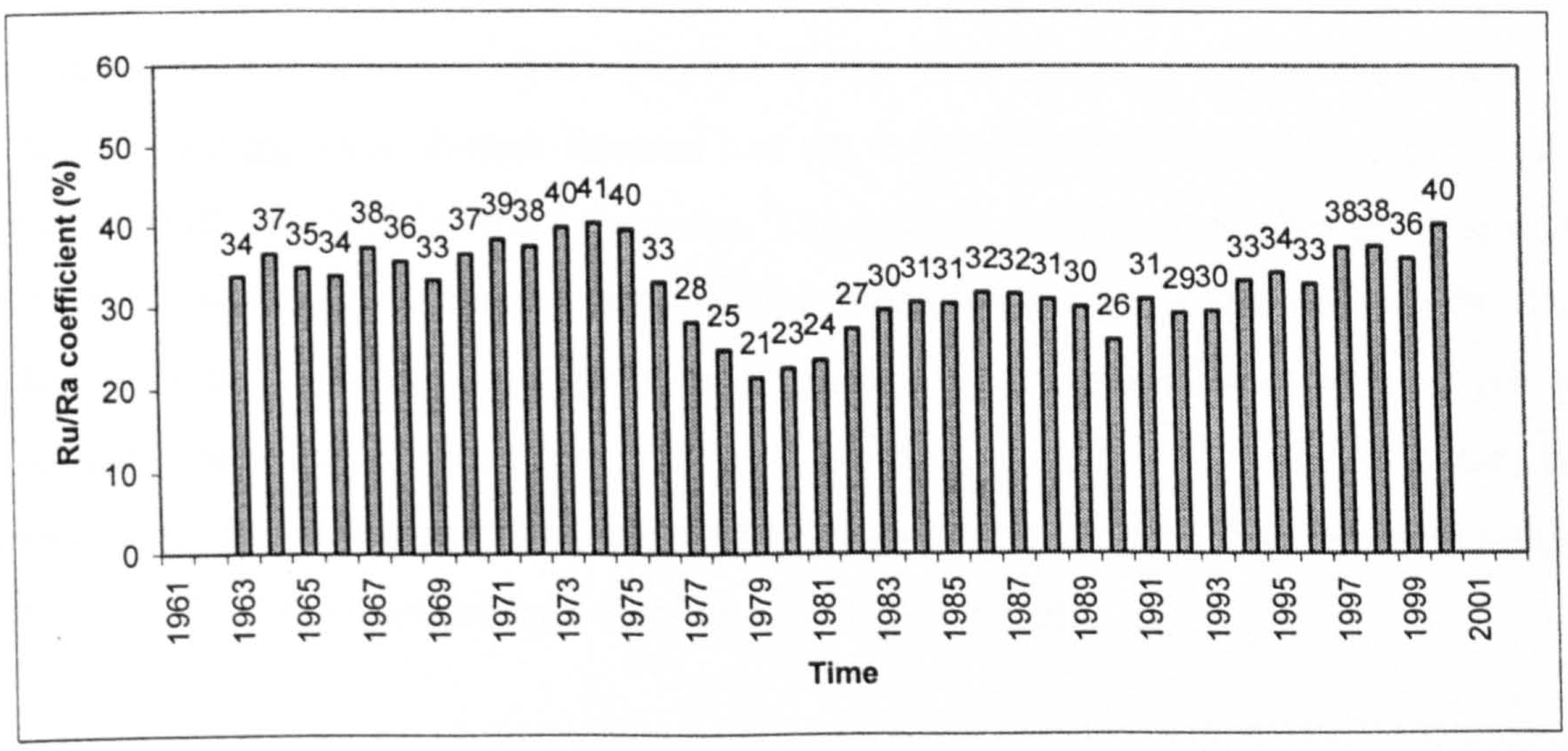


Figure 6.34: Linggi: rainfall-runoff coefficient for complete and partial monthly records – 5-year running mean (1961-2002)

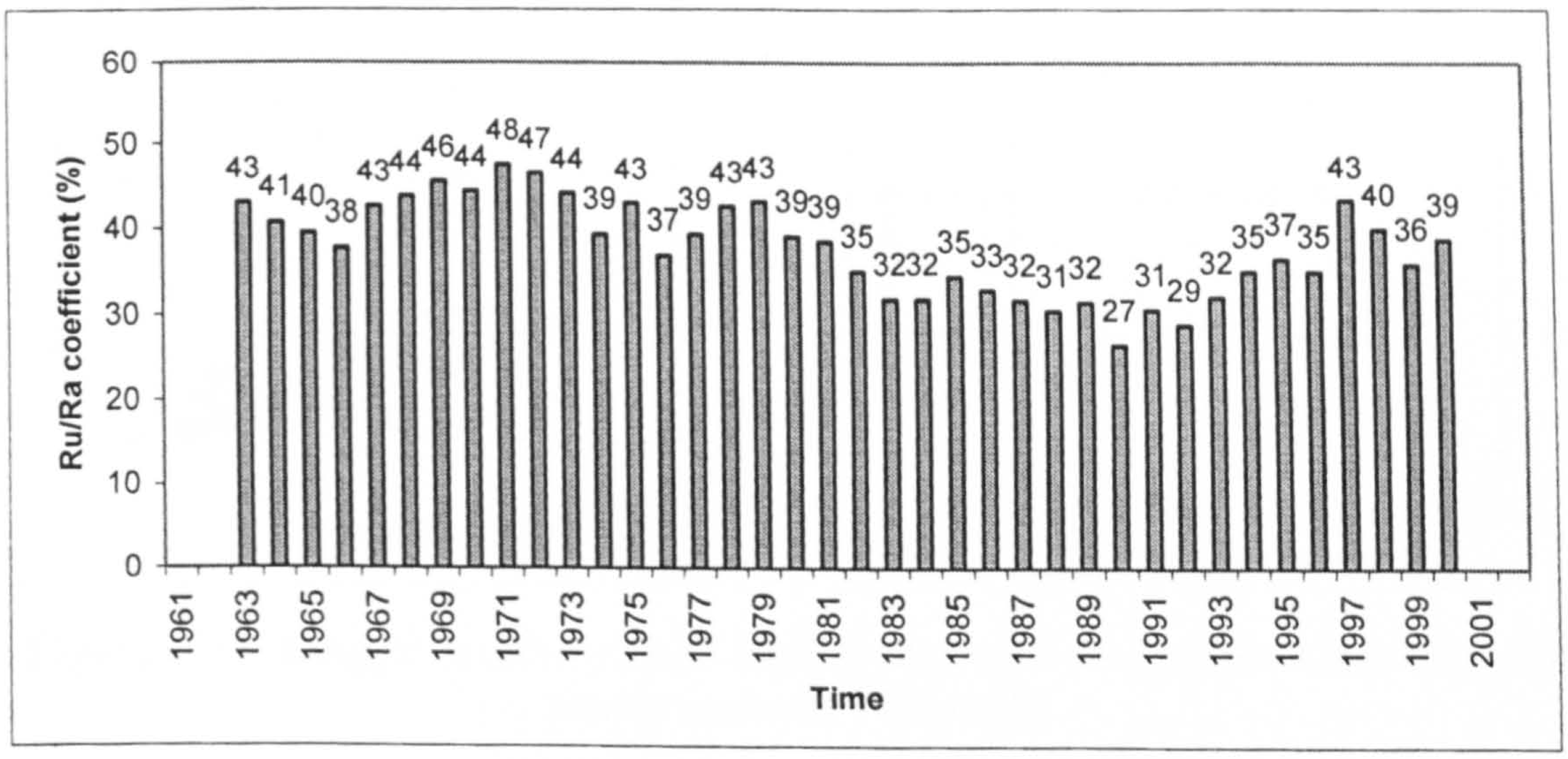


Figure 6.35: Bernam: rainfall-runoff coefficient for complete and partial monthly records – 5-year of running mean (1961-2002)

Based on the complete data set, the long-term monthly rainfall-runoff ratios reveal that Langat has 30% (**Figure 6.36**), whereas Linggi had slightly higher values (35%) due to a quicker runoff response in its smaller catchment (**Figure 6.37**). However, Bernam recorded a higher ratio with 39% (**Figure 6.38**). This figure is higher than those of Langat and Linggi even though Bernam has yet to be developed and this relates to the higher rainfall received by the catchment. The annual runoff ratios also show similar patterns. However, for Bernam it is quite high, which may have a connection with data quality control or some other physical element of the system that cannot yet be explained. The effect of variability in rainfall due to seasonal and spottiness factors are clearly show by the lower runoff recorded at all study catchments. The intercept values in this case do not reflect the base-flow level as it is too high.

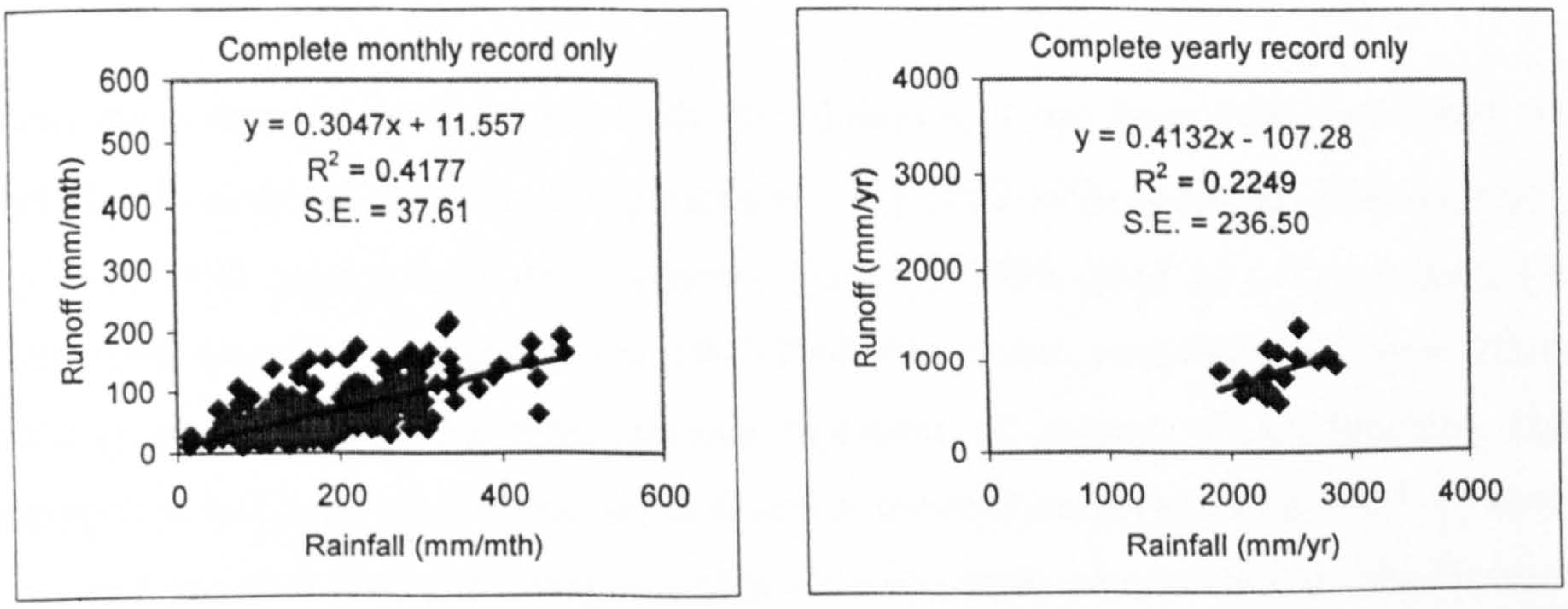


Figure 6.36: Langat: rainfall-runoff coefficient based on complete monthly and yearly records, 1961-2002

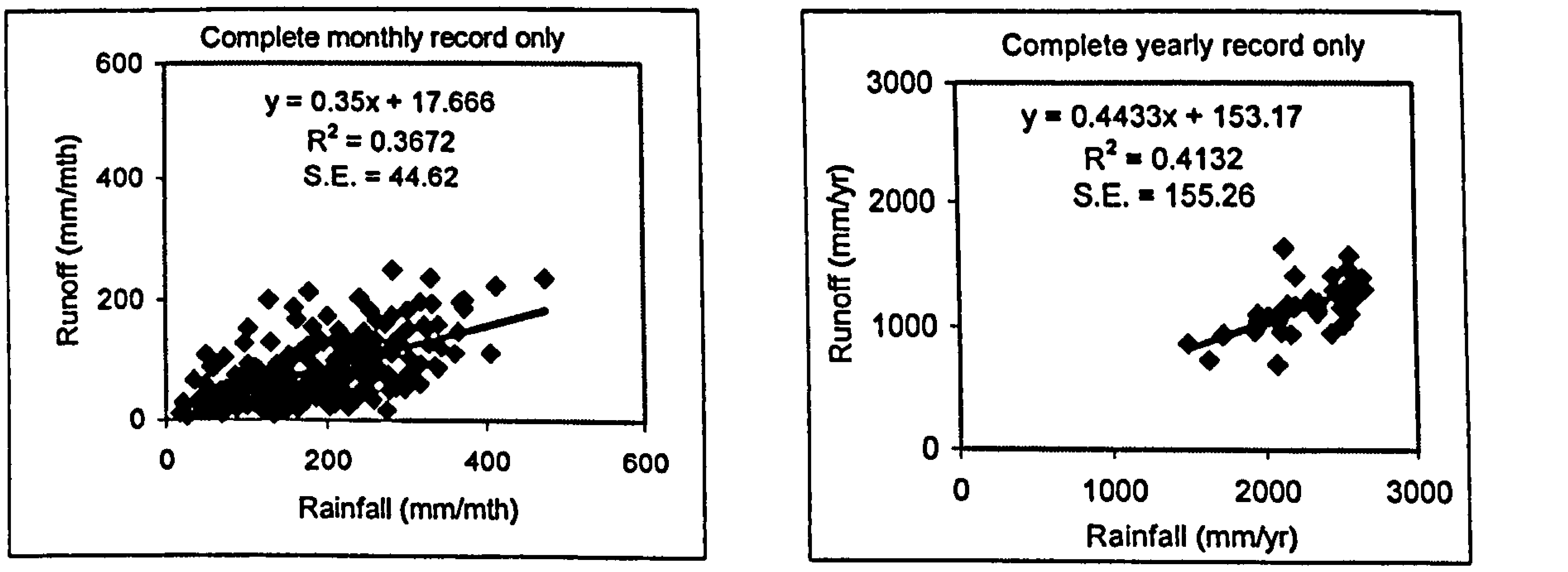


Figure 6.37: Linggi: rainfall-runoff coefficient based on complete monthly and yearly records, 1961-2002

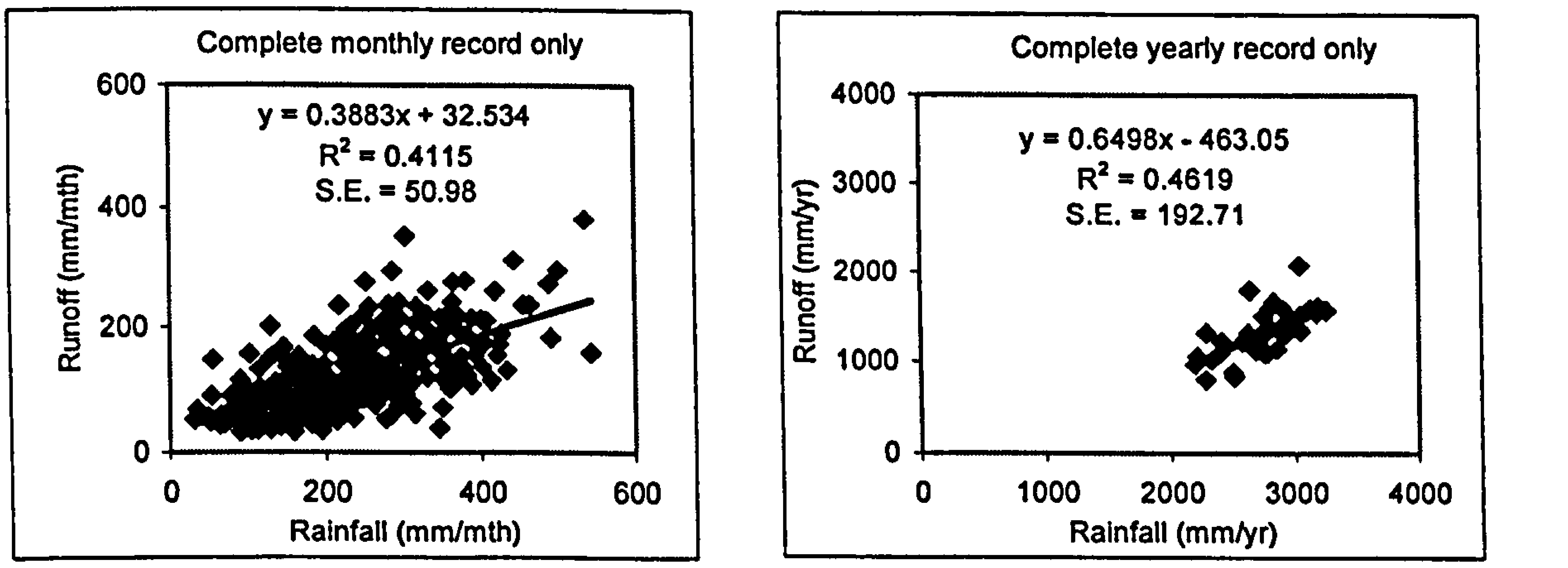


Figure 6.38: Bernam: rainfall-runoff coefficient based on complete monthly and yearly records, 1961-2002

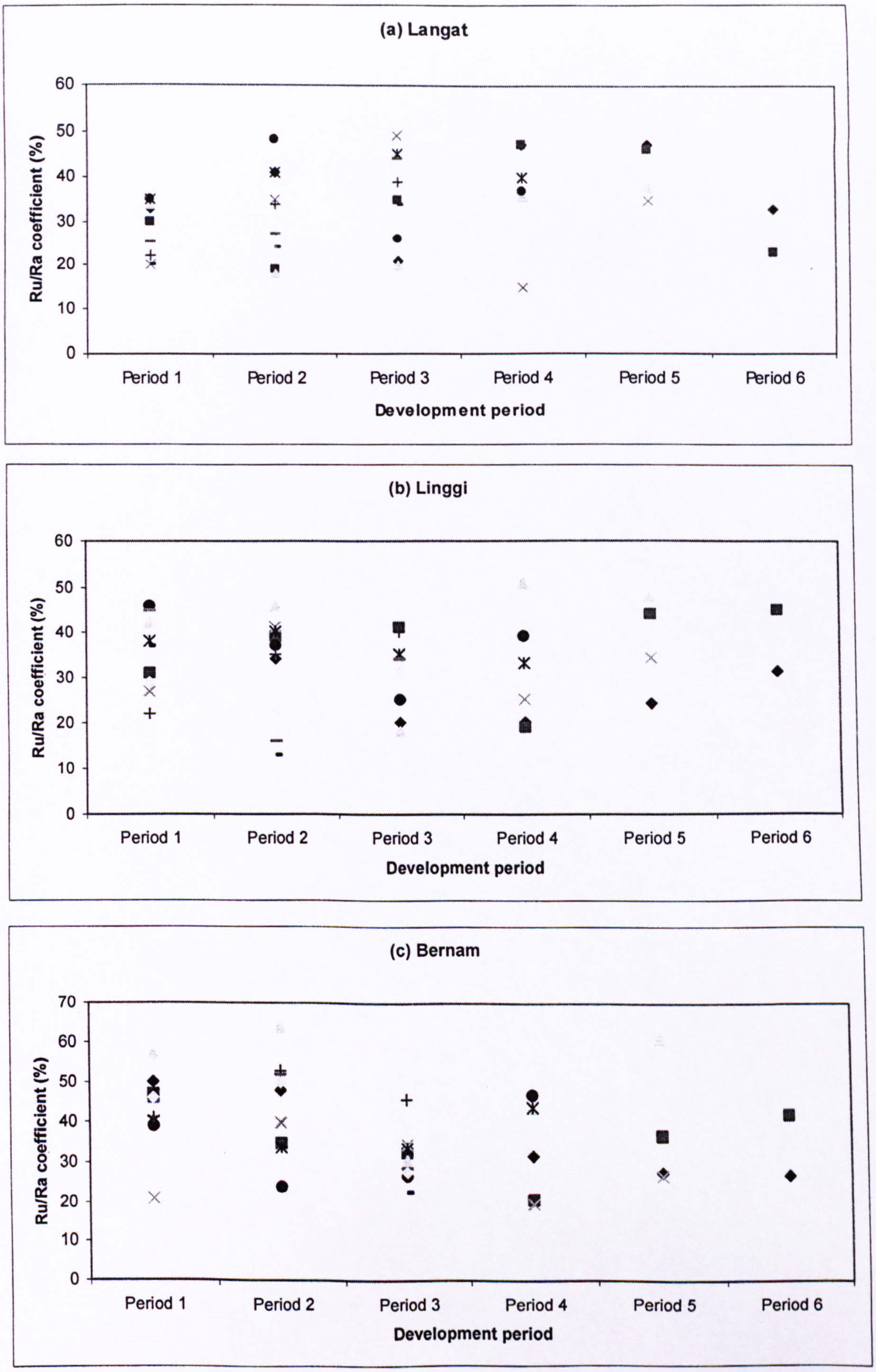
6.4.4 Relation between rainfall-runoff ratio and land use change by development period

From the economic development study for Malaysia, it has been recognised that six periods of development exist. The periods are; (1) 1960-1970 (early land conversion), (2) 1971-1980 (agricultural development), (3) 1981-1990 (start of urbanisation), (4) 1991-1996 (rapid urbanisation), (5) 1997-2000 (economic recession) (6) year 2001-2002 (post recession). As these periods represent all stages of development, this segregation has been chosen in order to examine the relation between the rainfall-runoff ratio and possible land use changes within all three study catchments. As the Bernam catchment has yet to be developed, Period 1 refers to an undisturbed phase, Periods 2 to

4 refer to agricultural development (conversion of native forest to crop trees), Period 5 remains intact, and Period 6 refers to the early land development for urbanisation.

Using both complete- and partial-month data for every year from 1960-2002, the comparison between those development periods has been established to detect whether the development has impacted upon the runoff (**Figure 6.39**). One-way ANOVA reveals that all study catchments have no significant difference in mean the runoff-ratio between development phases (p = 0.263, 0.324 and 0.422 for Langat, Linggi and Bernam, respectively). Furthermore, an analysis based on annual data was established according to the development phase. A similar result was found where there is no significant difference on mean runoff between those periods. The trend is clearly shown by the double mass curve analysis (**Figures 6.40 - 6.42**), where there is no significant change in slopes that can be related to the increase in runoff as a function of land-use development. This suggests that the significant conversion of forest to agriculture and urban areas has had no impact on the runoff-rainfall ratio.

In the periods 1960-1970 and 1971-1980 there were no changes in the runoff ratio for Langat catchment (maintained at 23%, **Figure 6.43**). Even the Langat catchment (situated in the most developed states since 1948 under the British Government) had been through early stages of forest conversion to agriculture and mining activity. As runoff data were not available before 1960, the situation prior to that date remains unknown. By 1971-1980, new tree crops (rubber and palm oil trees) had already achieved maturity, which takes about 8-10 years. The trees' canopy plays a role in intercepting the rainfall, while undergrowth protects the soil surface. An improvement of the drainage system would decrease the surface runoff and erosion rates, which, therefore, would decrease the suspended sediment yields to river system (Foster, *et al.*, 2003). Therefore, the effect of the land use changes on runoff contribution is expected to be minimal. However, both Linggi (**Figure 6.44**) and Bernam (**Figure 6.45**) show an increase in the runoff ratio in 1971-1980 compared to the period 1960-1970 with 40% (previous period, 35%) and 55% (previous period, 41%), respectively. However, it is not a statistically significant difference and there is no evidence from land use changes during this period for Linggi, as the development phase involves conversion of the forest to crop trees. Meanwhile, Bernam is still largely covered by forest. The only contribution is the variation in rainfall especially from wet years and influence from partial records (1971-1975 for Linggi and 1971, 1975-1977 for Bernam with high ratio), which causes slightly higher runoff.



Note: Period 1 to 6 in Bernam does not apply the same development phase as it occurs in Langat and Linggi. This is only for presentation to see the ratio range in Bernam during development in Langat and Linggi.

Figure 6.39: Runoff-rainfall ratio trend according to six development periods, 1961-2002

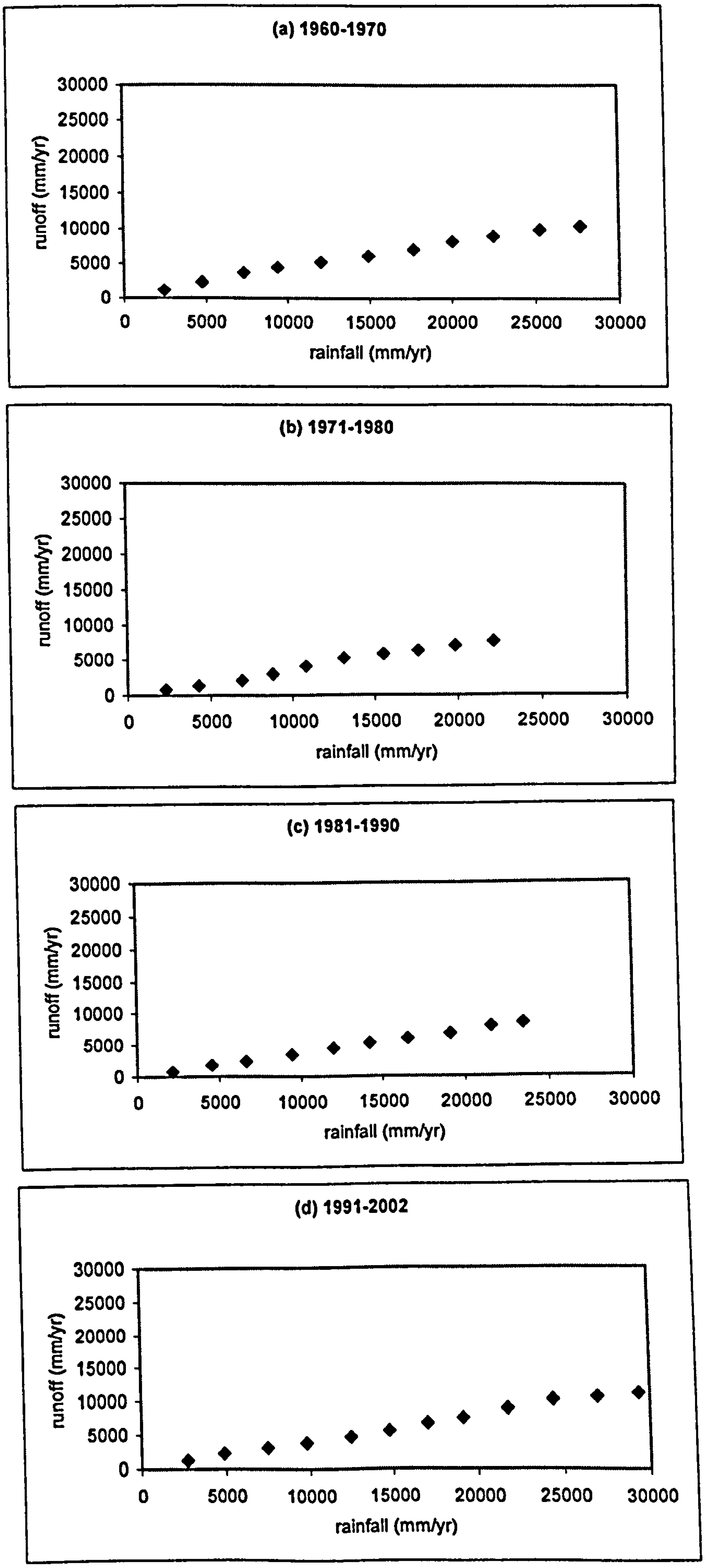


Figure 6.40: Langat – cumulative rainfall-runoff by development periods, 1960-2002

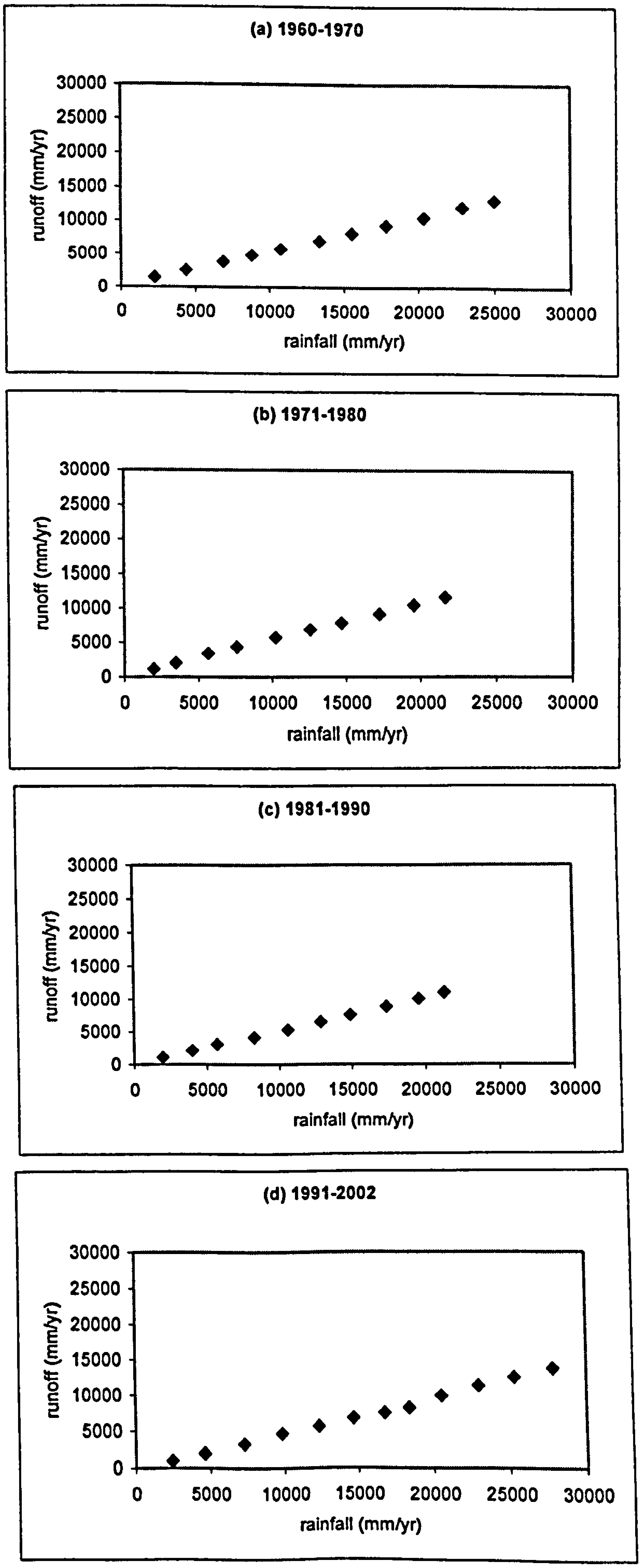


Figure 6.41: Linggi – cumulative rainfall-runoff by development periods, 1960-2002

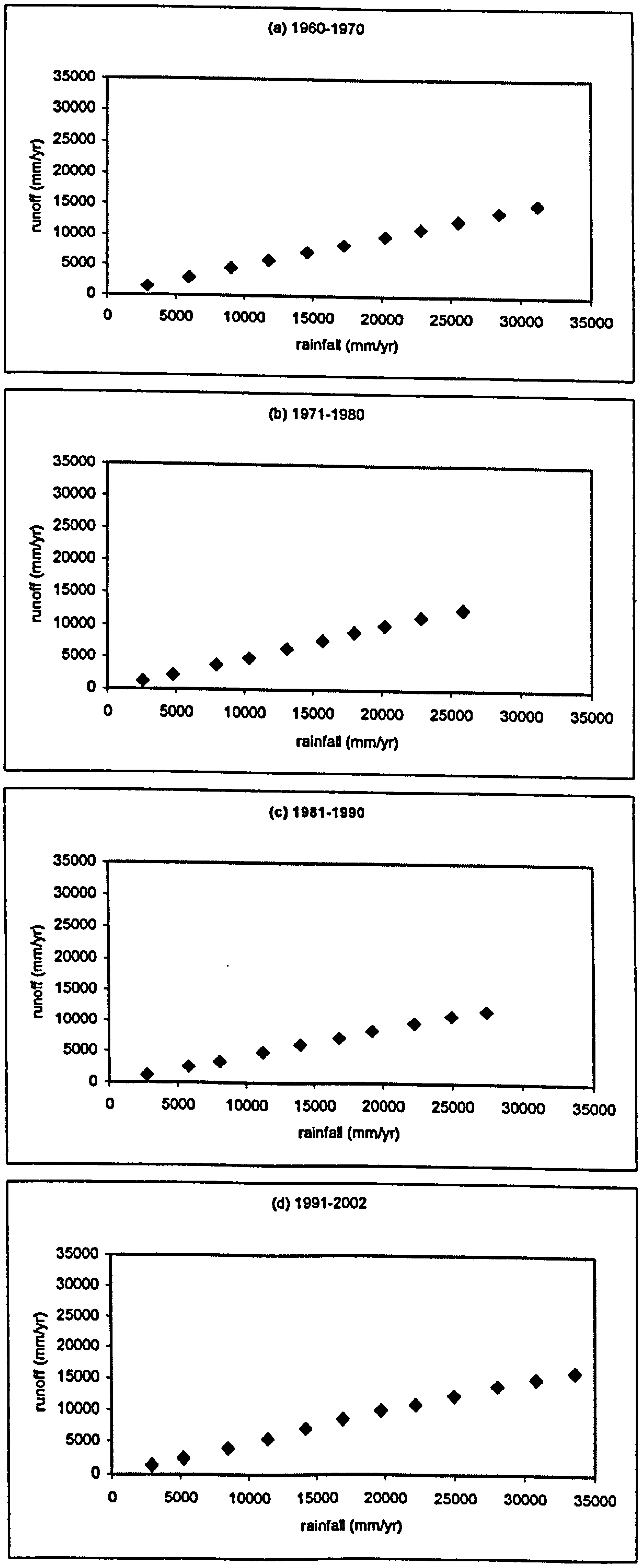


Figure 6.42: Bernam – cumulative rainfall-runoff by development periods, 1960-2002

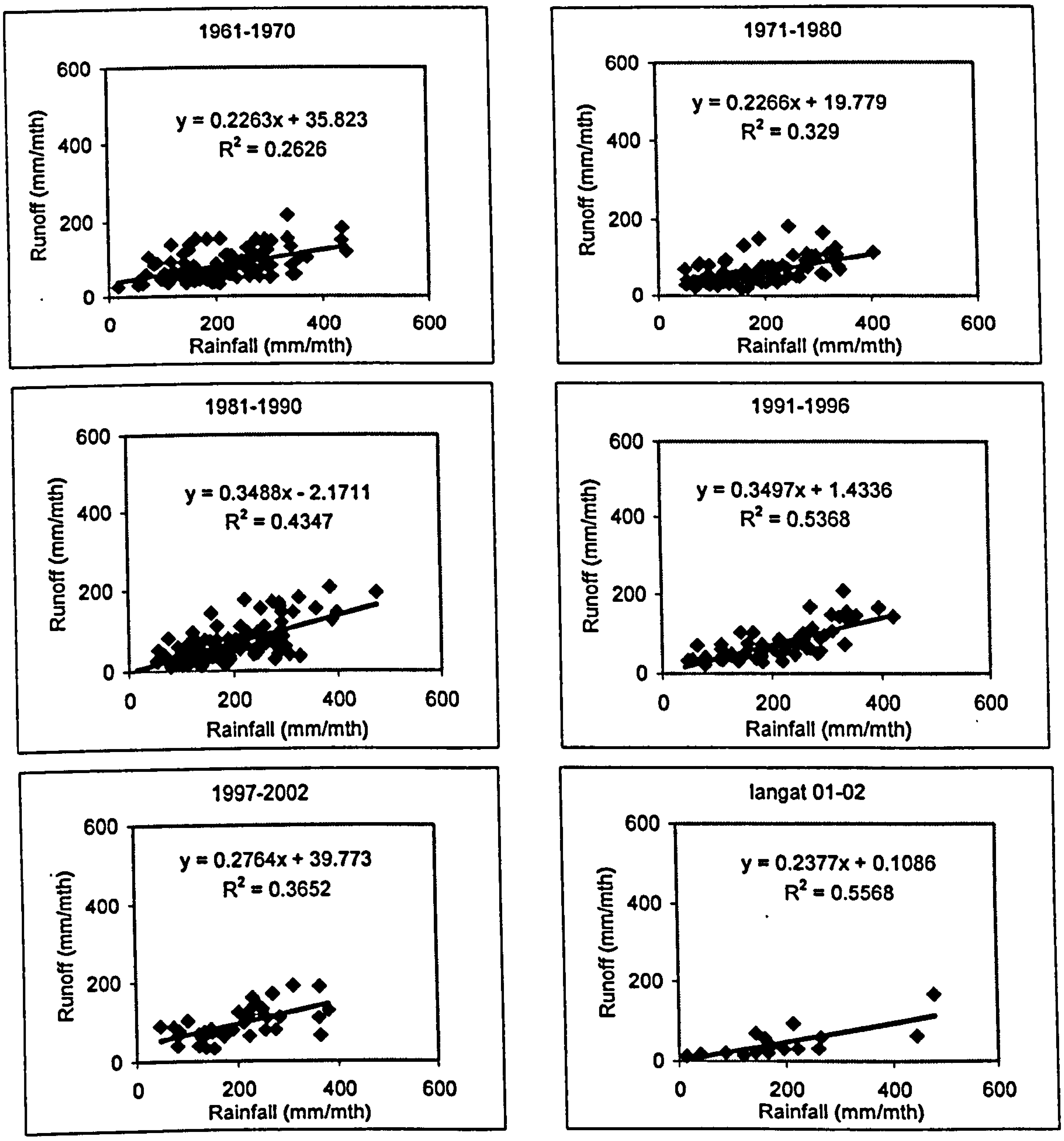


Figure 6.43: Langat: rainfall-runoff relation based on land development period (all monthly data)

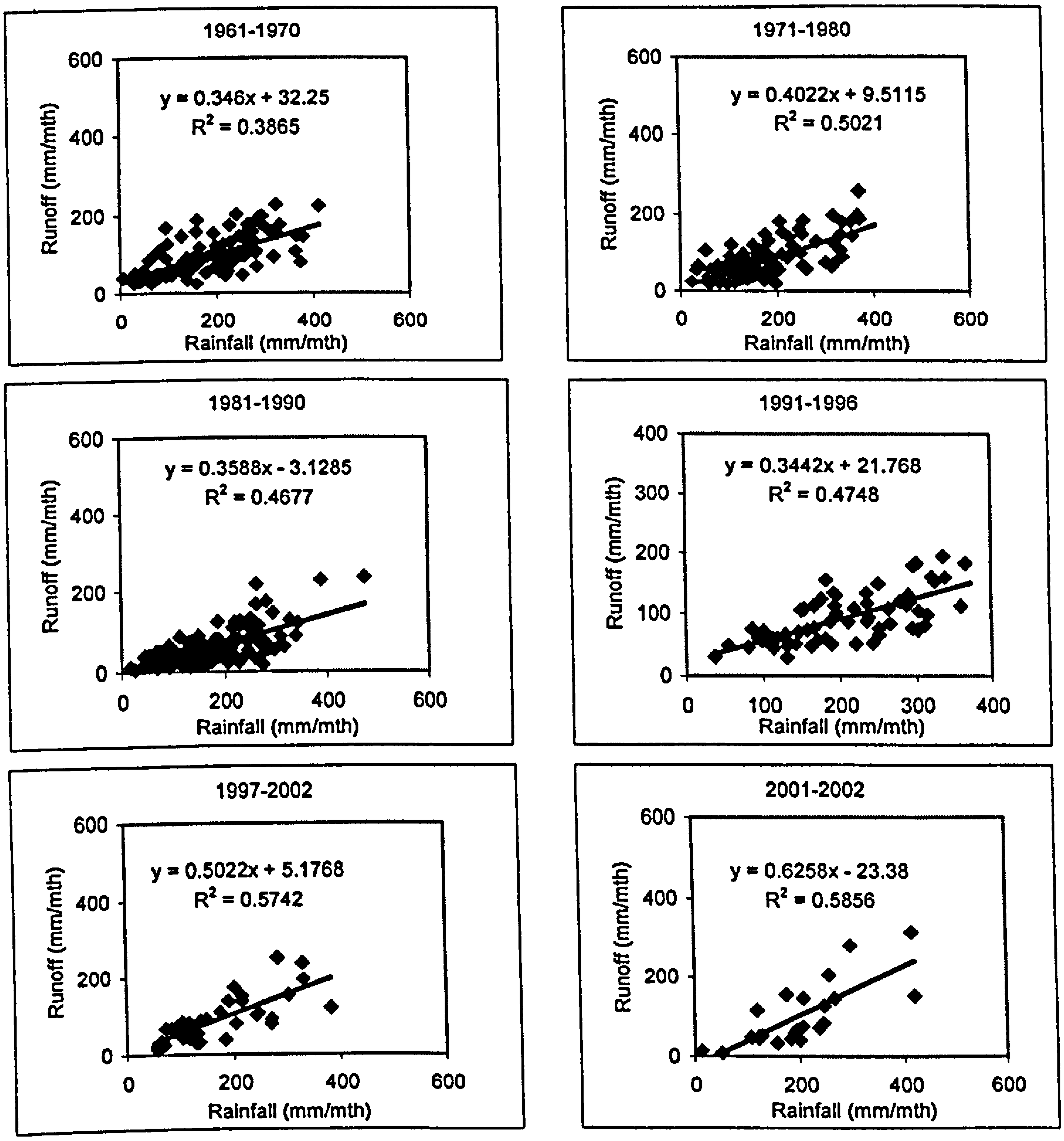


Figure 6.44: Linggi: rainfall-runoff relation based on land development period (all monthly data)

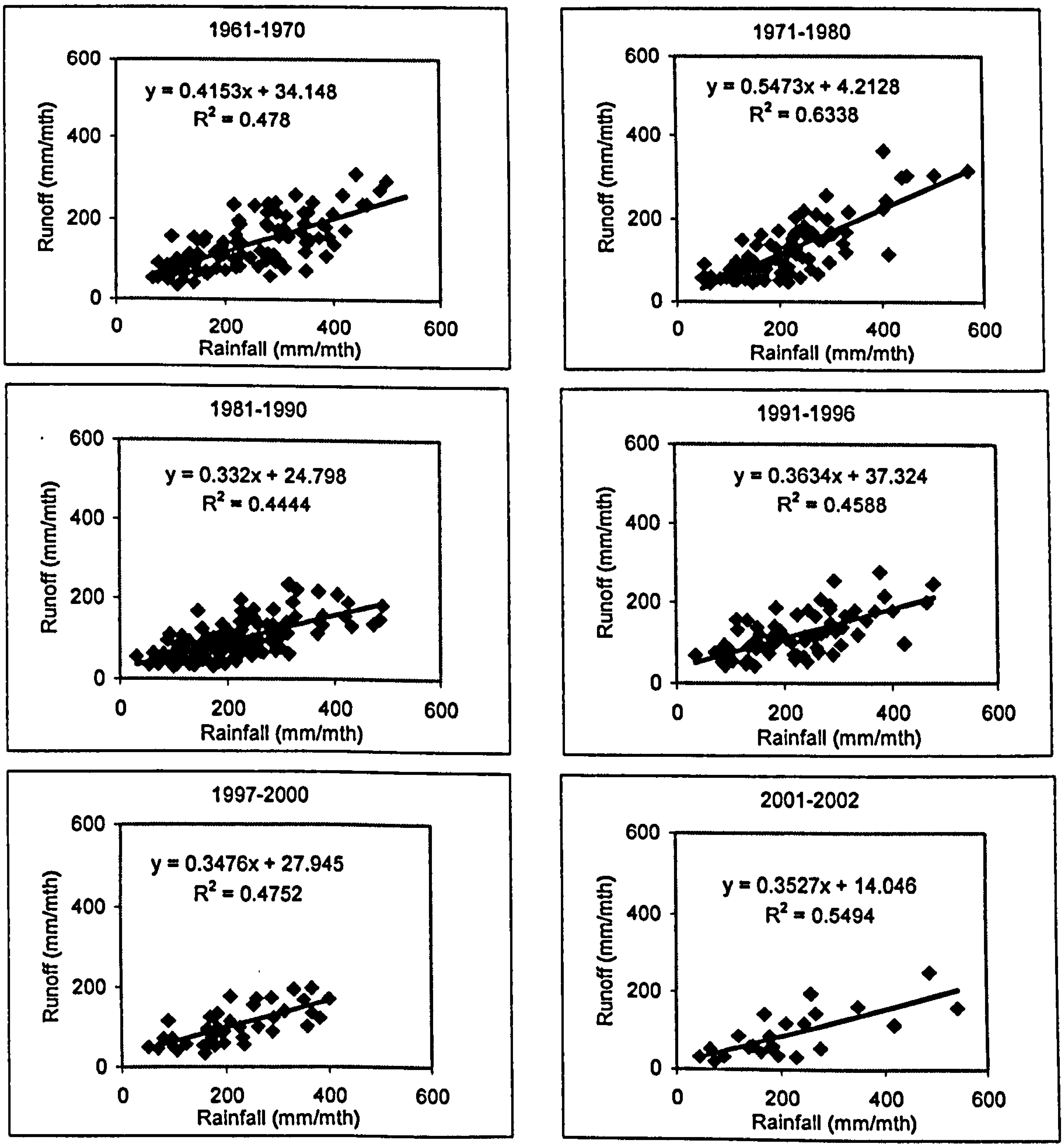


Figure 6.45: Bernam: rainfall-runoff relation based on land development period (all monthly data)

During the period 1981-1996, both Langat and Linggi recorded a rainfall-runoff ratio of 35%, which for Langat suggests a response to the increase in land development for urbanisation and industrialisation where the area increase from 38 km^2 in 1984 to 125 km^2 in 1997, but there is no statistical difference (paired *t*-test, p = 0.243), as the area comprises only 10% of the total catchment and large areas of catchment are still coverd by either native forest or tree crops. However, the coefficient slightly decreased for Linggi. The same occurred in Bernam, which recorded a ratio of 33% during the period 1981-1990, which could be related to the role of mature agricultural crops in minimising runoff while contributing to a higher evapotranspiration level (Abdul Rahim and Zulkifli, 2004). However, within the period 1991-1996, the ratio increased to 36%, which could reflect the first attempt to develop Bernam (which was suspended by the government due to the economic recession; Department of Urban and Rural Planning, 2000). Even though there is an indication of development activity on the changes of runoff-rainfall ratio, there is no difference between development phases in statistical terms (paired *t*-test, $p = 0.478$). This suggests that there is no significant impact from forest conversion on the volume of runoff flowing out through the study catchments within the 42 year of record.

This is in contrast with many finding from the tropics. Siriwardena *et al.* (2006) stress that in nearly all cases of experimental catchments (less than 25 km^2) studies of the impact of vegetation changes on hydrology (such as the conversion of forest to agriculture) have found significant changes in catchment runoff. There are many reviews in the literature, particularly by Hewlett and Hibbert (1967) and Bosch and Hewlett (1982), Abdul Rahim (1989), Douglas *et al.* (1993), Zhang *et al.* (1999), Best *et al.* (2003) and Andreassian (2004). Their studies indicated that removing more than 30% of forest cover during the first three years would produce increases in annual runoff between 145 and 820 mm (40-75%) from the annual rainfall, depending on where the study catchments located. Their areas of study have been mainly located in relatively high rainfall areas in the tropics, such as Borneo, Java and South America, which play a part in contributing to a higher runoff. Siriwardena also highlighted that there is no case reported in the literature that shows the effect of the manipulation of the vegetation cover of large catchments on hydrology. However, it is usual to predict the impacts vegetation changes in large catchments have using observations that have been made in small catchments and hydrologic models. However, the finding from these small catchments may not be able to provide information that translates directly to bigger study catchments. The Langat, Linggi and Bernam are moderate-size catchments, *c.* 1000 km^2, having differences in climate, geology, soil properties, catchment morphometry, vegetative cover and magnitude of land changes. The rainfall-runoff response to disturbance on land surfaces is certainly more complicated and there is a possibility that the impact of development activity will take a few years before becoming evident.

There may be no linear relations between the impact of rainfall-runoff and land use change. The change from forest to agricultural crops may counter the impact of land development so that no significant impact is evident. This assumption is based on the condition that the influence of the rainfall-runoff ratio largely depends on the speed of any land activities, the rate of replanting a new crop after clearance, the influence of the type of agricultural crop and any other factor from hydrology and climate. There is evidence from experimental studies in Malaysia and Java where, after 4-5 years of forest conversion to agriculture crops, the storm-flow will return to previous levels as a function of secondary growth (Abdul Rahim and Zulkifli, 1999; Bruijnzeel, 2004). From the analysis, it seems that the rainfall-runoff ratio is not a straightforward function of the rainfall, since there are appreciable variations for both dry and wet months. This is despite the fact that, in principle, the increases in runoff volume are closely proportional to the fraction of forest clearance. This change was a reflection of the different evaporative characteristics of mature tropical forest and young secondary or planted vegetation, which increases the storm runoff in response to rainfall (Bruijnzeel, 2004).

There is some evidence from researchers about this scenario. Pizarro *et al.*, 2006, studied runoff coefficients in the Purapel River basin, Chile where the native forest area was converted to *Pinus* plantations. Results showed no differences throughout the 40 studied years. However, runoff coefficients tend to increase in the 1980s due to greater rainfall, which was not related to the change of vegetation cover. They concluded that the principal factor controlling runoff is not the type of vegetation, but rather whether the soil is covered or not covered. This seems to be similar with the study catchments, where the forest areas have been converted to mainly rubber and oil palm trees. The outcome is less straightforward and counter intuitive when comparison is made with results from other experimental catchments in the tropics. It is concluded that the fraction of water flowing out the drainage basin remains similar where tree crops are an important replacement for native forest and where urbanization covers less than 20% of the total catchments areas. At the same time, the catchments are still largely dominated by vegetated surfaces (natural forest, rubber tree, oil palm tree and transition – grassland, pasture, orchards and horticulture). The findings give vital information for land developers as they are always blamed for the degradation of water in Malaysia. However, this does not mean that they can instigate new land development without considerations for water relations, as it could have other impacts on quality of the water upon which the local population will be relying.

6.5 Summary

This chapter has attempted to explain detailed characteristics of rainfall and runoff and their relation to land use change within the study catchments. The spatial and temporal variability of rainfall has been shown clearly. Temporal variability is related, in large part, to the influence of changes in global circulation brought about by El Nino and La Nina-related phenomena. At an annual scale, wet months in the study catchments occur during inter-monsoon seasons instead of the monsoons themselves, contradicting the definition used by The Meteorological Office which is applicable to the wider extent of the Malaysian peninsula. Seasonal factors inevitably play a significant role in the availability of water yield by the river system. A complex, long-term, runoff pattern with upward and downward fluctuations has been shown to mirror rainfall variability. However, there is no clear trend in the period 1960-2002 which can be related to changes in land use. The conversions of forest to other vegetative cover and to urban development are not having a significant impact on water yield.

Chapter Seven evaluates suspended sediment data and other water quality parameters as indicators of the impact from land use change within study catchments.

CHAPTER SEVEN:
SUSPENDED SEDIMENT AND WATER QUALITY CHARACTERISTICS

7.1 Introduction

The main objective of this chapter is to examine the quality and appropriateness of suspended sediment data and water quality parameters such as BOD, SS, Temperature, pH, Conductivity, Nitrate, Arsenic and Zinc as indicators of significant land changes during successive phases of development. The chapter also describes the complications in understanding the relations between rainfall-runoff and the impact of land development that result from the limitations of the hydrological data. Because the data for solutes and electro-chemical water quality attributes are sparse, there is more attention given to suspended sediment.

Surprisingly, it was found that the trend of Qss for both catchments is not a function of fluctuations in water discharge. Even though DID stressed that it used adequate stage-discharge rating curves in establishing the sediment discharge record, there is limited documentation about the procedures used. This, together with preliminary analyses, lead to the conclusion that the quality of the datasets remains spurious. As a consequence, the Qss datasets were discarded, leaving a limited amount of suspended sediment concentration (SSC) data to be evaluated and analysed for suspended sediment yield. These yield values have be used in an attempt to detect the impact of land use changes on water quality.

7.2 Evaluation of suspended sediment concentration (SSC) data

As the suspended sediment discharge (Qss) data could not be used for further investigation, attention has been focused on the limited amount of suspended sediment concentration (SSC) data. However, the datasets are only available for the Langat and Bernam catchments. The objective of using these data is to investigate whether they can provide transfer functions - i.e. relations between SSC and Q - in order to help generate synthetic sediment yields. Unfortunately, this proved impossible. However, it was still possible to use the data to reflect the influence of land use changes on the level of SSC for the limited periods represented.

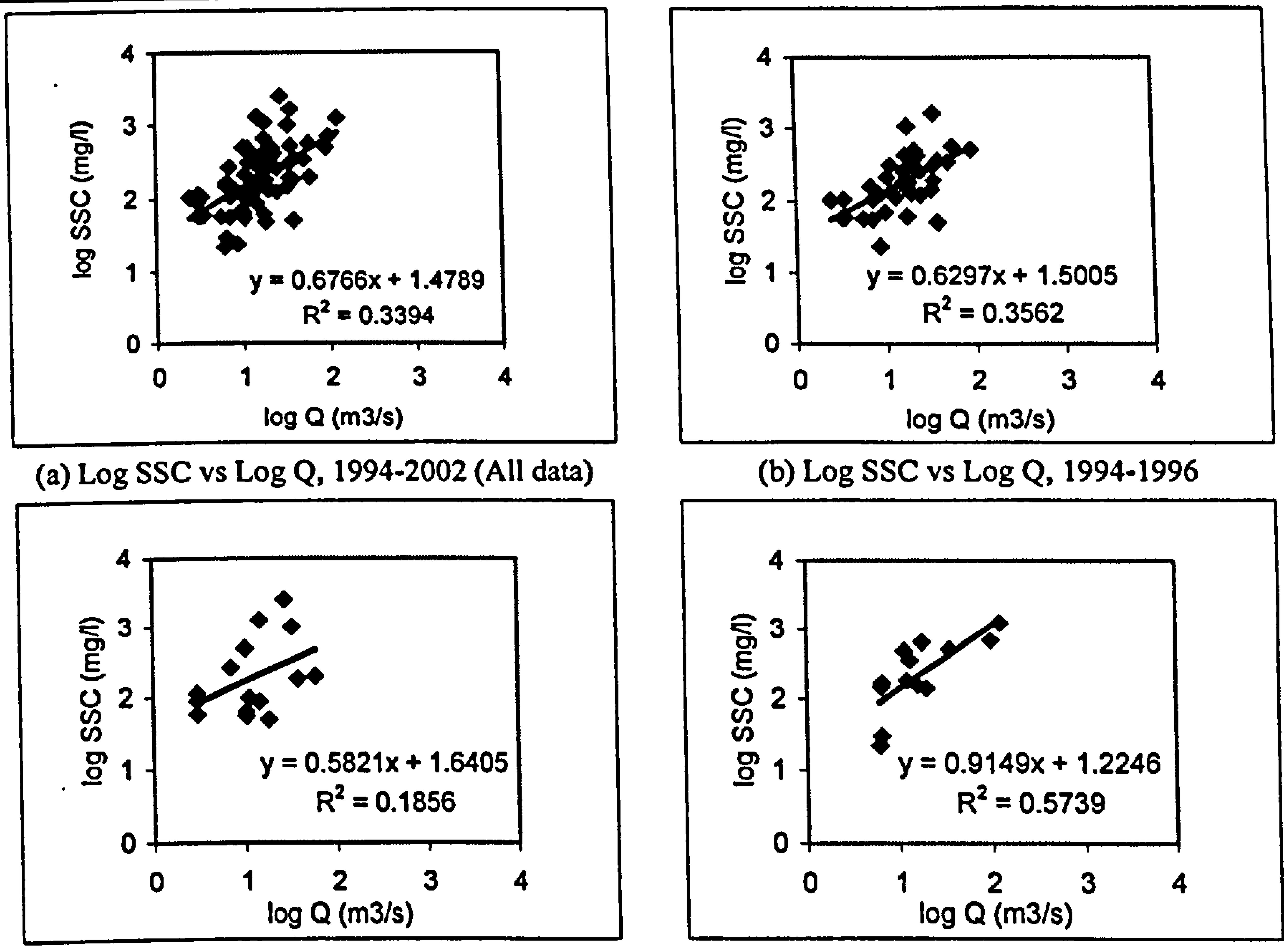
For the Langat and Bernam, records for SSC are only available from 1994-2002 and 1992-2002, respectively. These periods of record have to be able to provide coverage of both the land use change activities and seasonal factors. However, the strength of the evidence from the relations between SSC and Q is low, limiting their use as a basis for argument and evaluation. To establish transfer functions, the relations between SSC and Q were analysed using both ordinary least square regression (OLS) and Deming regression. These transfer functions will be used later to generate suspended discharge data, which will then be converted to sediment yield (if appropriate). As the quality of the suspended sediment datasets is subject to limitations, any discussion of the impact on water quality must be very circumspect. Sivakumar (2002) has stated that there is no simple relation between SSC and Q. To establish an accurate relation, it would be necessary to improve an understanding of SSC variations and to reduce errors in the Q measurement.

The Deming regression provides an alternative approach to the understanding of the nature of a complicated dataset (Linnet, 1998). It is obvious that the relation established by Deming regression is an improvement since it considers the errors in both the dependent and independent variables. The SSC estimated using this tool is higher, which could reflect the actual conditions on the ground.

Despite the limited number of years covered by the SSC dataset, the data were grouped based on the justification of the period of land development progress in each catchment. In Langat, the groups used were 1994-1996 (development), 1997-1999 (economic recession period), 2002 (post-recession) and also the full range of records from 1994-2002, which represent all periods of development. The transfer function for the full period (1992-2002) was selected in an attempt to establish synthetic sediment yield records for the Langat study catchment. Meanwhile, in Bernam, the groups established were 1992-1996 (pre-development), 2002 (post-recession) and also the full range of records from 1992-2002. There is no relation for the recession period due to the limitations of the data. Both, OLS and Deming analyses were developed using these periods in order to recognise any indication of SSC level within the catchments. All the analyses and the statistical properties for both catchments are shown in **Figures 7.1-7.4** and **Tables 7.1** and **7.2**, respectively.

From analysis (all data), the anti-logging SSC intercept values produced by OLS regression for Langat and Bernam are very small for wet catchments, with values of 4.79 and 2.95, respectively. These values resemble those for desert ephemeral regions reported by Alexandrov et al. (2006) in Eshtemoa, Beer Sheva, Israel (4.18 for a catchment size of 112 km^2) and by Frostick *et al.,* (1983) in Il Kimere, Northern Kenya (3.25 for a catchment size of 7 km^2). It also contrasts with the findings reported by Ruslan (1995) from the nearest tropical site in Penang, where the urbanised catchment of Terjun (8.87 km^2) recorded a value of 214 and the newly clear-felled catchment of Relau (11.52 km^2) recorded a value of 1555. However, the Deming regression can cope with the high degree of scatter and would improve the intercept value up to 14.58 and 15.04 for Langat and Bernam, respectively. This case shows how the Deming regression can be used as a satisfactory rating curve. In relation to the findings from other rivers, the exponent value and yield resulting from the use of OLS should be used together as it is commonly used by researchers. However, Mark and Church (1977) and Linnet (1998) have highlighted the weakness of OLS, which is only based on the independent variable as error-free within analysis. Comparison with those findings notwithstanding, the Deming exponent is still small, which could be related to the function of the catchment size, level of urbanisation, climate and physical aspects of the catchment.

Although the Deming regression is able to improve the relation, even it cannot be used to indicate errors in the analysis. Hence, it will be used - together with the OLS analysis - for this study, given that there is so little satisfactory data for water quality analysis. There is no doubt that the OLS is widely used by hydrologists. The transfer function established by OLS underwent a correction process as suggested by Ferguson (1986). This is because the rating curve established from the relation between SSC and Q underestimates SSC as a function of anti-logging. After applying the correction factor (explained in Chapter 4, Section 4.2.1.3 – Methodology), the transfer function will then be used to generate values of sediment yield in an attempt to recognize the impact of land use change from land-development activities within the Langat and Bernam catchments. The Linggi catchment does not have a record of SSC. However, it is expected that its SSC would be high, since the catchment is smaller and has been through a period of very rapid development since the early 1990s.



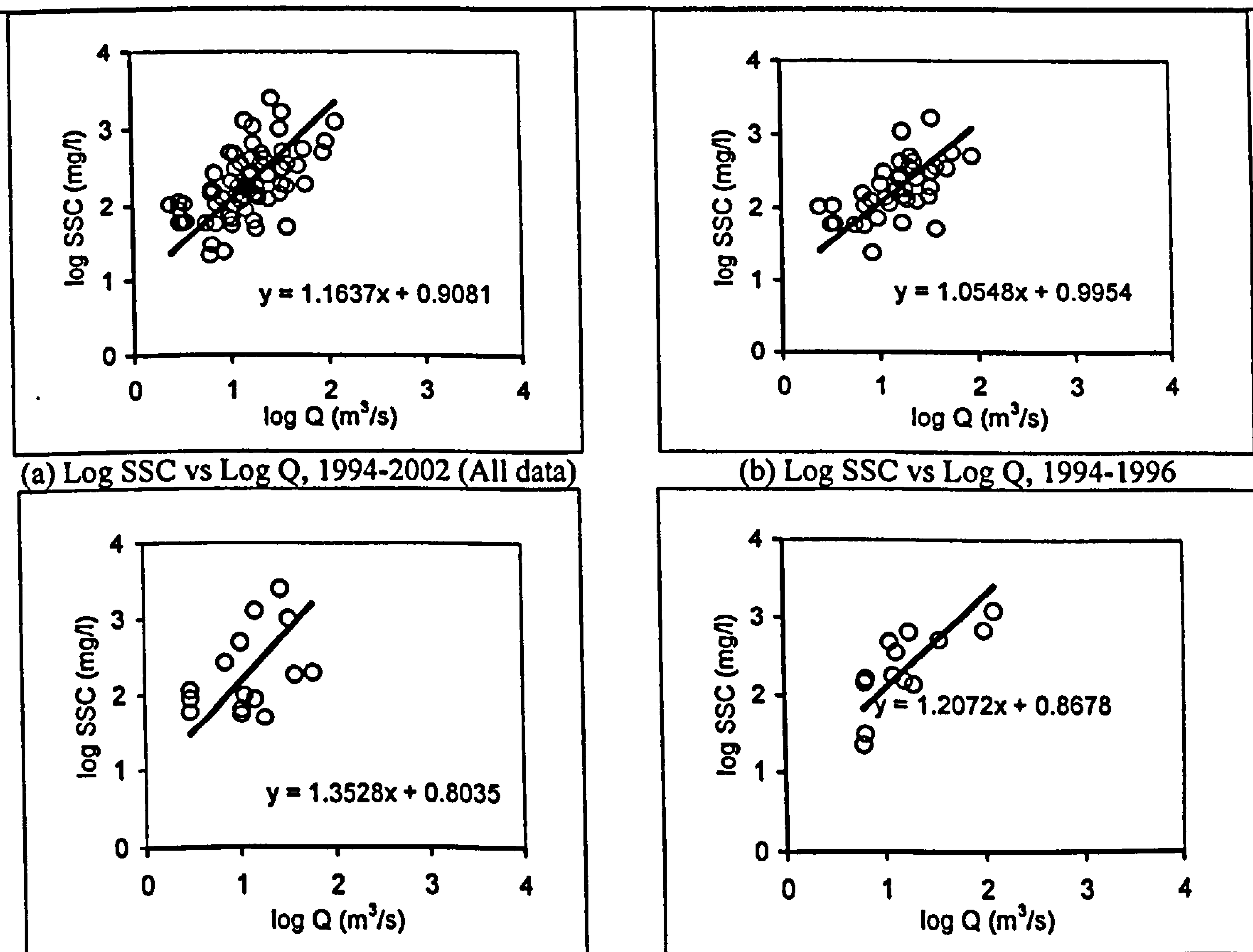
(a) Log SSC vs Log Q, 1994-2002 (All data)

(b) Log SSC vs Log Q, 1994-1996

(c) Log SSC vs Log Q, 1997-1999

(d) Log SSC vs Log Q, 2002

Figure 7.1: Langat – Log SSC vs Log Q (OLS Regression Analysis)



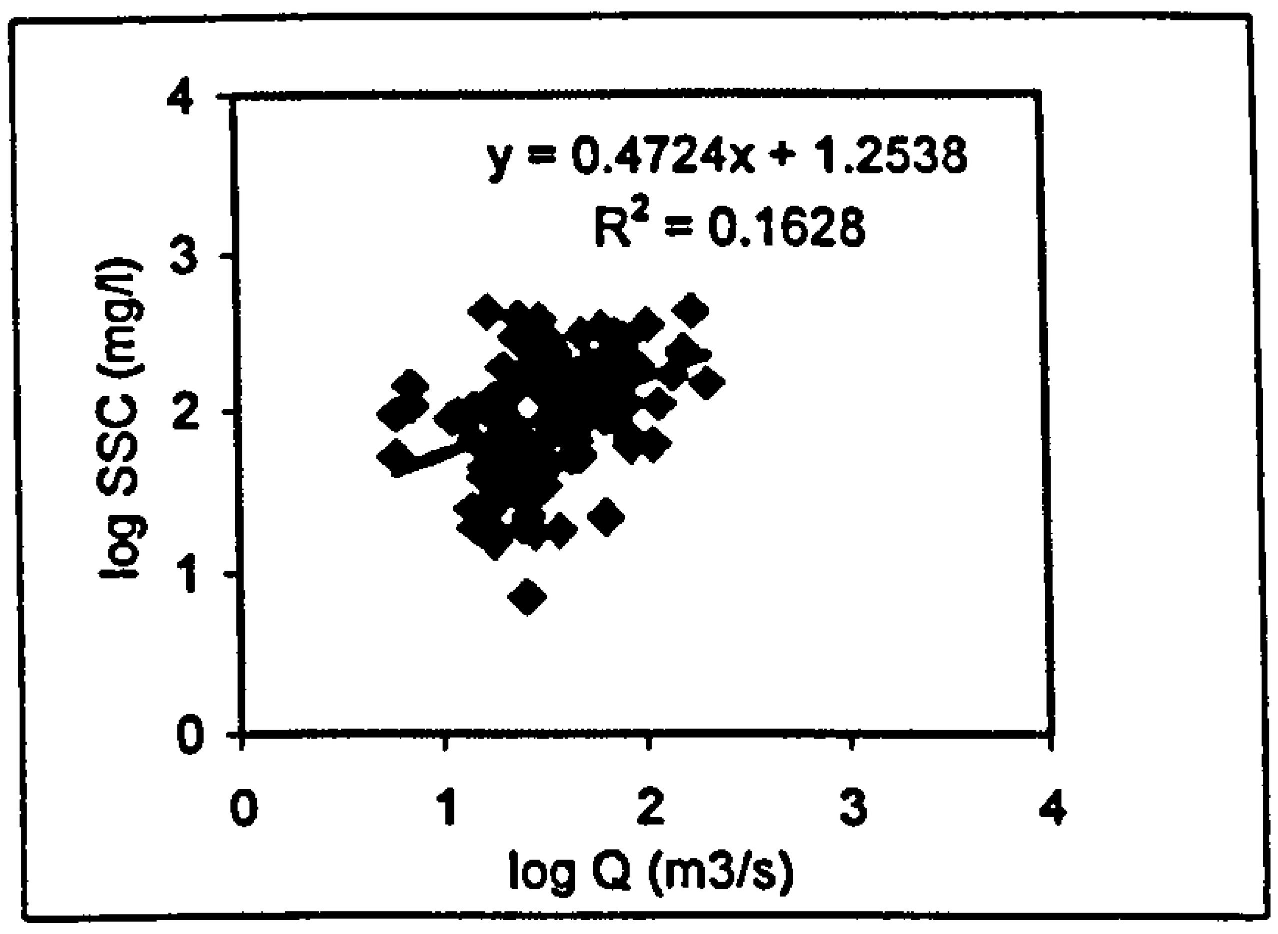
(a) Log SSC vs Log Q, 1994-2002 (All data)

(b) Log SSC vs Log Q, 1994-1996

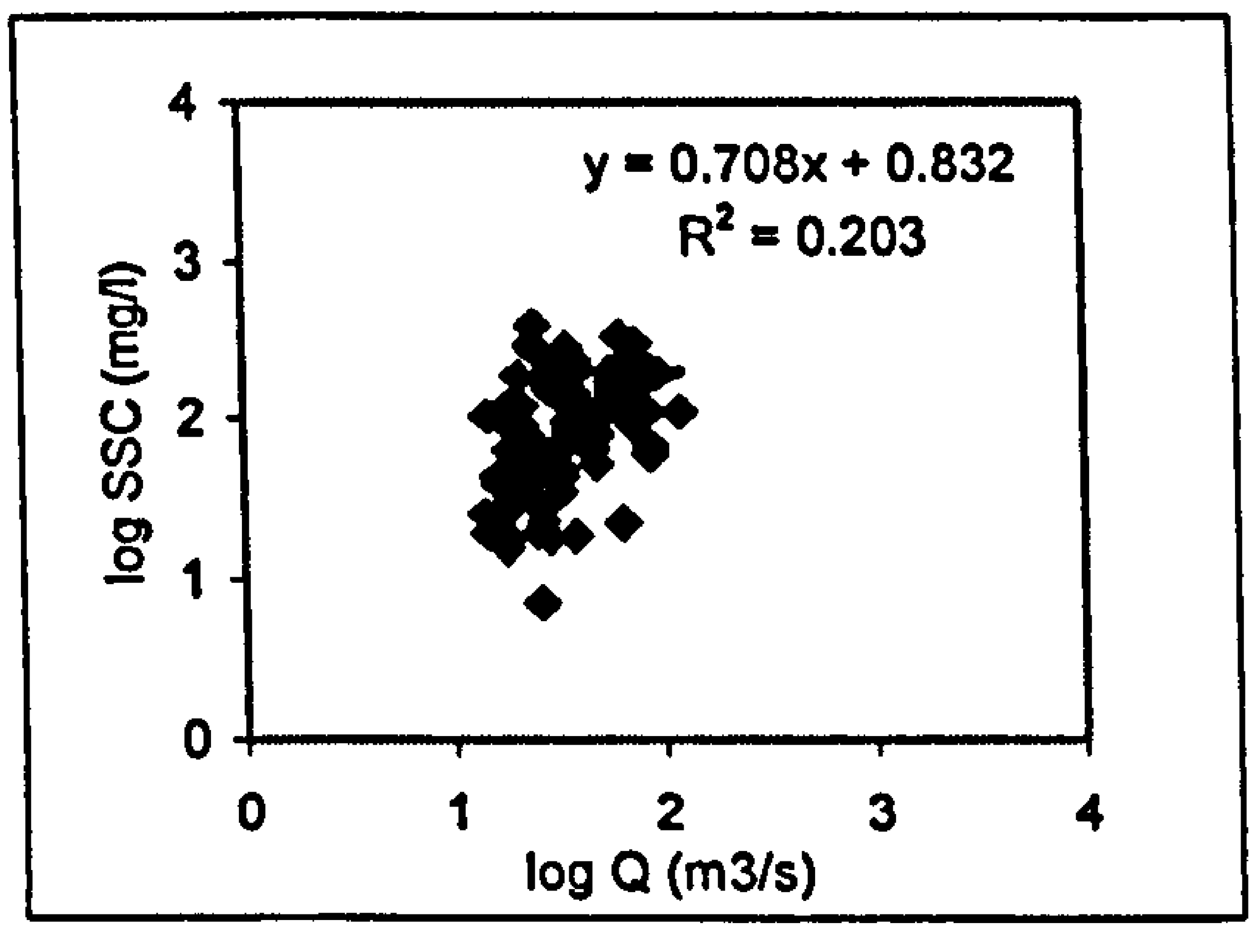
(c) Log SSC vs Log Q, 1997-1999

(d) Log SSC vs Log Q, 2002

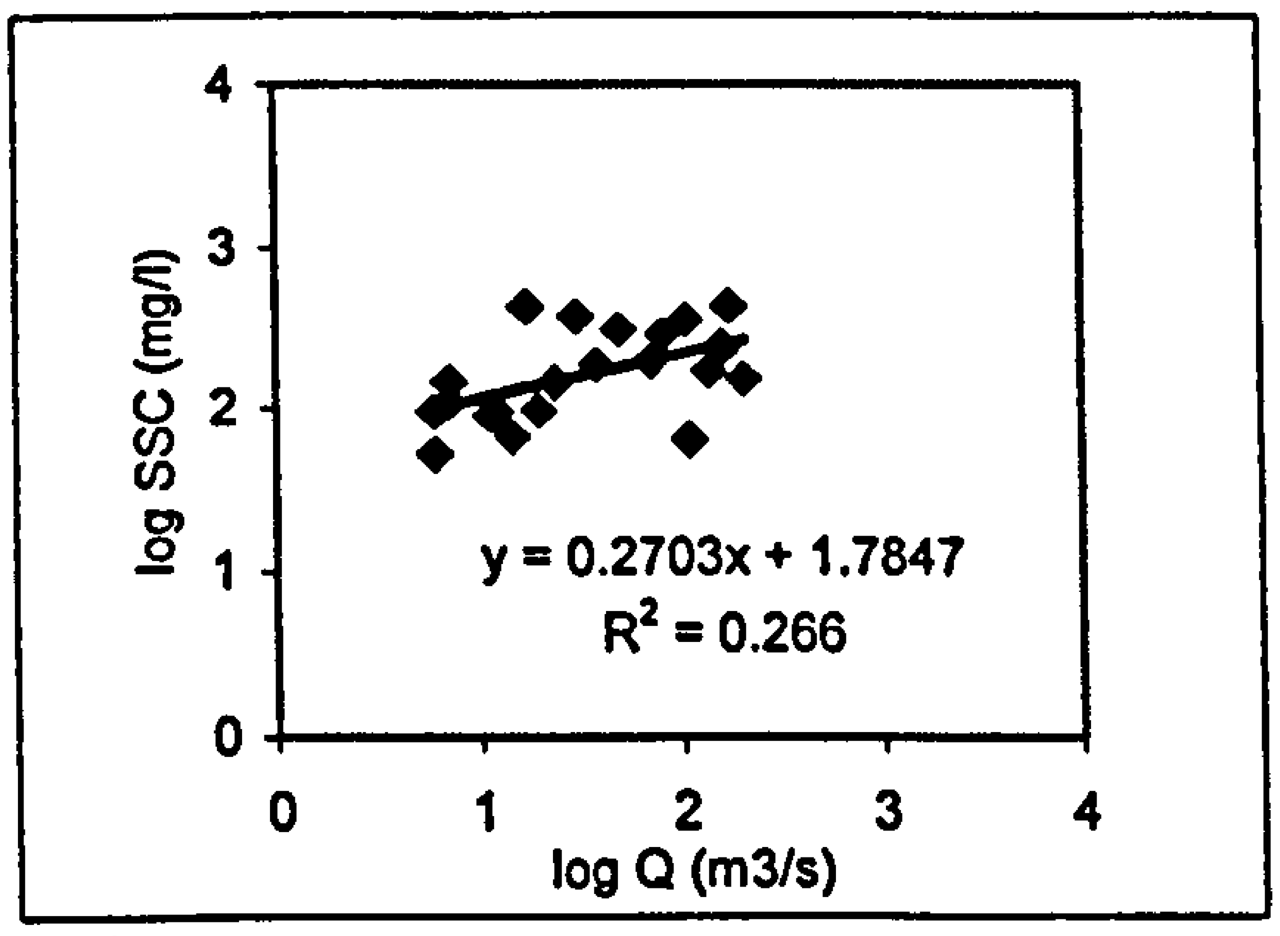
Figure 7.2: Langat – Log SSC vs Log Q (Deming Regression Analysis)



(a) Log SSC vs Log Q, 1992-2002 (All data)

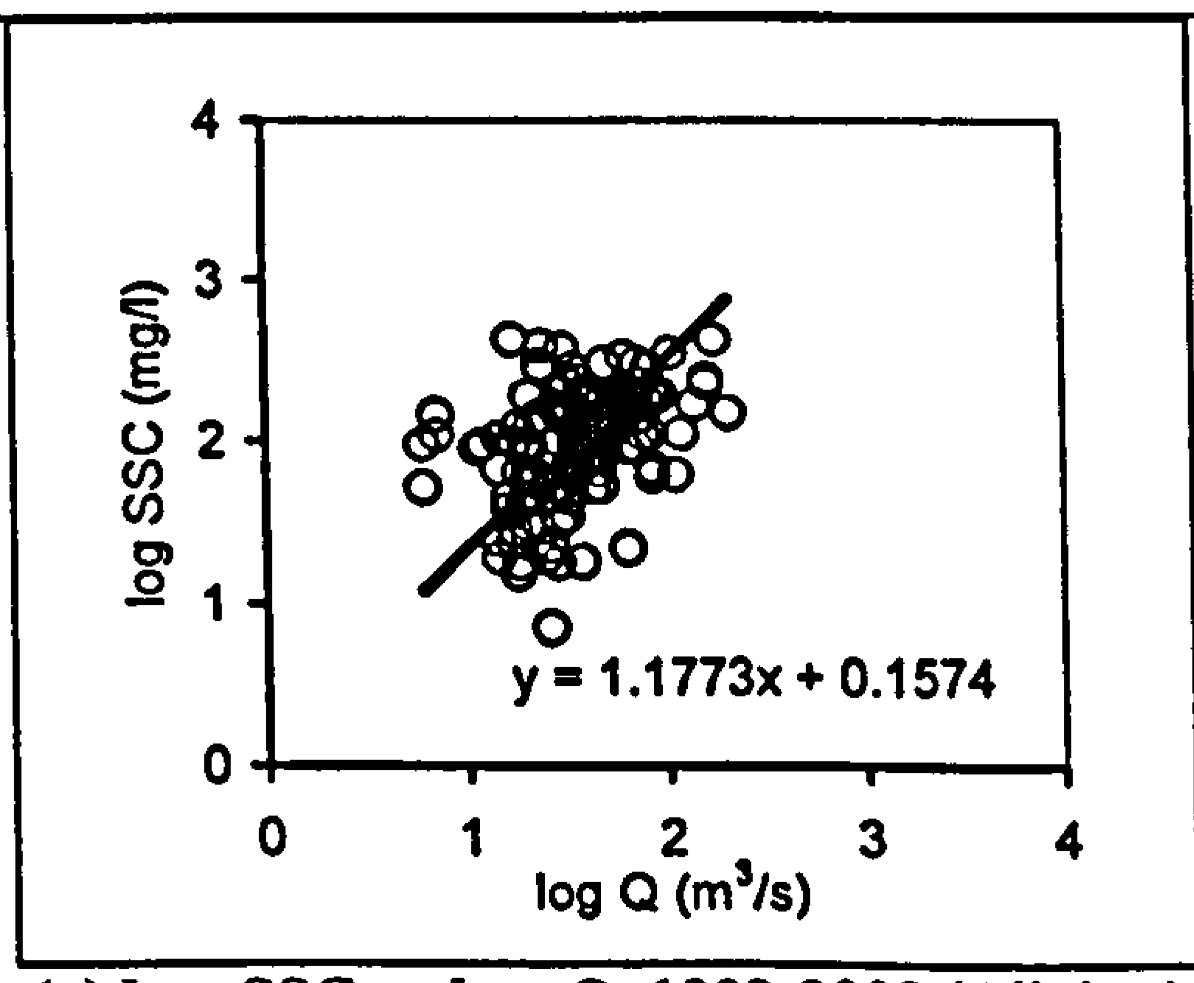


(b) Log SSC vs Log Q, 1992-1996

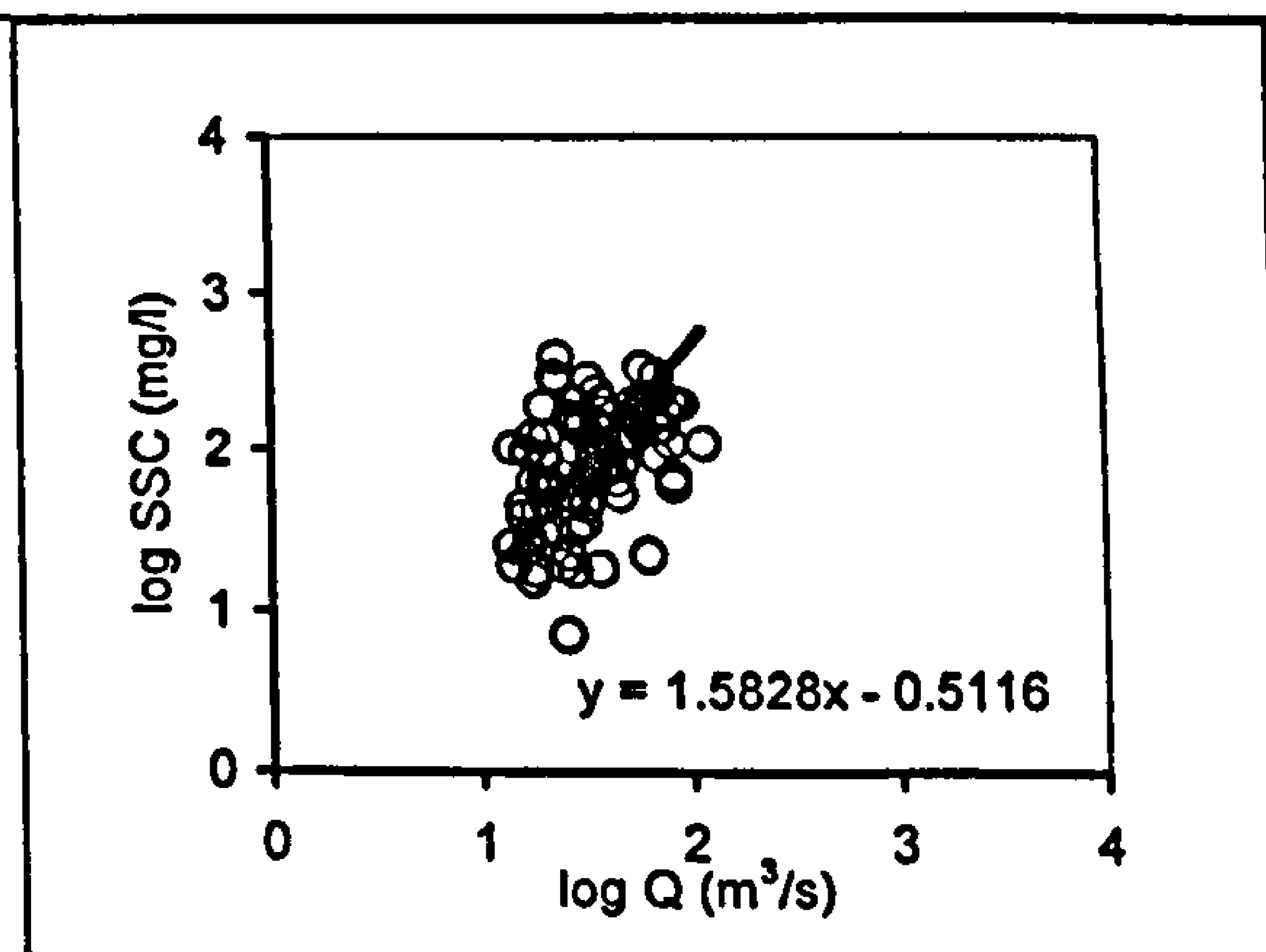


(c) Log SSC vs Log Q, 2002

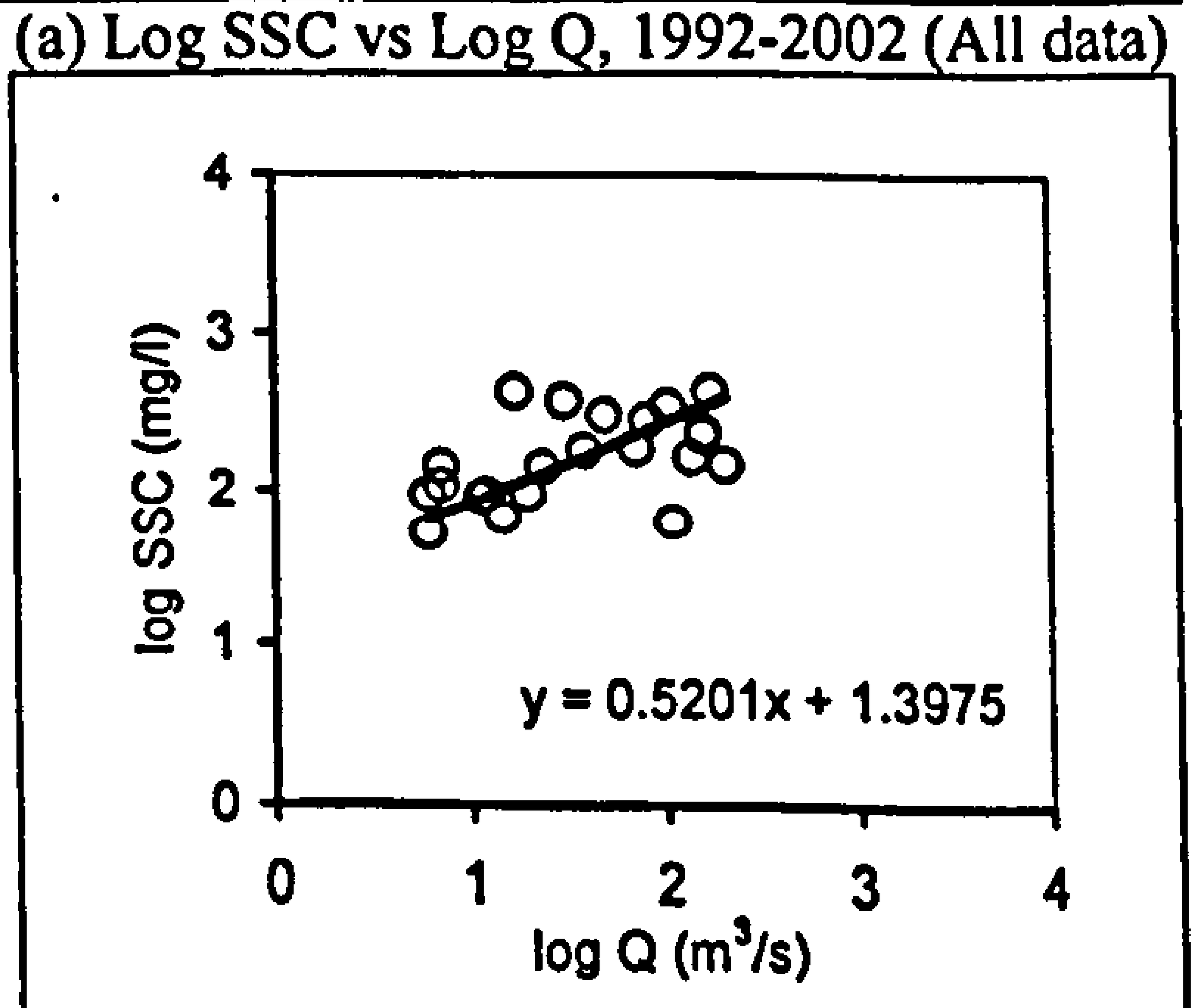
Figure 7.3: Bernam– Log SSC vs Log Q (OLS Regression Analysis)



(a) Log SSC vs Log Q, 1992-2002 (All data)



(b) Log SSC vs Log Q, 1992-1996



(c) Log SSC vs Log Q, 2002

Figure 7.4: Bernam– Log SSC vs Log Q (Deming Regression Analysis)

Table 7.1: Dengkil: Statistical properties for SSC-Q data analysis using Ordinary Least Square regression and Deming regression

Date	OLS; log y = log ax + log b							DEMING; log y = log ax + log b	
	a	b	R	R^2	SE	Sig. Level	df	a	b
1994	0.571	1.566	0.778	0.606	0.2264	0.002	12	0.7304	1.3771
1995	0.734	1.378	0.654	0.427	0.1808	0.040	9	1.1383	1.0024
1996	0.636	1.51	0.351	0.123	0.4303	0.167	16	1.8269	-0.0893
1999	0.779	1.523	0.52	0.27	0.5315	0.083	11	1.5212	0.762
2002	0.915	1.225	0.758	0.574	0.3524	0.003	12	1.2072	0.8678
1994-2002-all years	0.677	1.479	0.583	0.339	0.361	0.000	67	1.1637	0.9081
1994-1996 - development period	0.63	1.501	0.597	0.356	0.309	0.000	39	1.0548	0.9954
1997-2000 - economic recession	0.582	1.641	0.431	0.186	0.5064	0.109	14	1.3528	0.8035

Table 7.2: SKC: Statistical properties for SSC-Q data analysis using Ordinary Least Square regression and Deming regression

Date	OLS; log y = log ax + log b							DEMING; log y = log ax + log b	
	a	b	R	R2	SE	Sig. Level	df	a	b
1992	0.964	0.489	0.482	0.232	0.3836	0.009	27	1.951	-0.9126
1993	1.086	0.227	0.5	0.25	0.3751	0.025	19	2.1325	-1.3893
1994	0.292	1.562	0.291	0.084	0.2274	0.133	27	1.0168	0.3661
1995	0.714	0.643	0.504	0.254	0.2382	0.095	11	1.4661	-0.5017
1996	0.276	1.697	0.681	0.463	0.0968	0.319	3	0.4044	1.4982
2002	0.27	1.785	0.516	0.266	0.2448	0.014	21	0.5201	1.3975
1992-2002-all years	0.472	1.254	0.403	0.163	0.324	0.000	124	1.1773	0.1574
1992-1996-pre-development	0.708	0.832	0.45	0.203	0.3228	0.000	91	1.5382	-0.4519
1994-1996-pre-development	0.477	1.199	0.396	0.157	0.2534	0.008	43		

Data limitations are obvious: the analysis of SSC and Q (**Table 7.1** for the Langat and **7.2** for the Bernam) gives large errors and cannot be used to indicate the level of land development occurring in both catchments when, for example, the intercept values are plotted against time. In this case, the intercept values could act as an indicator of changes in SSC which reflect to changes in Q during a development phases. Three intercept values (for years 1994, 1996 and 1999) for the Langat are not significant, being controlled by outliers in the scattergrams. However, the values fall by 0.34 log units (28%) between 1994 to 2002. This might be taken to show that the impact of land development has decreased during that period and this could be related to the slower progress of development due to economic recession. It might also be related to the decrease in the area subjected to new development (**Figures 7.5** and **7.6**), while allowing for the expected fall off in SSC as already developed areas mature. The Bernam catchment shows no trend. The year 2002 shows an intercept value higher than that for the previous period and this might reflect the development that had just taken place (**Figure 7.7**). However, any conclusions that SSC reflects development have to be treated with considerable caution.

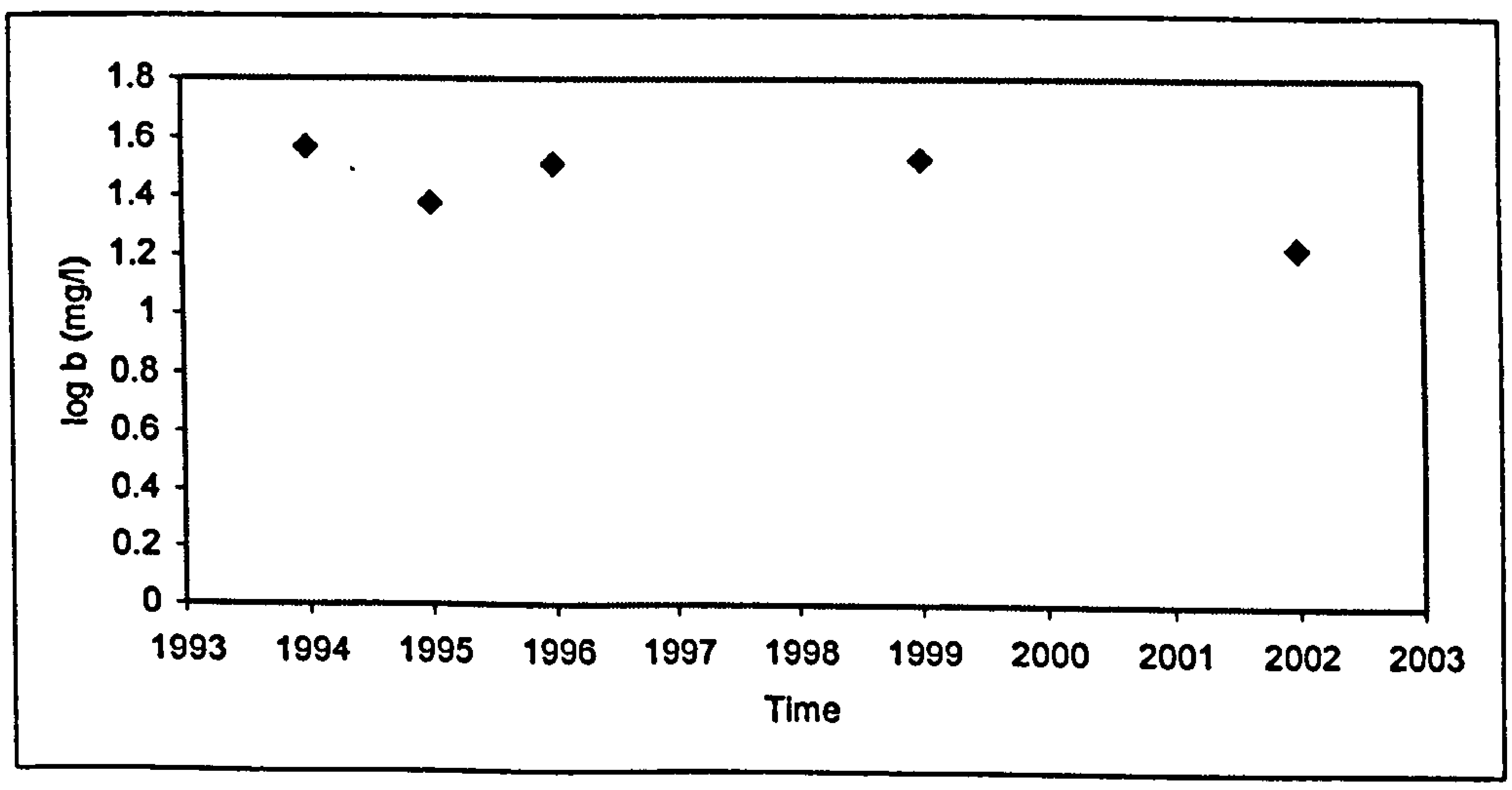


Figure 7.5: Dengkil: SSC rating curve – intercept value vs time, 1994-2002

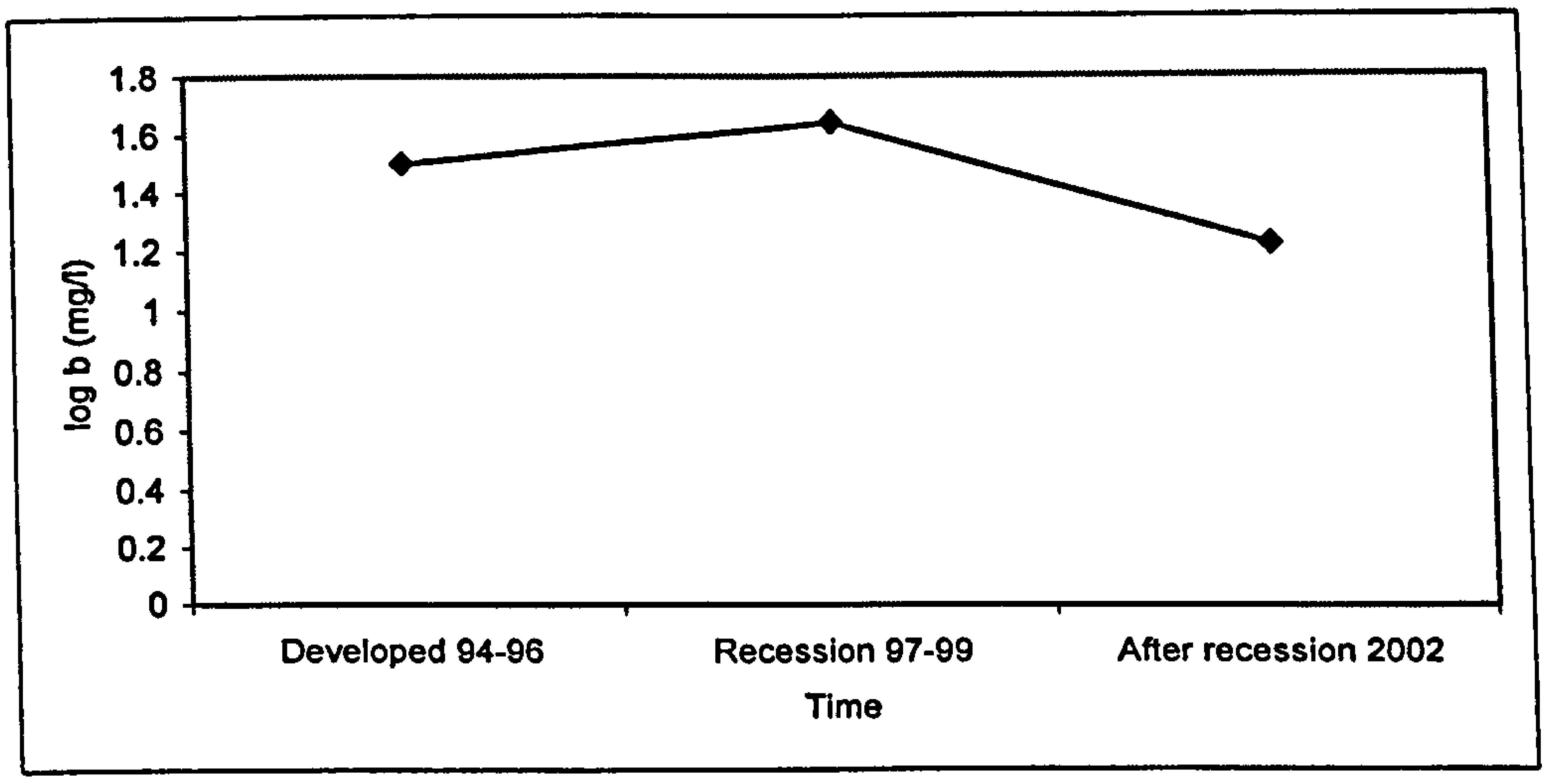


Figure 7.6: Dengkil: SSC rating curve – intercept value according to development phase, 1994-2002

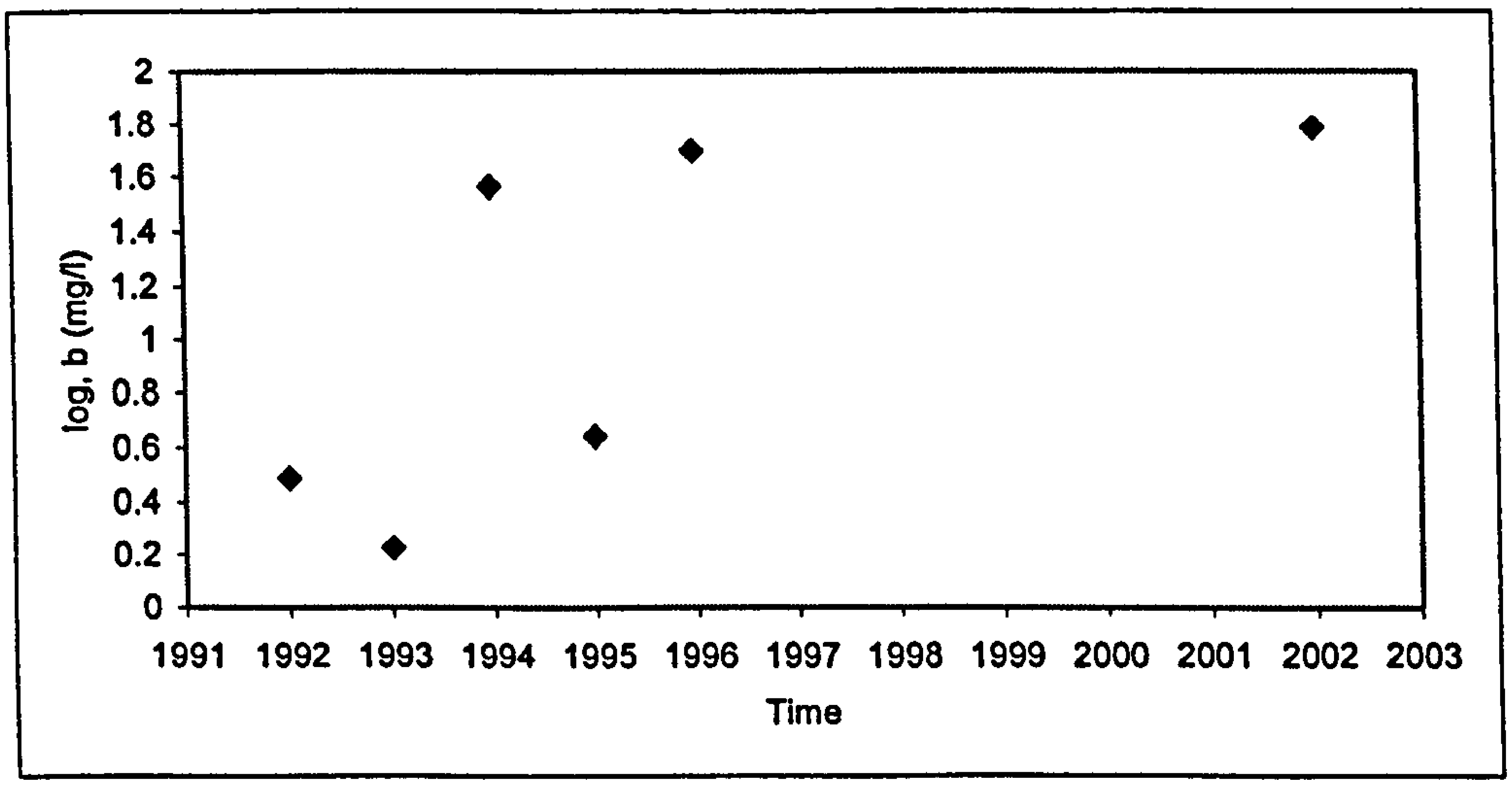


Figure 7.7: SKC: SSC rating curve – intercept value vs time, 1994-2002

Another way of analysing the data is to compare the period of development in Langat with the pre-development period in the Bernam during the same years (1994-1996) (**Figure 7.8**). From this analysis, the Langat catchment seems to carry higher suspended sediment concentrations than Bernam at any specific discharge. This difference is statistically significant (<0.001 – paired *t*-test). This is the only clear-cut indicator of the significance of the impact on water quality of development associated with economic growth. Even though, the Bernam catchment is yet to be developed, the range of SSC values is considerably higher as a function of the higher discharge and rainfall. There is a possibility that SSC will increase during the development phase and cause deterioration in water quality. This needs particular attention from development and river managers in order to monitor and minimise the impact.

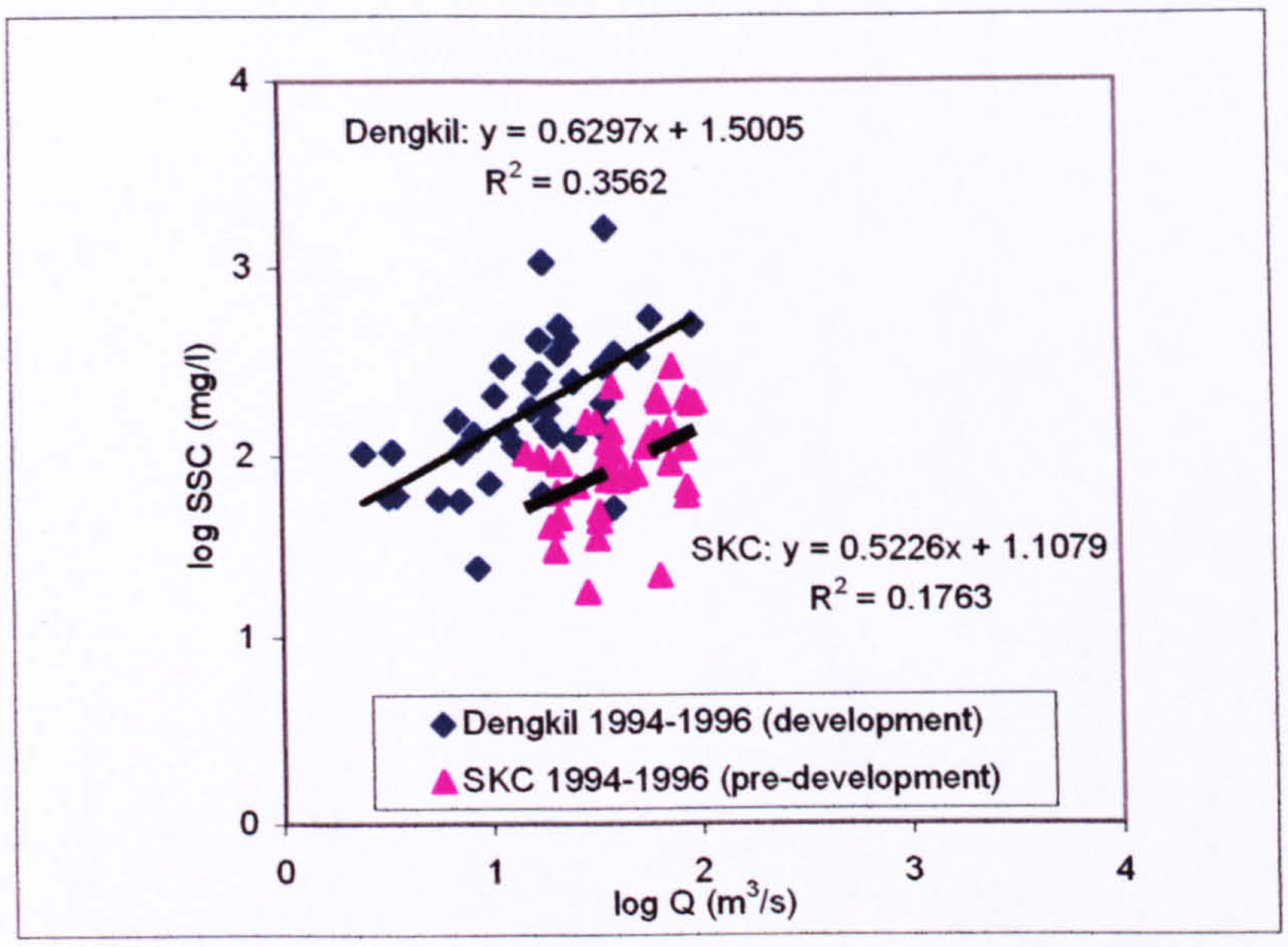


Figure 7.8: SSC – comparison between Dengkil (during development phase) and SKC (pre-development phase) 1994-1996

Due to the data limitations and errors in the SSC-Q transfer functions, synthetic suspended sediment yields could not be generated. This left little hope of assessing the impact on water yield and water quality of land development within study catchments. As a matter of sharing experience, yields based on the Deming transfer function are appreciably higher for both catchments than OLS-based yields. The OLS-based yields are still lower than those derived using Deming regression even after applying the Ferguson correction to the OLS relation, strong support for the statements by Mark and Church (1977) and Linnet (1998) about the low capability of the OLS method when dealing with complicated datasets. Despite this, OLS-based yields have to be used for purposes of comparison with other research studies because they are commonly derived by hydrologists worldwide.

It is expected that, during the land conversion processes, the yield will increase until secondary growth is sufficient to reduce the exposure of the land to the direct impact of rainfall. It is expected to increase again when development changed to urbanisation and industrialisation in a later period. Purwanto (1999) stressed that - in tropical countries - removal of the forest canopy and under-storey vegetation may lead to increased erosion rates and contribute to the higher suspended sediment load in water bodies. Precautionary measures need to be implemented if there are areas that are subjected to new development situated at elevations above 1000 m, as in the Bernam catchment.

Many researchers have stressed the important role of extreme events in moving large quantities of sediment within a short duration. For example, Douglas *et al.* (1999) in their study at Ulu Segama, Sabah, found that a single one-day storm could produce 41% of the total annual sediment yield. Similarly, Lai (1993) found that 50% of the annual sediment yield was produced from a disturbed catchment in Selangor in just six days. Therefore, prior to the implementation of land development for urban and industrial needs, the development manager especially in Bernam must be aware of the potential for high sediment loads during the wet season and its impact on catchment water resources.

7.3 Water quality

The available records of water quality (obtained from DOE) are not continuous for any of the catchments and the amount of data for selected physical and chemical attributes or constituents (BOD, SS, Temperature, pH, Conductivity, Nitrate, Arsenic and Zinc) depends on an adventitious sampling programme. With no discharge data measured at the same time as water quality parameters, it is difficult to interpret trends in the quality of the water in the catchments. So, for example, it is impossible to assess how seasonal changes in runoff or heavy rainfall and higher flood discharge dilute any of the pollutants.

In order to relate water quality to flow, an average of two day's discharge readings was generated for each date when water quality readings were taken. The intention is to represent discharge as best as possible given the limitations of the reported daily records knowing that water quality varies with discharge in ways that range from determinate to (often) capricious. The water quality data were separated into two identified land development periods (1980-1990 and 1991-2002) and the median values of eight selected quality parameters such as BOD, SS, pH, temperature and conductivity were assessed for differences.

From the analysis of available water quality parameters for Langat and Linggi, there is an increase in each between 1980-1990 and 1991-2002 (**Tables 7.3 and 7.4**). For the Bernam catchment (**Table 7.5**), a slight increase appears from 1998-2000 to 2001-2002 for temperature, pH and conductivity, when development had just started. It is likely that the increases in Langat and Linggi reflect land clearance and efflux of industrial and domestic waste from urban areas during the 1990s onwards. However, nitrate and other chemical parameters show a decrease and this might reflect implementation of industrial and domestic waste discharge regulations under the Environmental Protection Act 1974 (amendment 1997). However, a test for statistical significance of differences reveals that only the BOD indicator shows significant changes that can be related with the changes in development. Therefore, the other parameters provide only a general indication of development. The quality of much of the data remains spurious e.g. the some of the chemical measurement parameters (Nitrate, Arsenic and Zinc) have similar, small values for consecutive even when discharge has changed. Therefore, most of the parameters were discarded, leaving BOD to be analysed thoroughly as an indication of urbanisation and degradation of water quality in the Langat and Linggi. As the quality of dataset used here is subject to limitations, the discussion must be very circumspect.

Table 7.3: Langat: Water quality status based on available parameters between period 1980-1990 and 1991-2002 due to urbanisation process (based on median value)

Parameter	Median value		Change	Statistical significant
	1980-1990	1991-2002		
BOD (mg l^{-1})	2.2	5.5	Increased	Significant, $p<0.000$; df = 15
SS (mg l^{-1})	169	324	Increased	Not significant; df = 24
Temperature (°C)	27	28.3	Increased	Not significant; df = 21
pH	6.5	6.7	Increased	Not significant; df = 19
Conductivity (uS m^{-1})	75	106	Increased	Not significant*
	1997-2000	2001-2002		
Nitrate (mg l^{-1})	0.7	0.66	Decreased	Not significant*
Arsenic (mg l^{-1})	0.015	0.004	Decreased	Not significant*
Zinc (mg l^{-1})	0.05	0.035	Decreased	Not significant*

Note: * data very sparse, degree of freedom (df) less than 5

Table 7.4: Linggi: Water quality status based on available parameters between period 1985-1990 and 1991-2002 due to urbanisation process (based on median value)

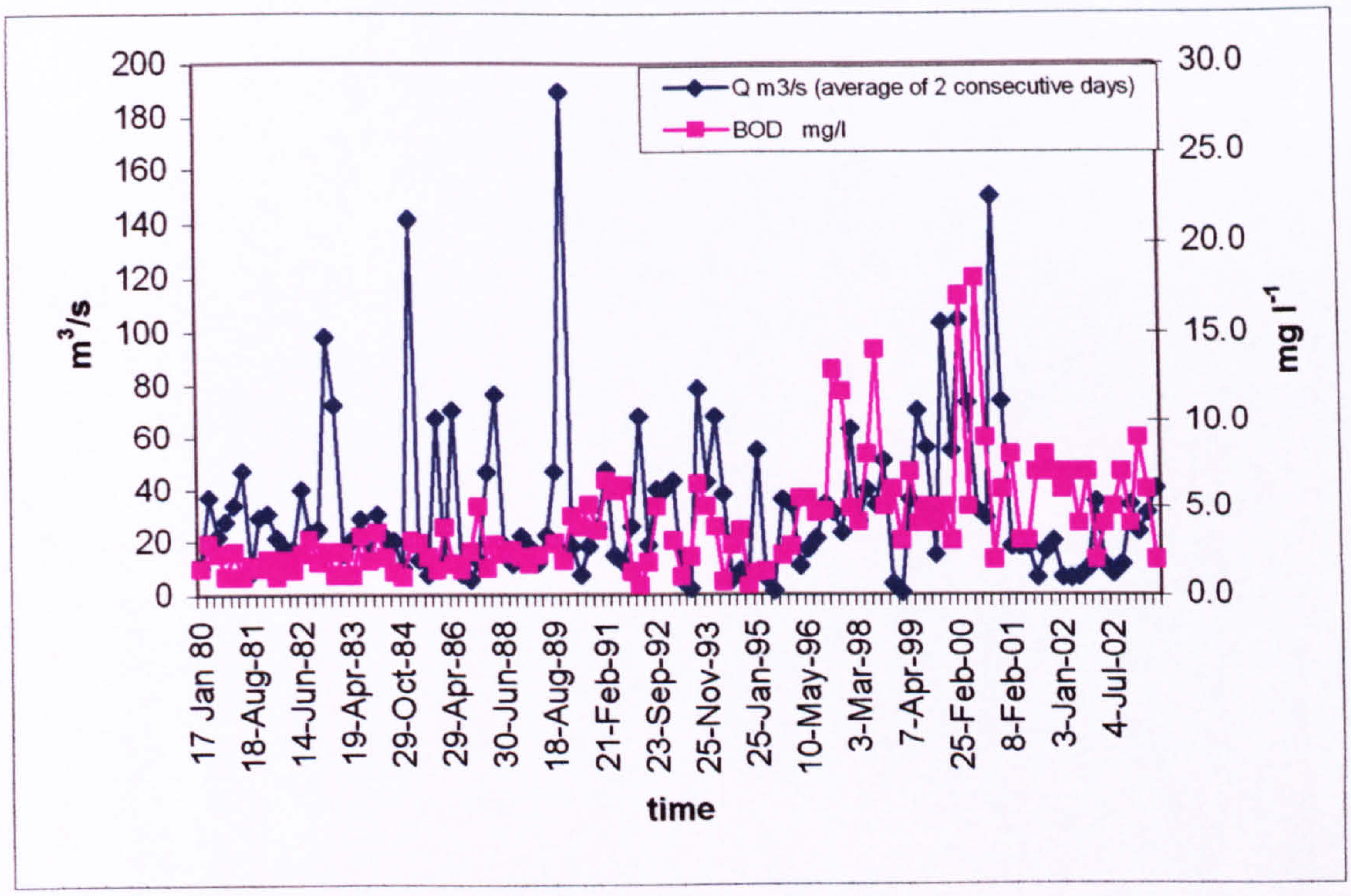
Parameter	Median value		Change	Statistical significant
	1985-1990	1991-2002		
BOD (mg l^{-1})	2.9	3.3	Increased	Significant, $p<0.05$; df = 20
SS (mg l^{-1})	138	128	Decreased	Not significant; df = 20
Temperature (°C)	27	28.5	Increased	Not significant; df = 18
pH	6.5	6.7	Increased	Not significant; df = 18
Conductivity (uS m^{-1})	90	130	Increased	Not significant; df = 18
	1997-2000	2001-2002		
Nitrate (mg l^{-1})	1.29	0.91	Decreased	Not significant*
Arsenic (mg l^{-1})	0.025	0.005	Decreased	Not significant; df = 16
Zinc (mg l^{-1})	0.05	0.05	Decreased	Not significant; df = 17

Note: * data very sparse, degree of freedom (df) less than 5

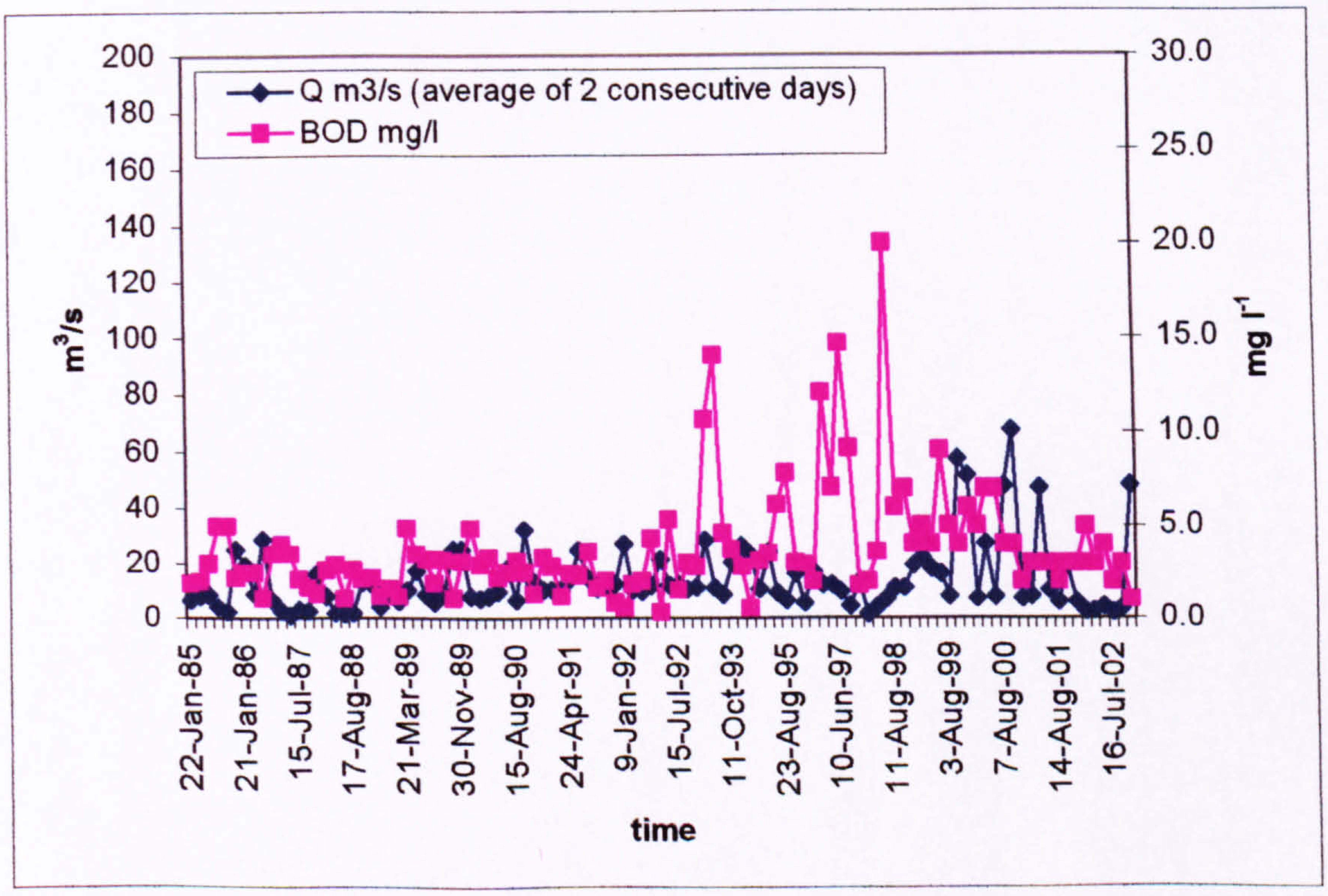
Table 7.5: Bernam: Water quality status based on available parameters between period 1998-2000 and 2001-2002 due to urbanisation process (based on median value)

Parameter	Median value		Change	Statistical significant
	1998-2000	2001-2002		
BOD (mg l^{-1})	2	2	No change	Not significant*
SS (mg l^{-1})	102	51	Decreased	Not significant*
Temperature (°C)	26.6	27.5	Increased	Not significant*
pH	6.6	6.78	Increased	Not significant*
Conductivity (uS m^{-1})	29.2	30	Increased	Not significant*
Nitrate (mg l^{-1})	0.36	0.30	Decreased	Not significant*
Zinc (mg l^{-1})	0.02	0.03	Increased	Not significant*

Note: * data very sparse, degree of freedom (df) less than 5



(a) Langat



(b) Linggi

Figure 7.9: Langat and Linggi catchments – Average of two consecutive days discharge and biological oxygen demand (BOD), 1980-2002

From these datasets for BOD, there is no clear-cut indication of the role of discharge in diluting the pollutant. However, occasionally, when discharge is very high BOD is small. (**Figure 7.9 – a** and **b**). The **Figures 7.10** and **7.11** show that there are some high values of BOD recorded at modest levels of discharge level. These occur in the wet season. At the beginning of rain season, surface runoff potentially brings higher pollutant loads of from urban waste. There are also illegal flush-outs from small industrial factories which are located along the river banks. As reported by DOE and the local authority (Ithnin and Sakke, 2000), the owner takes the opportunity during the wet season given by heavy rain days. Other sources are urban sewage ponds overflowing. In addition, BOD levels rise during low discharge when an effluent is released to the river during the dry season.

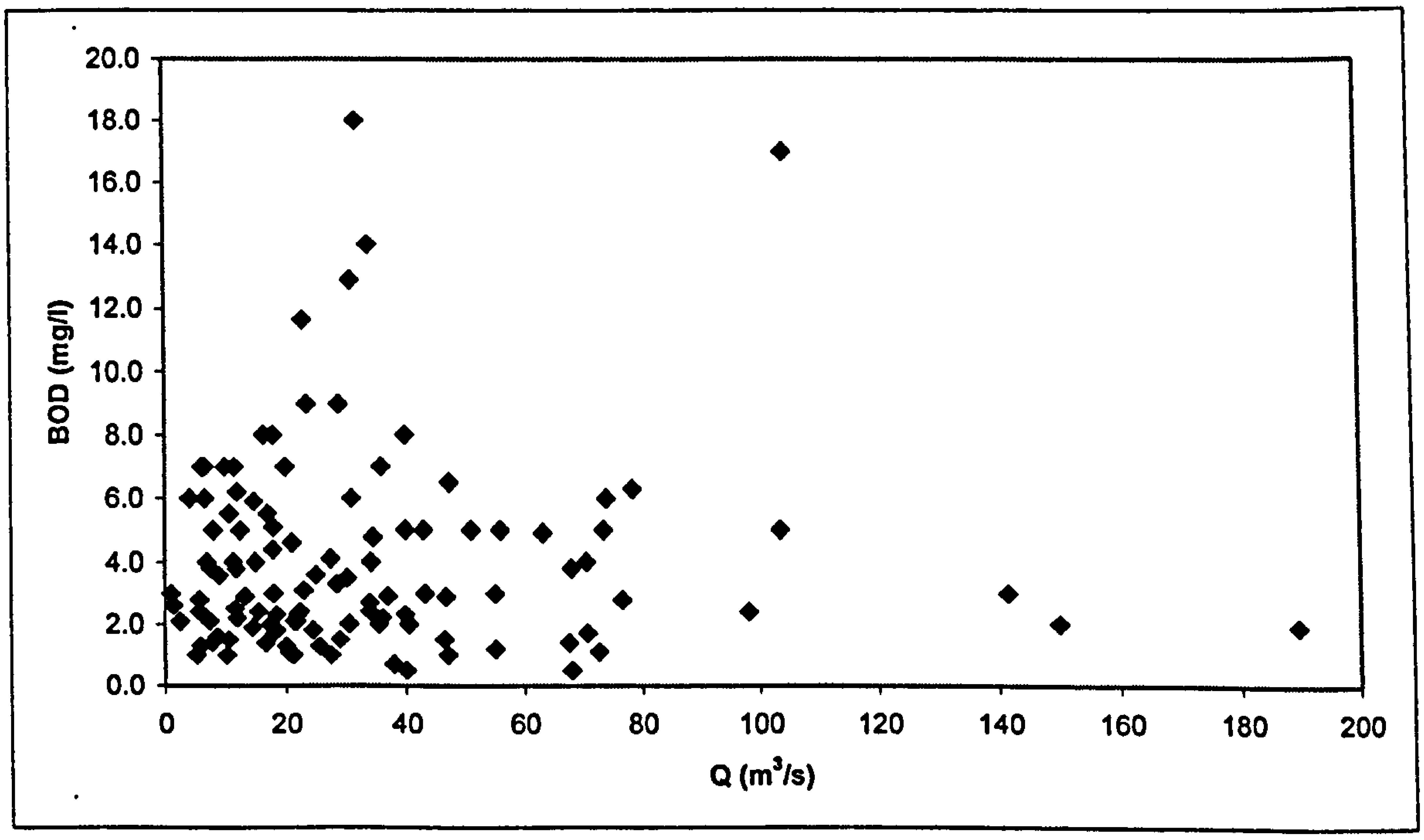


Figure 7.10: Langat catchment – biological oxygen demand (BOD) vs discharge (Q), 1980-2002

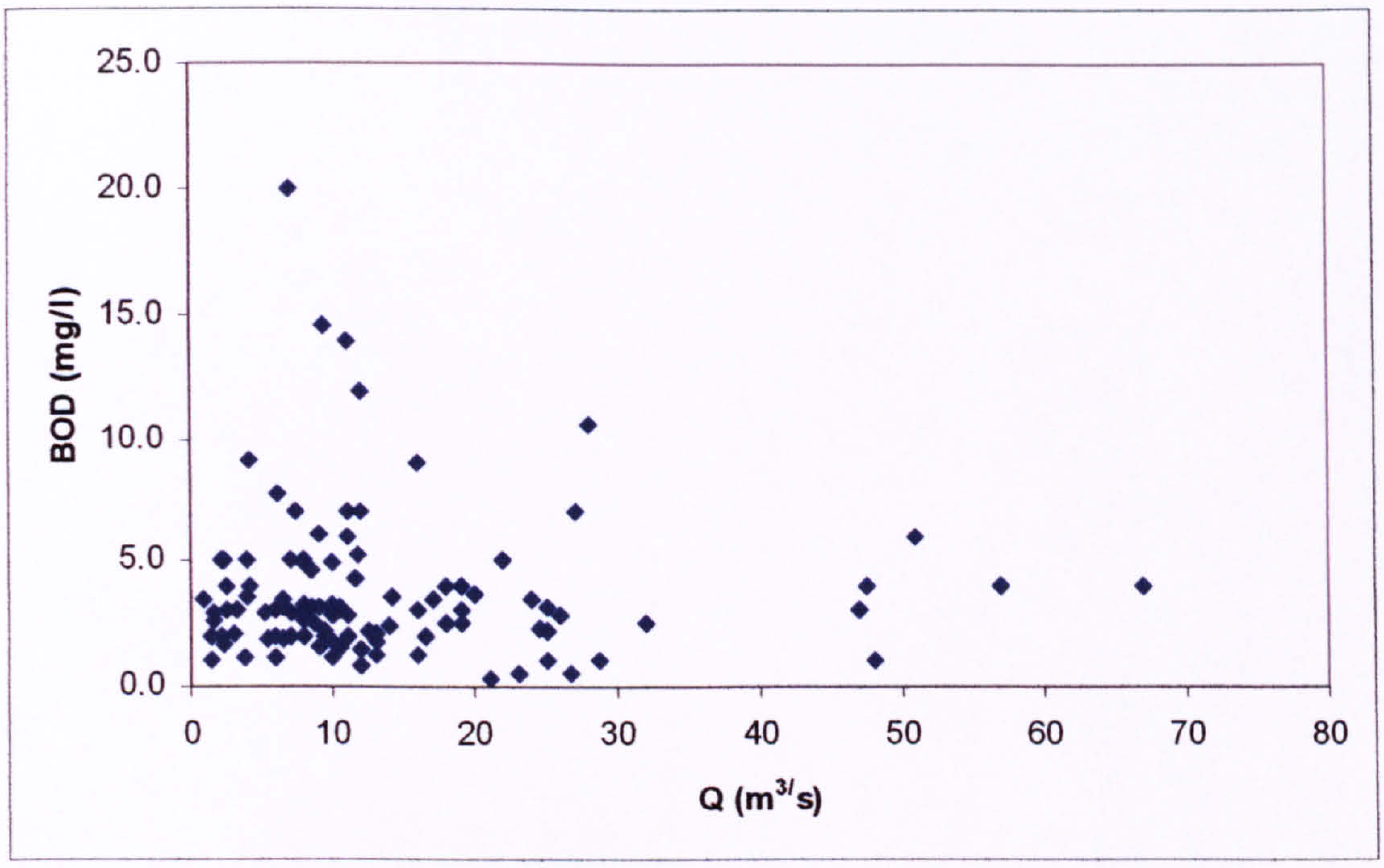


Figure 7.11: Linggi catchment – biological oxygen demand (BOD) vs discharge (Q), 1985-2002

As urbanisation expands after the 1990s, BOD levels rise between 1991-2002 in both the Langat and Linggi catchments (**Figures 7.12** and **7.13**). This reflects a similar pattern as the very early (1980-1987) and later (1995-2001) periods of urbanisation especially in the Langat catchment (**Figures 7.14** and **7.15**).

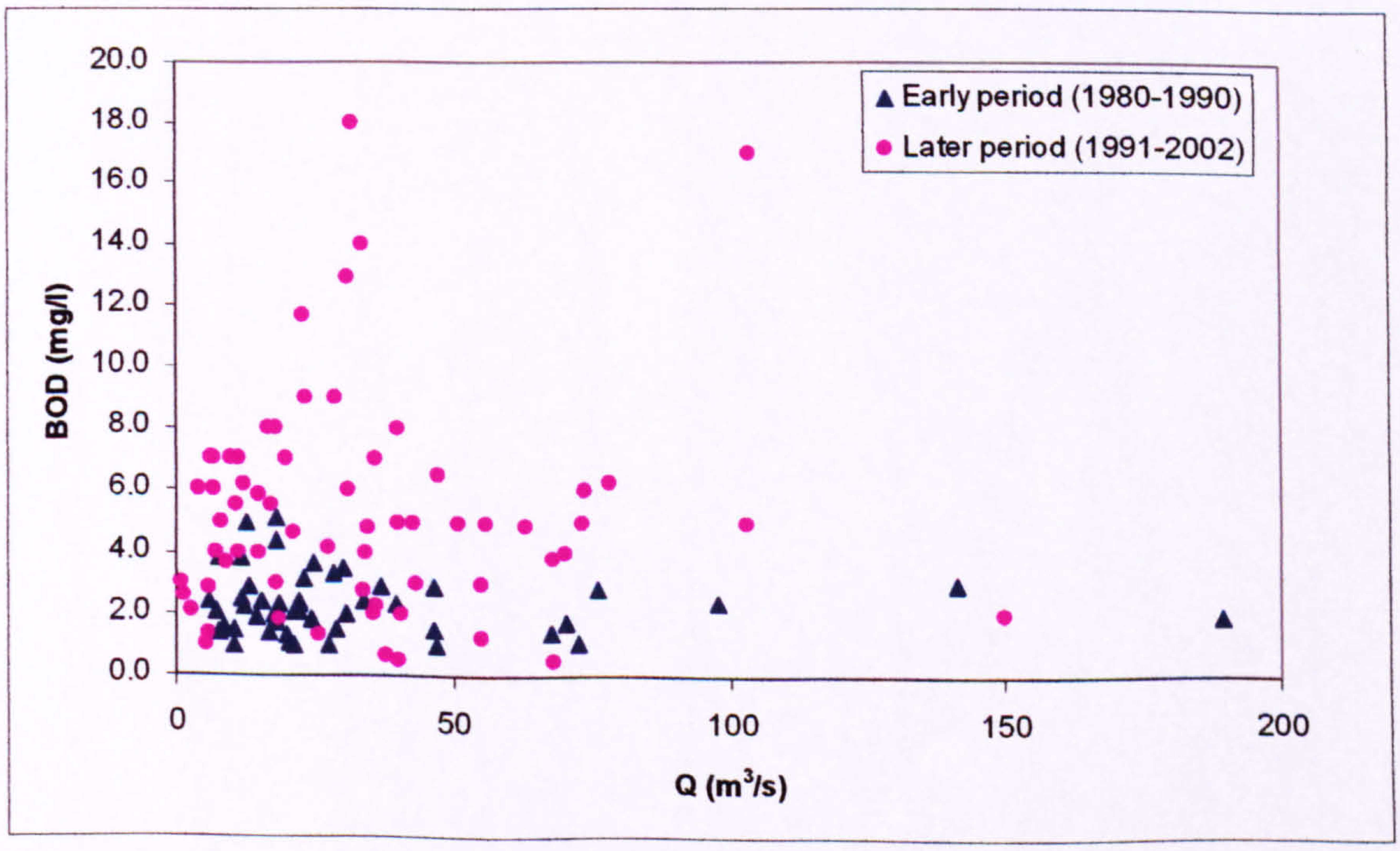


Figure 7.12: Langat catchment – biological oxygen demand (BOD) vs discharge (Q), for early and later periods

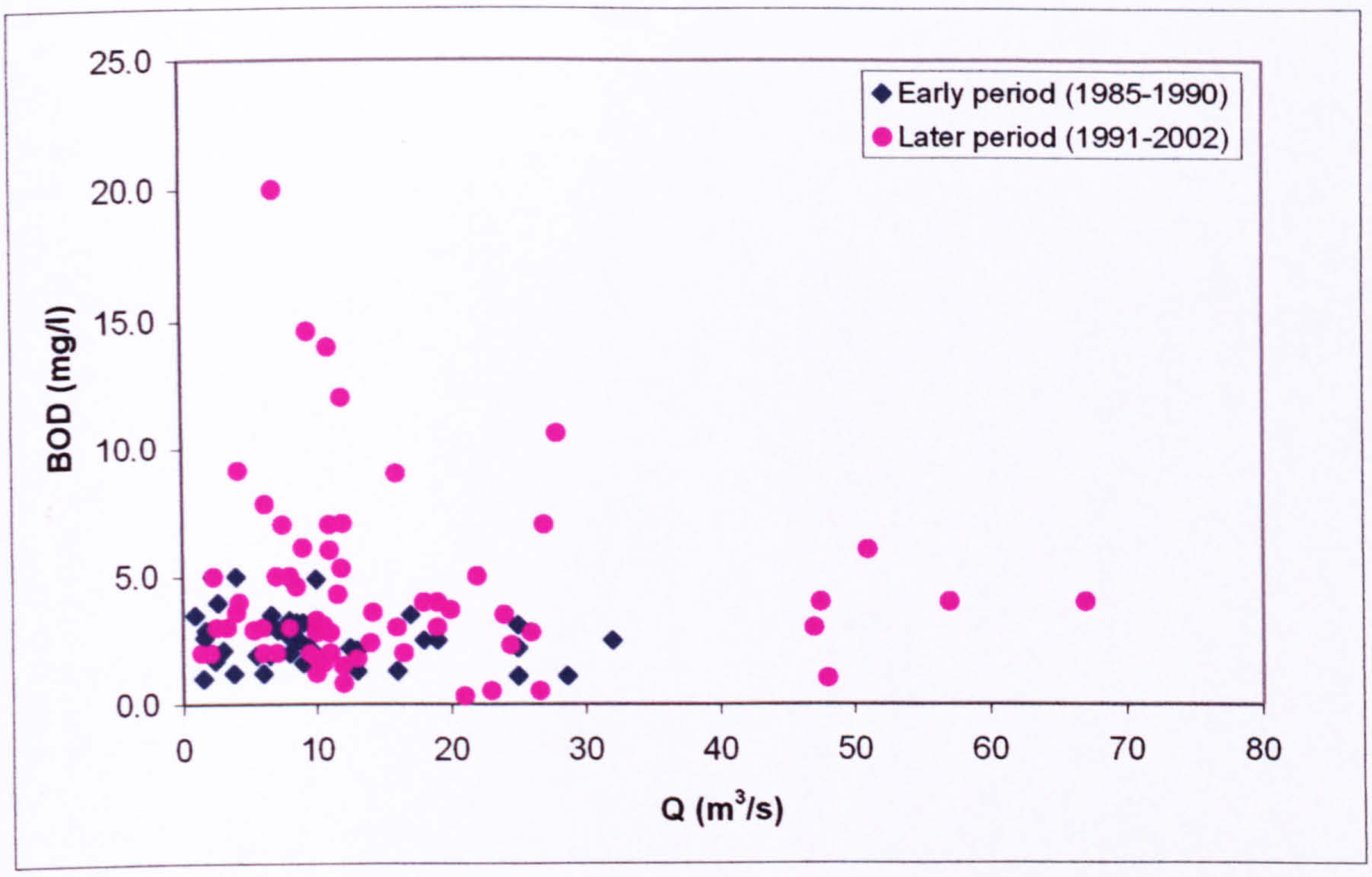


Figure 7.13: Linggi catchment – biological oxygen demand (BOD) vs discharge (Q), for early and later periods

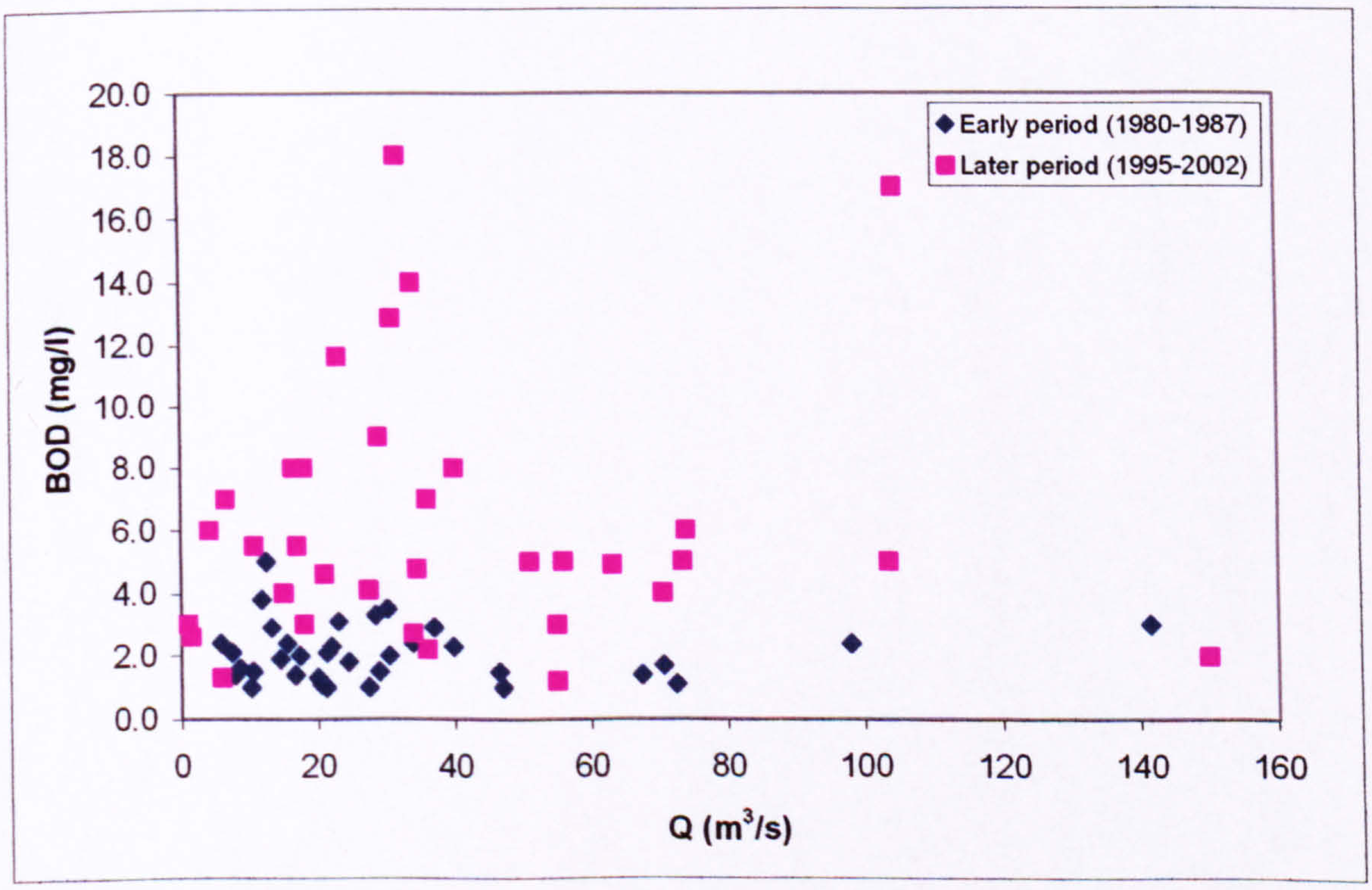


Figure 7.14: Langat catchment – biological oxygen demand (BOD) vs discharge (Q), for very early and later periods of urbanization (full range of Q)

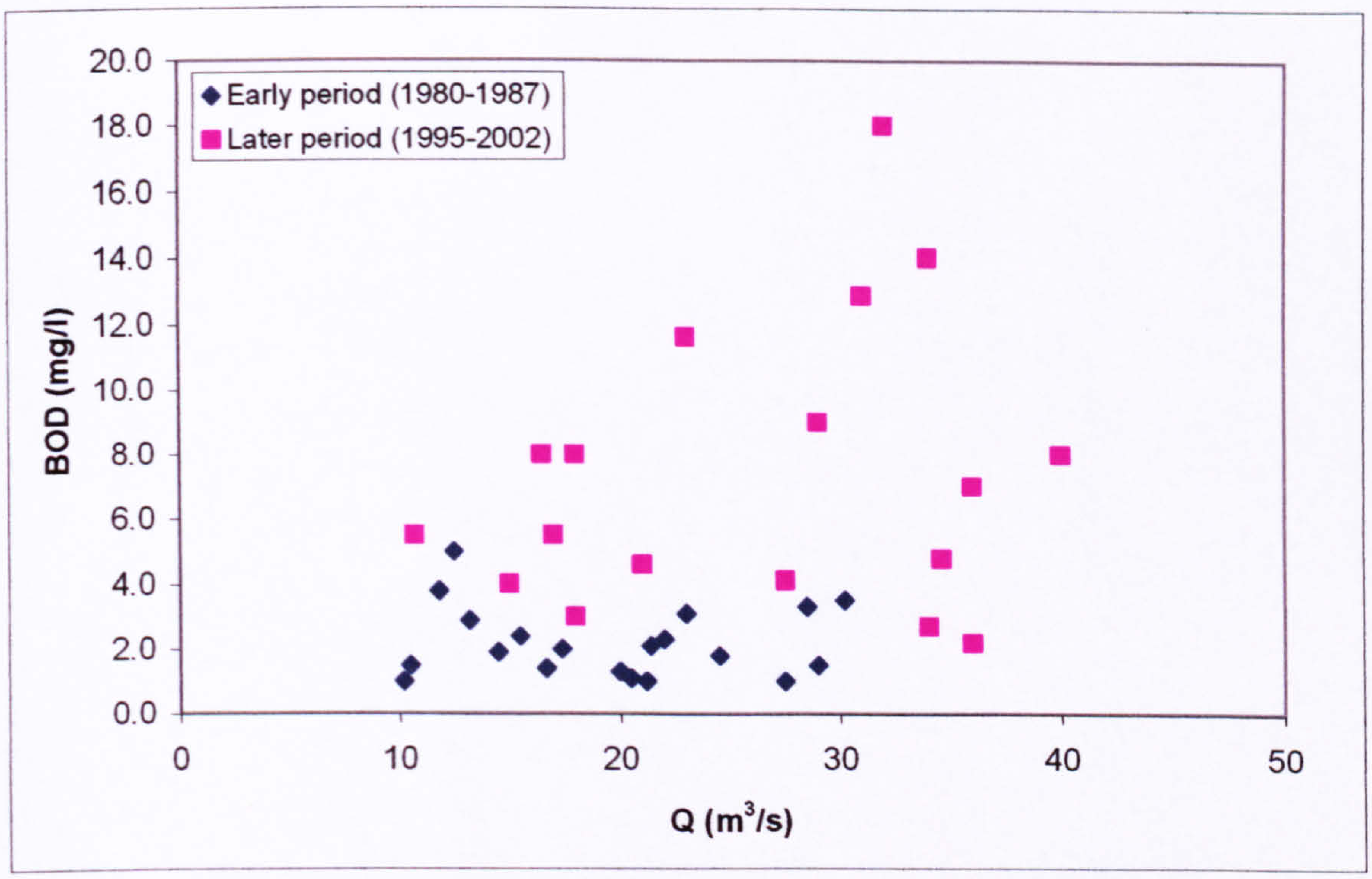


Figure 7.15: Langat catchment – biological oxygen demand (BOD) vs discharge (Q), for very early and later periods of urbanization (smaller range of Q)

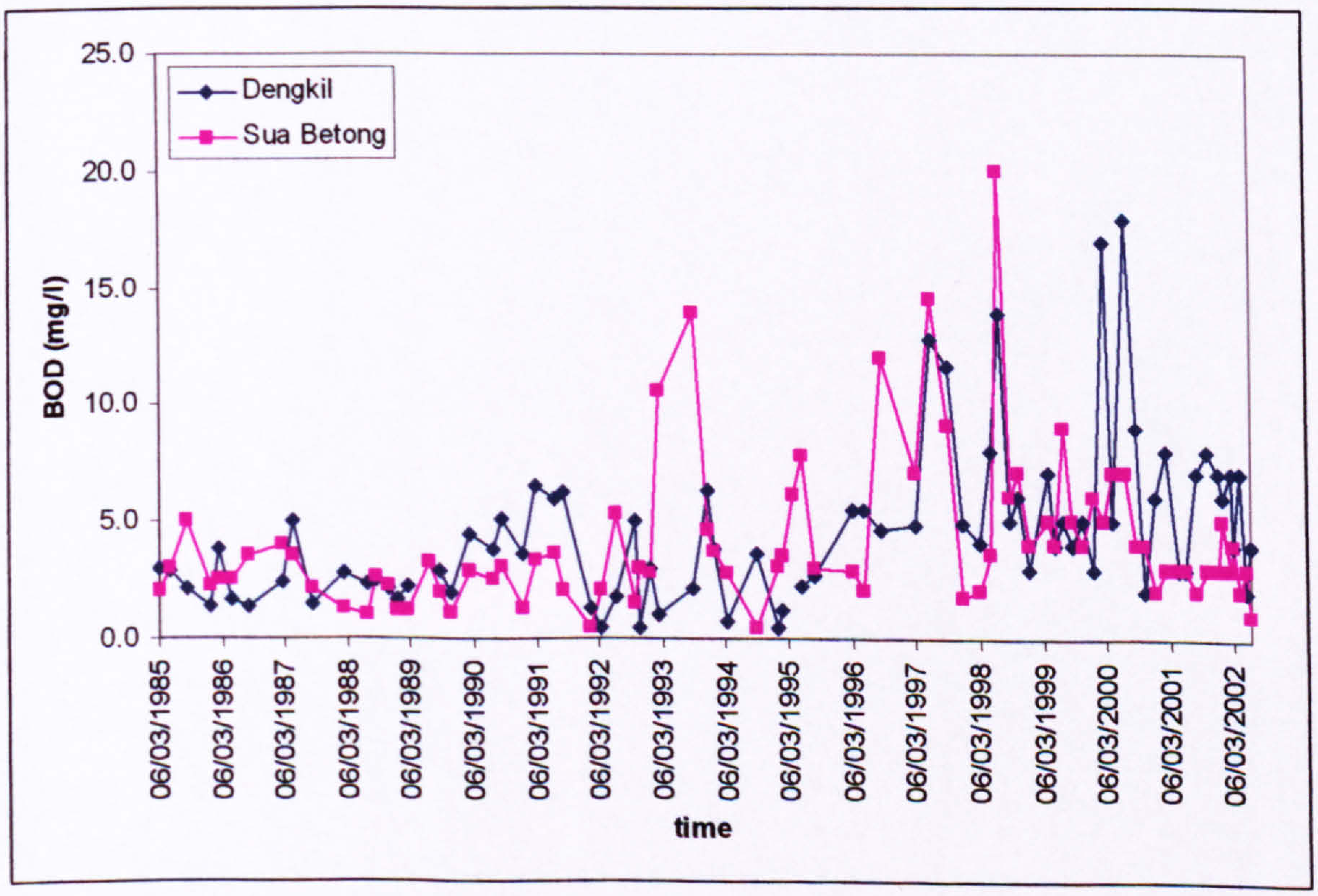


Figure 7.16: Langat and Linggi catchments – the level of biological oxygen demand (BOD), 1985-2002

Through an investigation of the limited data sources, it is concluded that the impact of urban expansion in the Langat and Linggi catchments which has caused a significant increase in pollutant of the river system. The BOD trend clearly increases for both catchment especially after 1997, which, in this case, reflects the contribution from domestic waste water (**Figure 7.16**). The shift of development emphasis by the Federal Government, which chose the adjacent river basin of the Klang Valley as the new hub of development during the later half of 1990s by placing the mega-project of Kuala Lumpur International Airport and the new administrative centre of Malaysia (Putrajaya), has placed heavier pressure on neighbouring catchments to maintain clean water resources for various needs. The main source of the BOD, as reported by DOE in the early period of the 1970s, when it came from rubber and oil palm factories has shifted to the urban population. As the urban population is projected to reach one million in the Langat river basin by 2010, the possibility of deterioration water ability remains high. For Bernam, there is a need for proper planning of buildings and housing infrastructure in order to minimise any impact on water quality.

7.4 Summary

This chapter has evaluated the appropriateness of the using available SSC and flow data for sediment yield calculations in the study catchments. It was originally hoped that suspended sediment yield data would be able to corroborate other water quality status data and reflect land use changes. However, the establishment of transfer functions from SSC-Q data has been constrained by data limitations and unexplained errors. This means that much of the analysis has not been possible to perform. The intercept values of the SSC-Q relations show no significant trends that relate to land use changes. The only information that appears to reflect the impact on water quality of land use changes is that for BOD, which shows some evidence that it increases in the Langat and Linggi after the catchments have been through a period of urban expansion between 1984 and 2002.

Chapter Eight reviews the aims and objectives set-up earlier in this study, suggesting directions for future research. It then draws conclusions from the work carried out to date.

CHAPTER EIGHT:
CONCLUSIONS

8.1 Introduction

This concluding chapter evaluates the research achievements in relation to the aims and objectives set up at the outset. It provides an honest appraisal of the problems faced in examining the impact of land use change on water relations within the study catchments. Based on the findings, this chapter highlights some of the directions for future research in catchment research in the wet tropics.

8.2 Research Achievements

Land use change reflects the complex interaction of human behaviour and structural factors associated with demand for products, technological capacity, and changing social relations as these affect the environment and are, in turn, affected by environmental capacity (Verburg, *et al.* 2004). Hydrologists have given considerable attention to the impact of land use changes, particularly with respect to their effects on water yield (Turner *et al.,* 2001). As a tropical economy growing rapidly, Malaysia launched in 1990 a big development plan through Vision 2020 in order to be a developed nation by the year 2020.

To be a developed nation means that the focus of the economy has to change quite dramatically from agriculture to industry in order to boost the economy growth. This led to global discussion on how Malaysia would manage the countryside, which is still largely covered by tropical forest and which provides a sustaining influence on the global environment (Jamaluddin, 2000; Abdul Hadi and Abdul Samad, 2000). As the vegetation faces disturbance, there will be more pressure put on the quantity and quality of the water resources of people living downstream. There is a conflict of interests involving the need to conserve forest resources and the desire to generate space for more development, especially in catchments as yet untouched. The Langat, Linggi and Bernam catchments which have been used as study areas in this research have been subjected to disturbance of the watershed through land use activities which alter hydrological processes such as infiltration, surface runoff and water yield, surface erosion and sediment yield, and groundwater recharge.

First research objective – data validation assesment. To understand water resources in the wet tropics require information on the past and present spatial and temporal variability of rainfall, as well as the hydrological response to development policies and climate change (Manley and Askew, 1993). For this research, all the data for Langat, Linggi and Bernam have been through a thorough validation process. The historical hydrological, water quality and land use data obtained from various government agencies in Malaysia are incomplete. Many of the datasets contain errors especially that for suspended sediment discharge, where it has been discarded even though there are claims that monitoring processes followed established procedures. A thorough data screening and validation exercise has been necessary to provide a set of records of acceptable quality. For instance, through this process, it was found that rainfall data collection in all catchments is affected by changes in rain gauge type from 1973 onwards, but DID failed to note this during data gathering. A transfer function has been established using a dataset for the period 1973-2000 which is arguably of better quality and can be used to correct data for the period 1960-1972 in all three catchments.

Lack of the quality available records for the period before development in the Langat and Linggi, contributes to an uncertain explanation of rainfall-runoff response and water quality status which could be vital to an understanding of the trends of rainfall-runoff ratio throughout the development phase. Wilk *et al.*, (2006) has stressed that the assessment of water resources over large or small river basins is often complicated by limited data availability and this leads to lower accuracy of prediction. The data sources for this Malaysian study are not exceptional in this regard.

Second and fifth research objectives – morphometrics and analogue catchment assessment. As catchments in Peninsula Malaysia are increasingly subjected to land development projects, there is a pressing need to investigate the impact of land use change on water yield and water quality. As a contribution to this need, this study focuses on two developed catchments - Langat and Linggi - to assess their mophometrics in preparation for their use as analogues for development elsewhere. From the analysis, the Langat catchment is a good analogue for the comparatively undeveloped Bernam, with similar characteristics especially total area, drainage density and shape of catchment. Even though the Linggi catchment is small, it has not been left out of the analysis since it gives some indications that allow us to understand the rainfall-runoff response during the vital development period. By using the finding from these catchments, information is available about the likely hydrological response when forest and agricultural areas are clear for urbanisation. The findings will help development authorities to manage and minimise the impact of land development in newly developed catchments such as the Bernam.

Third research objective – El Nino and La Nina-related phenomena assessment. The Langat, Linggi and Bernam catchments, situated in the tropical region, are subjected to the influence of shifting patterns of global atmospheric circulation now known to be influenced by periodic changes in ocean-atmosphere interactions in the eastern Pacific. The severe effect of drought in Southeast Asia in 1997-1998 has been reported by Kane (1999), but there has been no specific study by local meteorologists of the impact on catchment water resources, even though the authorities of the Klang, Langat and Linggi Valleys have been forced to ration water and bring in water from the other areas to cope with the demand from the population, agriculture and industry. However, the Malaysian Meteorological Office (MMO) Centre does monitor these atmosphere-ocean phenomena as they impact on local climate.

This study has revealed the impact of El Nino Southern Oscillation (ENSO) events of 1958, 1972, 1983, 1990 and 1998 on annual rainfall catch within the study catchments. The deviation of annual rainfall from the long-term mean (2508 mm) was -260, -574, -437, -416 and -403 mm during each ENSO year, respectively. According to the MMO Centre, the latest Sea Surface Temperature (SST) data and information for the central Pacific Ocean have indicated that already severe conditions are expected to worsen in the region in 2007 (Department of Meteorology, 2006). Indeed, there is need for urgent planning as economic development goes on.

Fourth research objective – assessment of key relations between hydrology, water quality and land use change. This objective intends to quantify the type and magnitude of land use changes and assess their impact on water yield and water quality within the study catchments. From this research, significant trends in land use change throughout the three catchments have been documented for the period 1984 to 2002, confirming that tropical countries such as Malaysia have undergone very rapid changes involving deforestation, agricultural conversion and urbanisation. The major driving forces behind these activities are the expanding economy and population growth. Many urban developments have been permitted on floodplains by local authorities. In assessing the impact of land use change on hydrology, it is important to consider the impact of new land uses on water quality and rainfall-runoff. According to Braga (2001), many urban communities in both the developed and developing world currently face difficulties in supplying an adequate quantity of water with acceptable quality for domestic, industrial and other uses. For this reason, methods for predicting the impact of land use change in areas which are vulnerable to urbanization are important (Schoonover and Lockaby, 2006).

The results of pursuing this objective are based on the integration of the various sources of land use maps and a primary analysis of Landsat imagery. This study has produced a new set of eight land classifications which can be closely related to water yield and water quality impact of development. This is an improvement on the previous studies in the area which developed five broad land use class. These new classification can be applied to other hydrological studies elsewhere in the wet tropics, where there is a need to investigate the potential impact of land use change on the water yield and water quality. In the field studied here, the results clearly show the trend of changes from natural forest to agriculture at the beginning of a development phase and, later, the focus on urbanisation at the expense of both the forest area and agricultural area. To detect any significant impact on water yield is quite complicated, because the tropical system is complicated. However, the expansion of urban area is clearly related to deterioration of water quality through BOD.

Rainfall is an important element in land use and rainfall-runoff relation studies which then reflect to the ability of river manager to make a good planning of water resources. Malaysia has a humid tropical climate and it experiences predominantly convective precipitation. It receives abundant rainfall, with an annual average of more than 2540 mm and with most places receiving rain everyday. Surprisingly, this study found that rainfall spottiness is very significant not only between catchments but within a single catchment. For instance, the covariation of catch values between rain gauges in the Langat, Linggi and Bernam catchments lies between 0.52-0.79 as distances between gauges falls from 11 to 0.2 km. This corroborates the conclusions of Desa and Niemczynowicz (1996) who stressed that temporal and spatial variations in humid tropical rainfall is a feature of short-term records (i.e. daily and monthly). To overcome the variability over a catchment, a systematic areal averaging technique has been applied using the long-term rainfall record (annual). The variability of the rainfall within a catchment is important to understanding the timing and volume of runoff.

The rainfall-runoff relation of the Langat and Linggi catchments showed no significant change. From the analysis, there is no significant increase in water yield (runoff) through 42 years of development. This development phase started from conversion of natural forest to agriculture crops, followed by the conversion of rubber trees to another more economical valuable crop such as palm oil trees. The current trend is for conversion of some of these agricultural areas and for some areas of natural forest through urbanisation and industrialisation.

The end-effect of any kind of land conversion within a watershed is a degraded environment. The river basin plays a significant part in water resources for various needs. As the urban area expands and with people migrating from rural areas, living standards increase and this causes ever increasing demands for good quality municipal and industrial water. Therefore, the river should be protected from pollution. As the pollution load increases, resources are required in order to treat the water to quality levels which are safe for drinking. In the Langat, increasing BOD reflects a significant increase in domestic sewage and industrial waste discharges to the river as a function of higher population and industrial growth since the 1990s. This is an inevitable fate for the Bernam River as economic development increases.

Sixth research objective – development of of a transfer function for the Bernam. From the rainfall-runoff study in the developed Langat and Linggi catchments, a transfer function was to be established in order to predict the impact of land development on water relation in the Bernam. However, throughout the development period, the runoff-rainfall coefficient for both Langat and Linggi lies between 22-48 % and a similar range is also recorded in Bernam, where the catchment is yet to be developed. This could be highlighted as 'good' news for the developers, especially in the Bernam basin, as they are always blamed for water resources degradation in Malaysia. But this finding refers only to water yield; the quality of the water remains a big issue at national level. On the one hand, there is benefit that water flow maintains the availability of surface water resources. However, water quality has been shown to deteriorate, especially the suspended sediment concentration, mainly arising from land clearance. In the case of a rainfall-runoff relation, it was unnecessary to develop a transfer function that could be used to assess the likely future change in water yield in the Bernam, since the changes are not significant.

This is a counter-intuitive but important finding as many experimental catchments in the tropics suggest that there is a significant increase in runoff when natural forest are been cleared. However, there are findings from experimental catchments to corroborate the results for Langat and Linggi where, after 4-5 years of forest conversion to agriculture, the storm-flow returns the level it previously reflected under forest as a function of secondary growth (Abdul Rahim and Zulkifli, 2004; Bruijnzeel, 2004). For a comparatively large catchment, such as the Langat and Linggi, where the rate of urban development, through rapid since 1990, still cover only 14 % and 18 % of the catchment, respectively, by 2001, it is still dominated by vegetated surfaces (natural forest, rubber tree, oil palm tree and transition – grassland, pasture, orchards and horticulture). Small experimental catchments may not be able to provide information that translates directly to bigger study catchments.

The literature suggests that there is an impact on rainfall-runoff and water quality with urbanization and development. This study shows that, in moderate-sized catchments of c. 1000 km^2 in the wet tropics, the outcome is less straightforward. While water quality deteriorates, the fraction of rainfall leaving the drainage basin through the gauging station remains similar where tree crops are important replacement for native forest and where urbanization covers less than 20% of the catchments. Nevertheless, water quality considerations dictate that the catchment must be protected and managed to balance the needs of development against those of preservation of forestland. The initial intention to establish a predictive tool of land use impact on water relations i.e. a transfer function developed in analogue catchments that could be used to mitigate the effects of development has been abandoned in favour of assessing hydrological process-response in catchments as yet to be developed so that the findings can be used to inform land use management.

8.3 Research limitations and the direction of future research

As the developing world economies keep growing, the relationship between human population and deforestation will continue and this obviously highlights that more stress will be placed on the already deteriorating natural resources of watersheds, especially in the wet tropics. Therefore, a comprehensive study of the impact of disturbance of tropical watersheds on water yield and water quality is required. However, within such a study, problems inevitably arise which limit the outcome and achievements, as discovered here. The main problems with archived data are the incomplete nature of each dataset and the lack of data quality control by the data provider (in this case, government agencies). The availability of datasets also becomes a factor because many hydrological monitoring station do not have long-term records and do not provide good areal coverage (number of station) in a river basin. This is a problem throughout the country. For instance, discharge data are only available in daily average form instead of at minute or hour intervals and the number of gauging stations within a catchment is limited, with no stations situated in headwater areas which could be used as control stations for purposes of hydrological and land use studies. In addition, the water quality data is not continuously monitored and the number of parameters available is limited.

As a developing country just 50 years since independence, these issues might be expected due to lack of expertise and inferior equipment. However, the agencies have been in existence and financed by government (i.e. DID and DOE) since the 1970s. Millions of Ringgit Malaysia has been allocated by government for the purposes of monitoring, which should have given the data provider the resources to monitor, collect and evaluate all data efficiently. For a study of land use change and its impact on water relations, it is vital to have complete historical data. Complete datasets would be able to provide sufficient information to detect any changes during progression of land development, especially in pre-, pro- and post-development phases. These would help researchers to predict the potential impact of development on rural catchments that are due for future development. Improvements in data gathering should be done sooner rather than later for the purpose and benefit of future research in this field.

This research has made attempts to recognise the relation between water yield and water quality and land use changes. It has been thwarted by data limitations, especially those relating to water quality. Therefore, suspended sediment yield, which could act as one of the indicators of the magnitude of changes in land use within the study catchments, cannot be established. The water quality data i.e. BOD, SS, pH, Temperature, Conductivity, Nitrate, Arsenic and Zinc are only available for short periods and are not continuous so that all-important short-term rainfall-induced flushes and dilutions cannot be detected. In future, all water quality indicators should be examined thoroughly in conjunction with rainfall-runoff. Therefore, a study of a modest sized headwater catchment (i.e. one or two years duration geared to the hydrological calendar) is vital to primary data collection in order to provide useful base-line information that can be used to understand the complexity of hydrological responses due to land use change.

This research shows that there are lot of issue that can be improved in this field of study especially in Malaysian catchments. So, for example, smaller monitoring intervals would allow estimation of quick-return flow and, consequently, hydrograph separation. Hydrograph separation is important in order to understand the varying contribution from ground water where different lithology causes differences in low flow within the river system. Separation also helps to determine the rainfall hang-over from one storm to the next. Therefore, in future, primary data collection should allow hydrologists to explain the lag between rainfall and runoff and differences in response between seasons.

This research also reveals that the Bernam catchment has a larger rainfall catch compared with the Langat and Linggi, even though both of catchments are situated on the West coast of the Peninsula and close to each other. The upper part of the Bernam catchment is still largely covered by natural forest and instrumentation is needed to understand its hydrological behaviour. In addition, a study on different land covers and their effect on runoff and water quality during monsoon and inter-monsoon seasons is required in order to detect the scale of impact arising from future land-use changes. From this information, a predictive model might be established which could be used to recognise the likely impact of any future land development in catchments which have similar physical characteristic. This would be useful for local authorities and project managers.

This research has revealed that a medium size catchment has a very complicated rainfall-runoff response. This contrasts with studies carried out by many researchers on small experimental catchments. The impact of land use changes has been found to be less straightforward where the catchment is still largely covered by vegetation. Within Malaysia, a similar study should be conducted on the East coast of the Peninsula or in Borneo (Sabah and Sarawak) where the monsoon emanating from the South China Sea brings heavy rainfalls.

There is no doubt that population and economic growth and the influence of globalisation have brought more rapid change to tropical countries than those of temperate regions in the last thirty years (The World Bank, 1998). The disturbance of tropical watersheds by deforestation cover has raised global alarm because carbon sequestration by tropical rainforests is believed to be closely related to global climate stability and catchment hydrology. The serious 1997 economic recession in South East Asia also contributed to environmental degradation (i.e. intensification of traditional slash and burn of forest land for agriculture in Sumatra caused severe haze episode for the region).

To conclude, an integrated study of land use, climatology and hydrology within river basins is essential to understanding the potential impact on the water quantity and water quality of an expanding population that is increasingly urbanised. This study provides information for the local river manager and development planner that will assist in minimizing negative impacts of development on water resources while promoting sensible planning within river basins.

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Appendix 1: Summary of morphometric properties for all three catchments

Langat catchment

Characteristics	Catchment	Sub-Catchment (Gauging Station)			
		Lui	Kajang	Semenyih	Lenggeng
Area (km²) *(Tamaya Digital Planimeter-Planix 7 Japan)*	1257	78	366	248	220
Drainage Perimeter (km) *(Map wheels/ Opisometers)*	186	34	104	77	63
Drainage Density (km/km²)	**Dd=4.2** Approximate value based on systematic random sampling for 3 point of 25 km² area in upstream, middle and downstream				
Stream Order *(Strahler, 1952)*	1- 5169 2- 1261 3- 276 4- 52 5- 14 6- 4 7- 1 (7)	1- 185 2- 43 3- 13 4- 5 5- 2 6- 1 (6)	1- 1342 2- 314 3- 75 4- 21 5- 5 6- 1 (6)	1- 976 2- 233 3- 59 4- 13 5- 3 6- 1 (6)	1- 708 2- 235 3- 51 4- 14 5- 4 6- 1 (6)
Bifurcation Ratio	1/2=4.10 2/3=4.57 3/4=5.31 4/5=3.71 5/6=3.50 6/7=4.00 Rb=4.20	1/2=4.30 2/3=3.31 3/4=2.60 4/5=2.50 5/6=2.00 Rb=2.94	1/2=4.27 2/3=4.19 3/4=3.57 4/5=4.20 5/6=5.00 Rb=4.25	1/2=4.19 2/3=3.95 3/4=4.54 4/5=4.33 5/6=3.00 Rb=4.00	1/2=3.01 2/3=4.61 3/4=3.64 4/5=3.50 5/6=4.00 Rb=3.75
Total Length (L) (km)	52 *104.55cm x 0.5km*	12 *23.4cm x 0.5km*	33 *66.9cm x 0.5km*	26 *52.8cm x 0.5km*	16 *32.85cm x 0.5km*
Shape of catchment					
Form Factor *(Horton, 1932)*	0.451	0.532	0.322	0.348	0.794
Circulatory Ratio *(Miller, 1953)*	0.449	0.774	0.416	0.513	0.672
Elongation Ratio *(Schumm, 1956)*	0.760	0.280	0.641	0.666	1.006

Linggi catchment

Characteristics	Catchment	Sub-Catchment (Gauging Station)		
		Pantai	Seremban	Mambau
Area (km^2) *(Tamaya Digital Planimeter-Planix 7 Japan)*	528	24	189	240
Drainage Perimeter (km) *(Map wheels/ Opisometers)*	127.00	24.5	74.4	82.33
Drainage Density (km/km^2)	**Dd=4.1** Approximate value based on systematic random sampling for 3 point of 25 km^2 area in upstream, middle and downstream			
Stream Order *(Strahler, 1952)*	1- 2740 2- 651 3- 130 4- 26 5- 4 6-1 (6)	1- 152 2- 37 3- 9 4- 1 (4)	1- 1156 2- 257 3- 56 4- 12 5- 3 6- 1 (6)	1- 1373 2- 317 3- 69 4- 14 5- 3 6- 1 (6)
Bifurcation Ratio	1/2=4.21 2/3=5.01 3/4=5.00 4/5=6.50 5/6=4.00 Rb=4.94	1/2=4.11 2/3=4.11 3/4=9.00 Rb=5.74	1/2=4.50 2/3=4.59 3/4=4.67 4/5=4.00 5/6=3.00 Rb=4.15	1/2=4.33 2/3=4.59 3/4=4.93 4/5=4.67 5/6=3.00 Rb=4.30
Total Length (L) (km)	39 *77cmx0.5km*	10 *19.8cmx0.5km*	18 *36.5cmx0.5km*	23 *46.2cmx0.5km*
Shape of catchment				
Form Factor *(Horton, 1932)*	0.400	0.206	0.556	0.443
Circulatory Ratio *(Miller, 1953)*	0.397	0.422	0.420	0.438
Elongation Ratio *(Schumm, 1956)*	0.660	0.512	0.841	0.751

Bernam catchment

Characteristics	Catchment	Sub-Catchment (Gauging Station)		
		Tanjong Malim	Bernam-Tanjong Malim (L)	Slim-Trolak (R)
Area (km^2) *(Tamaya Digital Planimeter-Planix 7 Japan)*	1123	179	502 (Left trunk)	621 (Right trunk)
Drainage Perimeter (km) *(Map wheels/ Opisometers)*	175	60	96	129
Drainage Density (km/km^2)	Dd=4.6 Approximate value based on systematic random sampling for 3 point of 25 km2 area in upstream, middle and downstream			
Stream Order *(Strahler, 1952)*	1- 5803 2- 1366 3- 287 4- 61 5- 13 6- 3 7- 1 (7)	1- 1129 2- 265 3- 56 4- 14 5- 3 6- 1 (6)	1- 2598 2- 628 3- 136 4- 34 5- 8 6- 2 7- 1 (7)	1- 3205 2- 738 3- 151 4- 27 5- 5 6- 1 (6)
Bifurcation Ratio	1/2=4.25 2/3=4.78 3/4=4.70 4/5=4.69 5/6=4.33 6/7=3.00 Rb=4.29	1/2=4.26 2/3=4.73 3/4=4.00 4/5=4.67 5/6=3.00 Rb=4.13	1/2=4.14 2/3=4.62 3/4=4.00 4/5=4.25 5/6=4.00 6/7=2.00 Rb=3.84	1/2=4.34 2/3=4.89 3/4=5.59 4/5=5.40 5/6=5.00 Rb=5.04
Total Length (L) (km)	41 *81cmx0.5km*	17 *33.1cmx0.5km*	32 *70.5cmx0.5km*	41 *80.4cmx0.5km*
Shape of catchment				
Form Factor *(Horton, 1932)*	0.677	0.652	0.478	0.378
Circulatory Ratio *(Miller, 1953)*	0.454	0.619	0.676	0.458
Elongation Ratio *(Schumm, 1956)*	0.930	0.911	0.780	0.694

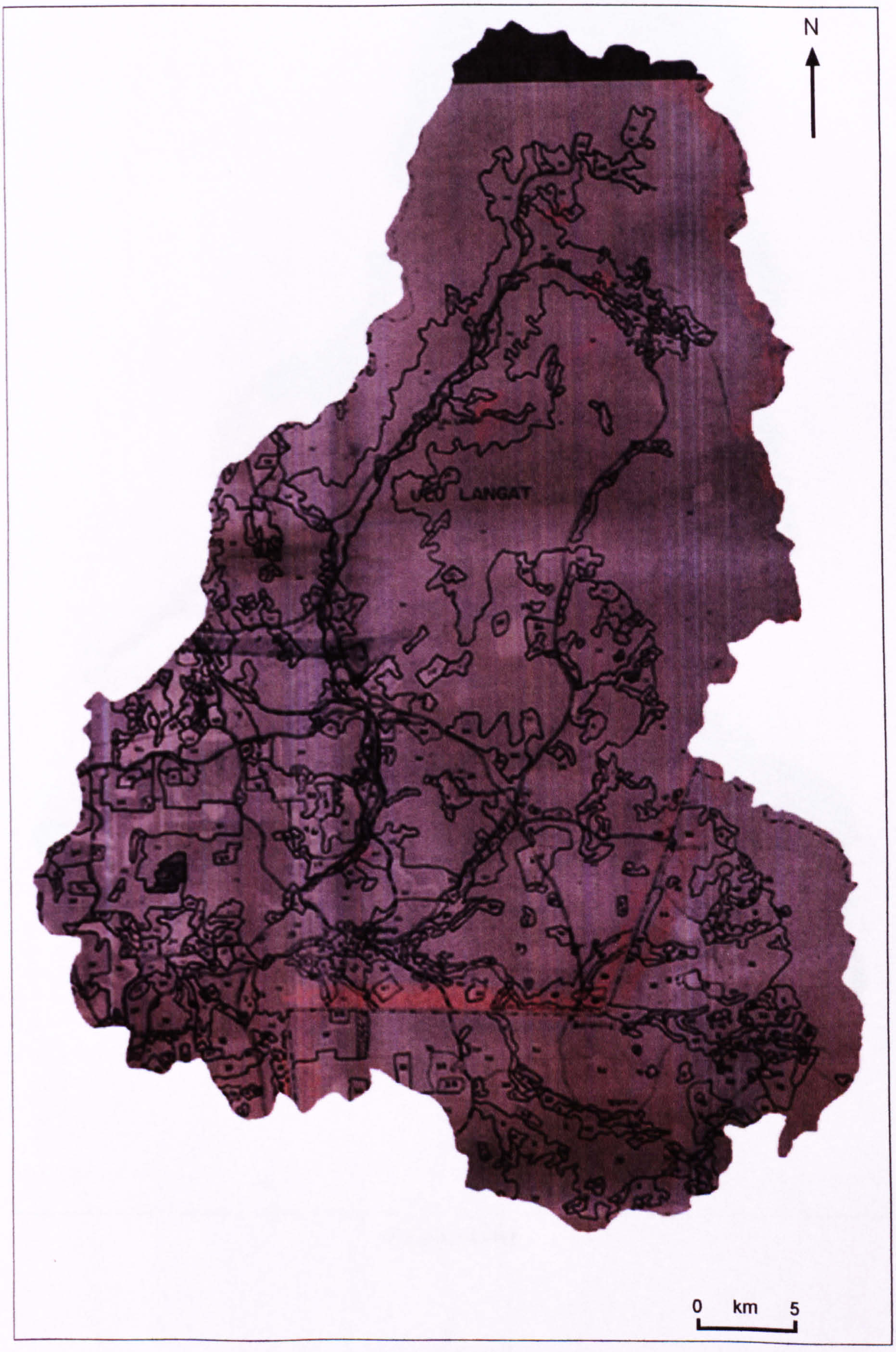
Appendix 2: The hydrological and water quality data checklists of selected gauging stations for all three catchments

Catchment	Data	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02
Langat (Dengkil)	Rainfall	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Discharge	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	SSQ																		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
	SSC																																			■	■	■	■	■	■	■	■	■
	BOD																					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Linggi (Sua Betong)	Rainfall	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Discharge	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	SSQ																																											
	SSC																																											
	BOD																										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Bernam (SKC)	Rainfall	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Discharge	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	SSQ																		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
	SSC																																	■	■	■	■	■	■	■	■	■	■	■
	BOD																																							■	■	■	■	■

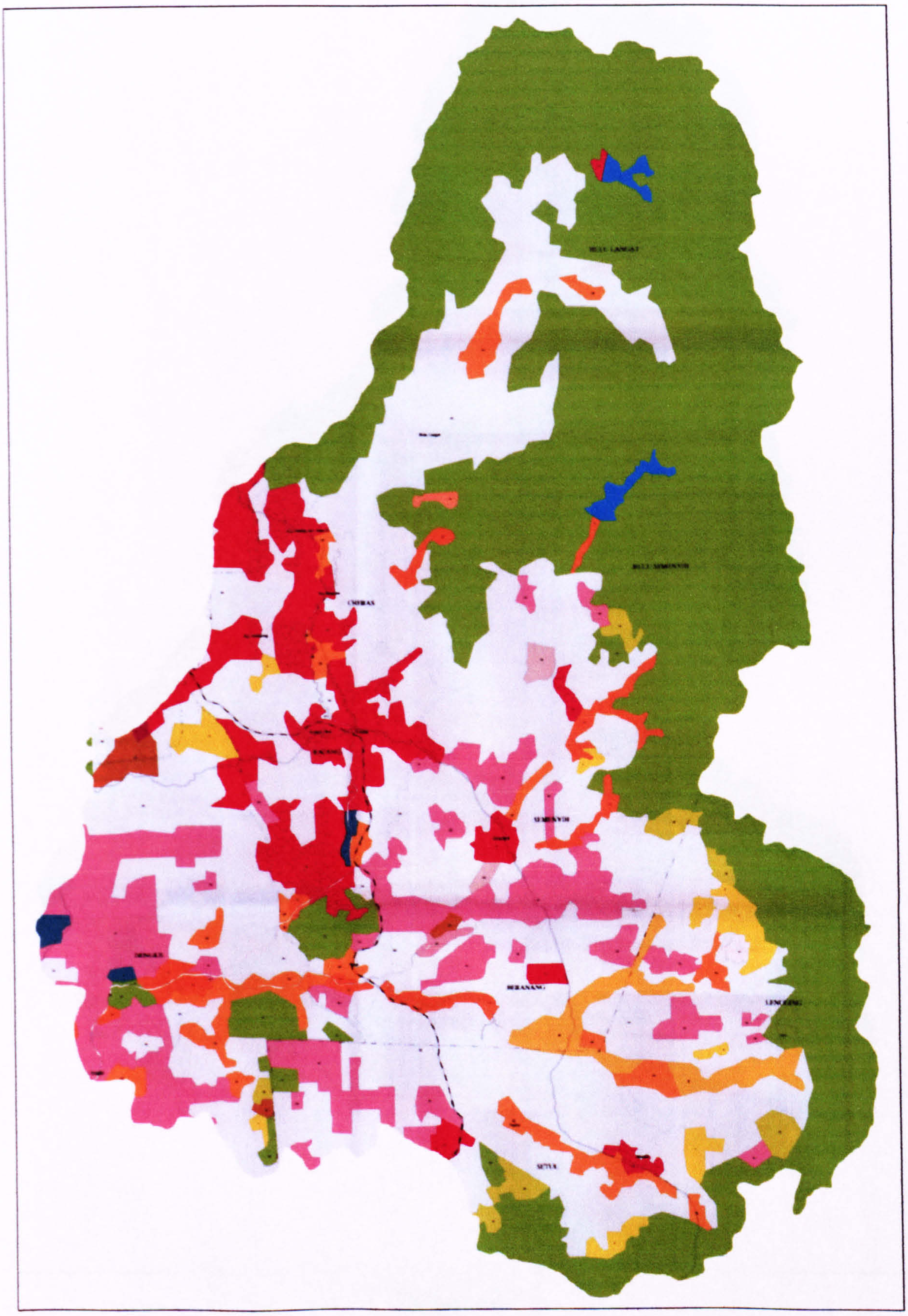
Notes: SSQ (Suspended sediment discharge); SSC (Suspended sediment concentration); BOD (Biological oxygen demand)

Appendix 3: Classified land use maps for all three catchments, from Department of Agriculture (refer 1984 map in each catchment for scale and N point)

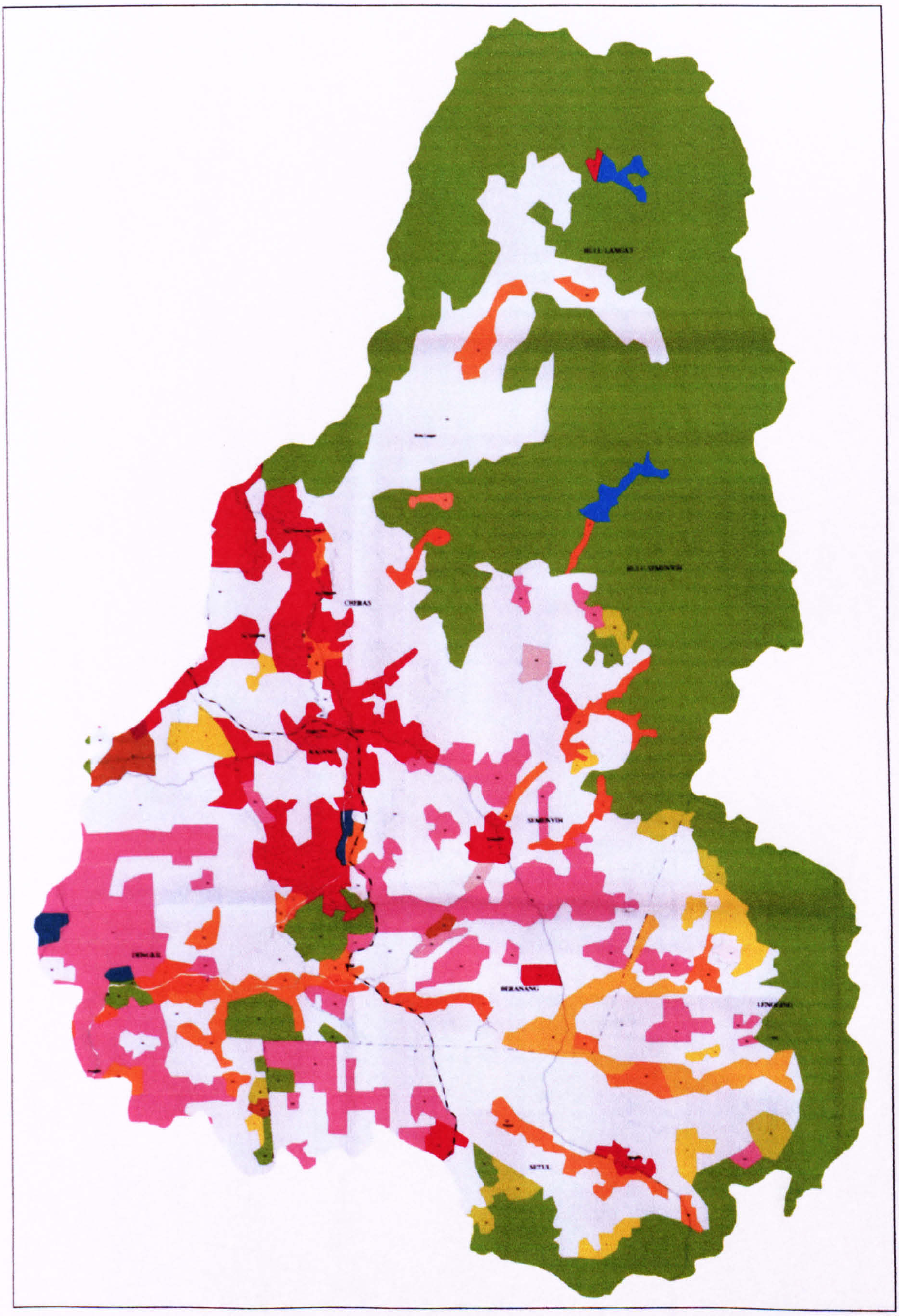
Langat catchment



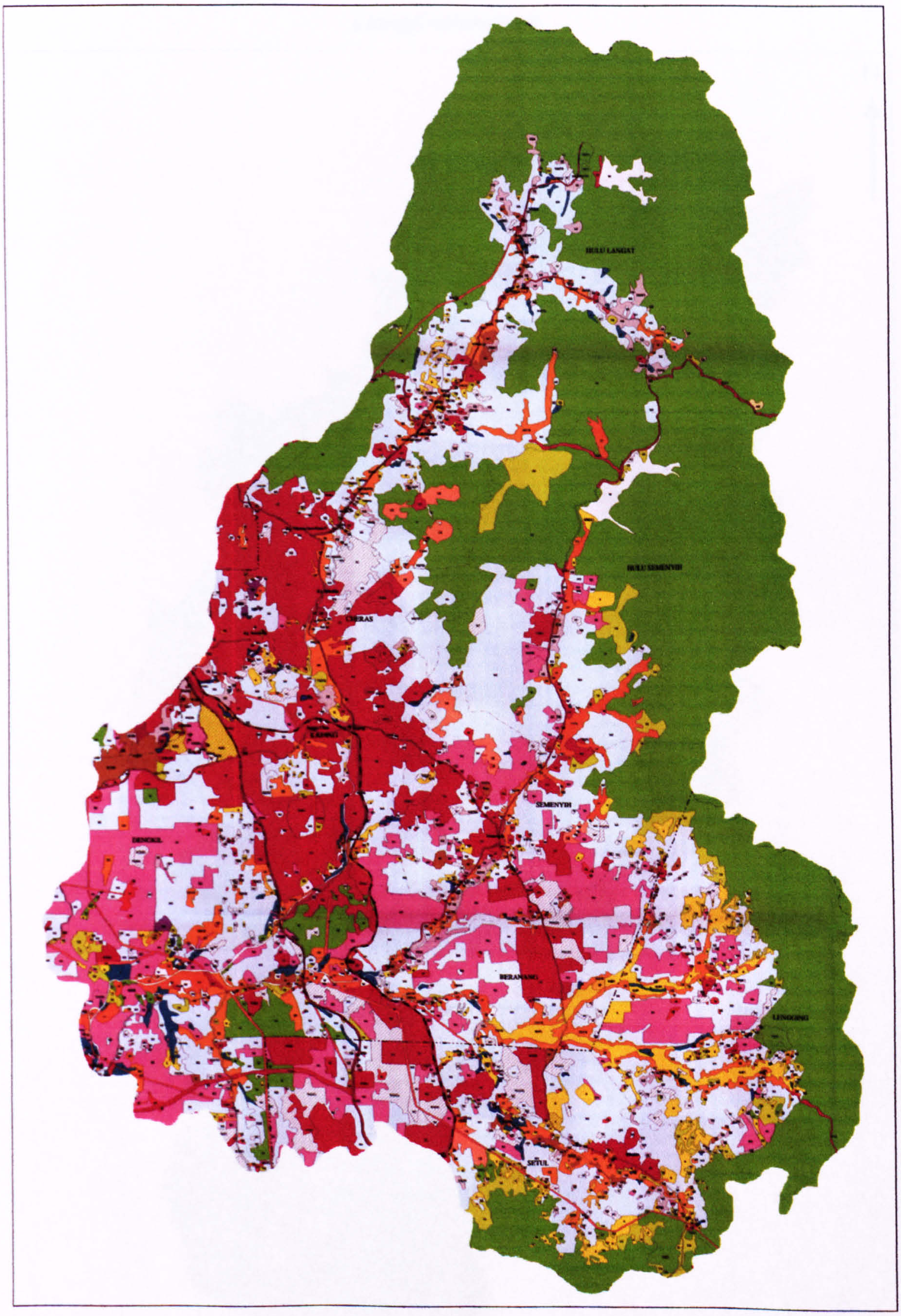
Langat 1984



Langat 1990



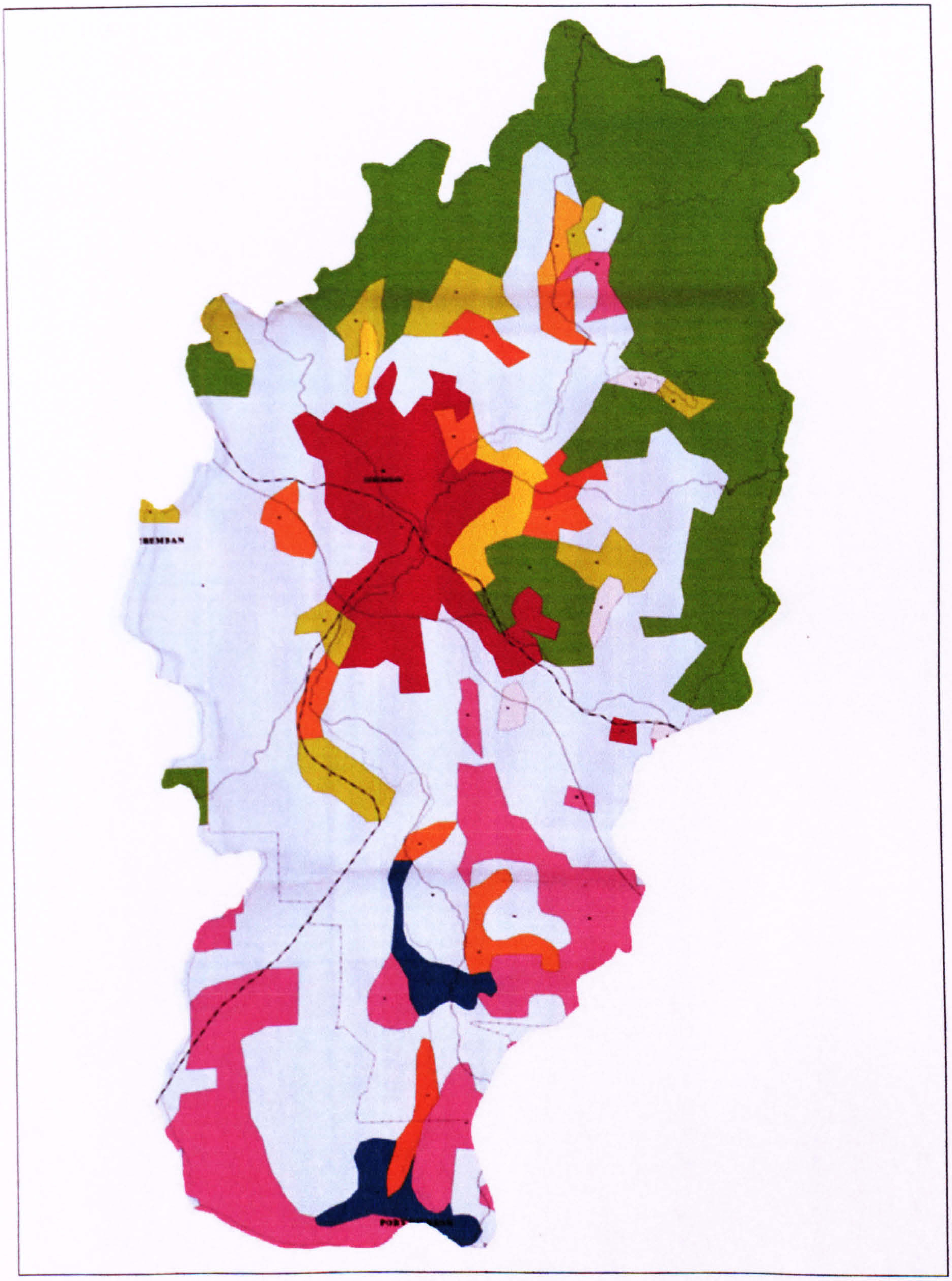
Langat 1997


HULU LANGAT
HULU SEMENYIH
CHERAS
DENGKIL
SEMENYIH
BERANANG
SETUL

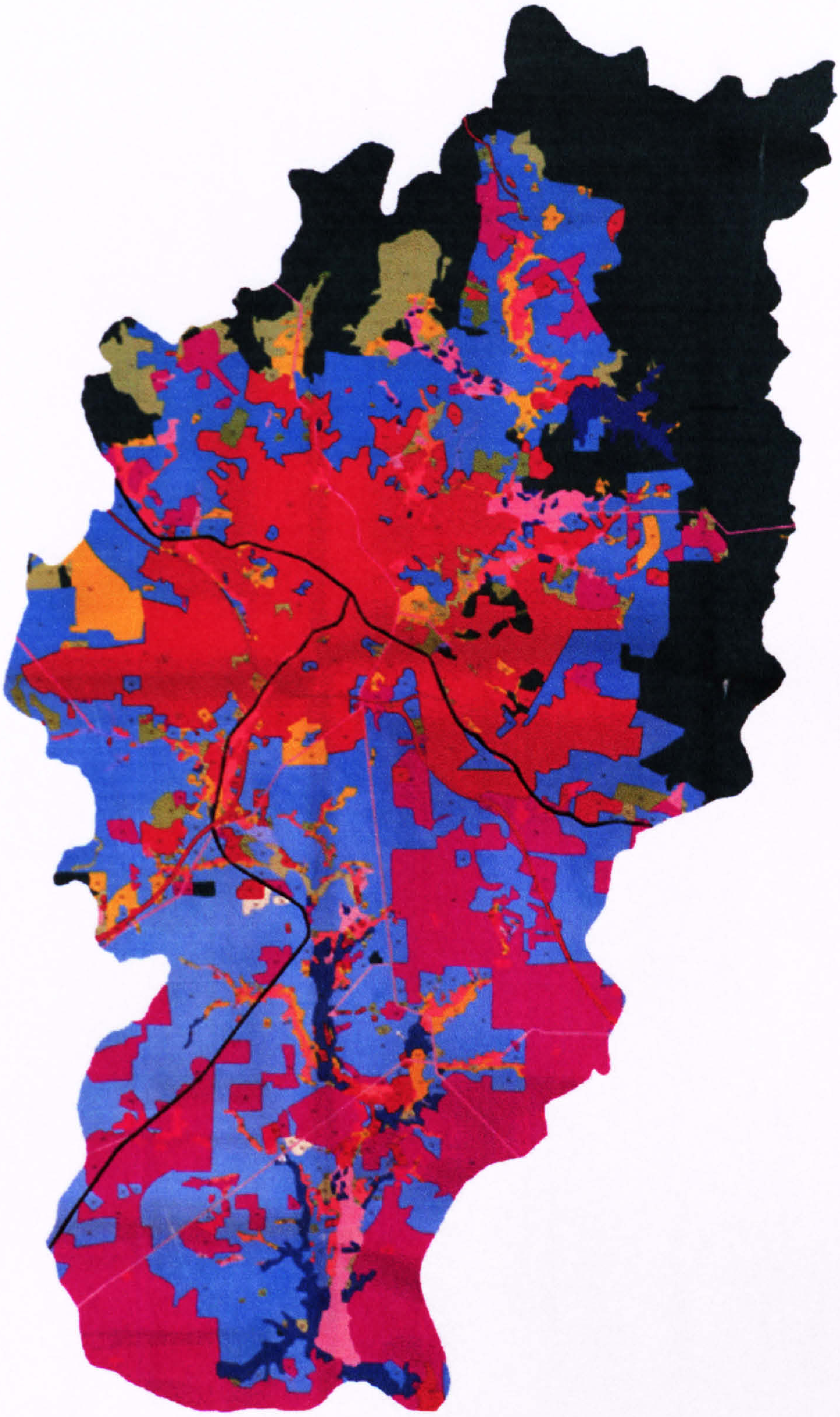
Langat 2000

Linggi catchment

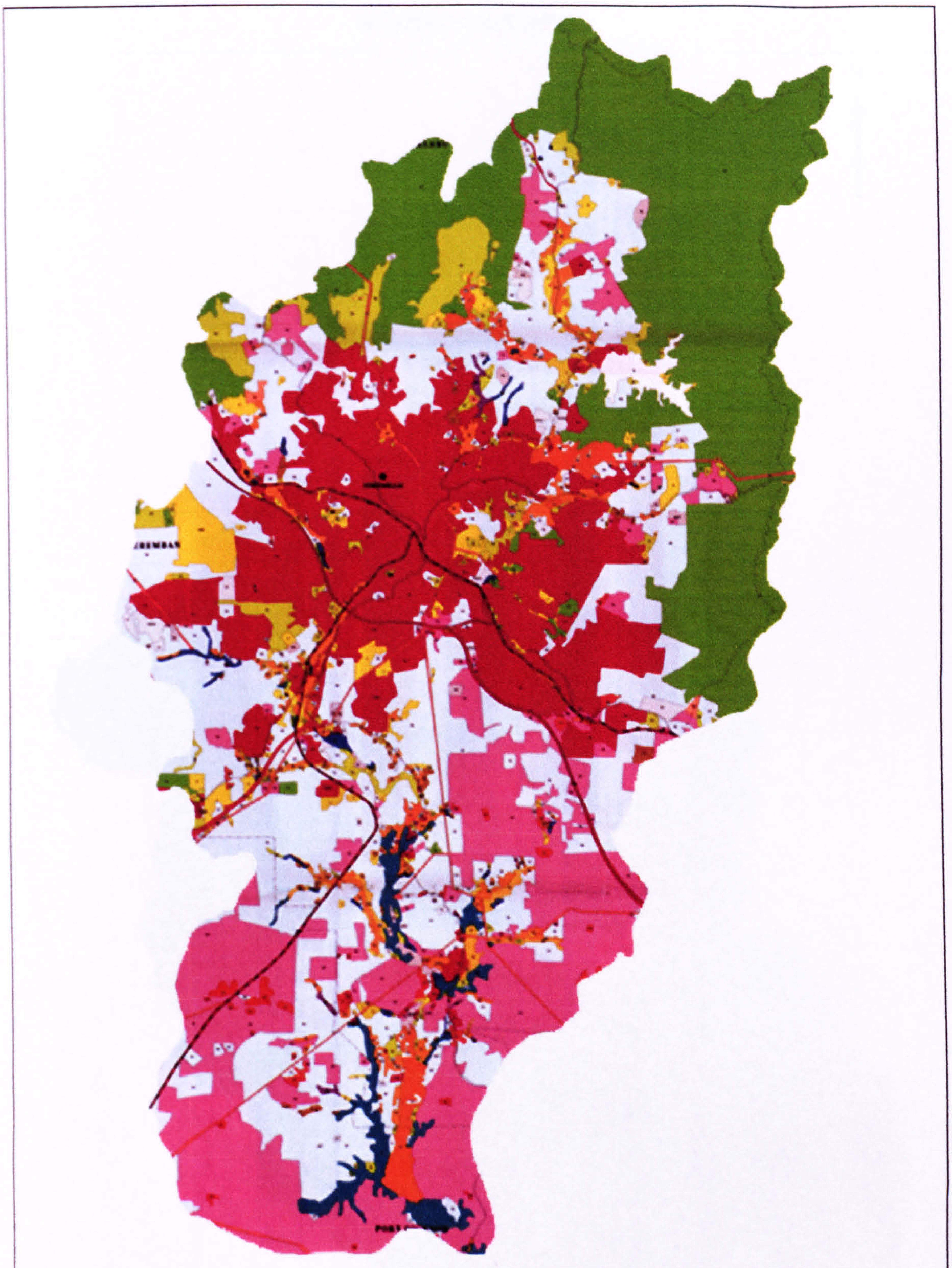
Linggi 1984



Linggi 1990

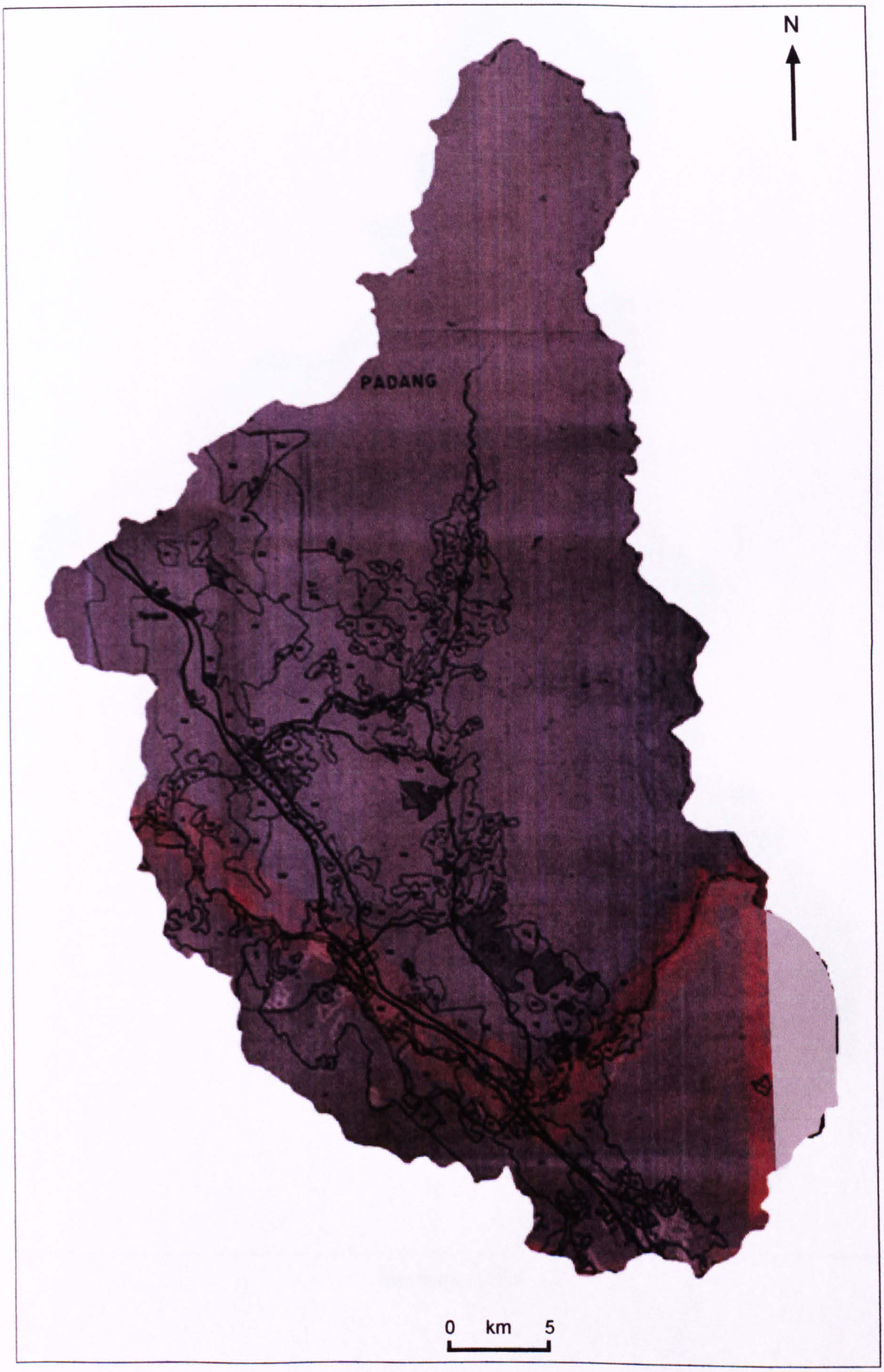


Linggi 1997

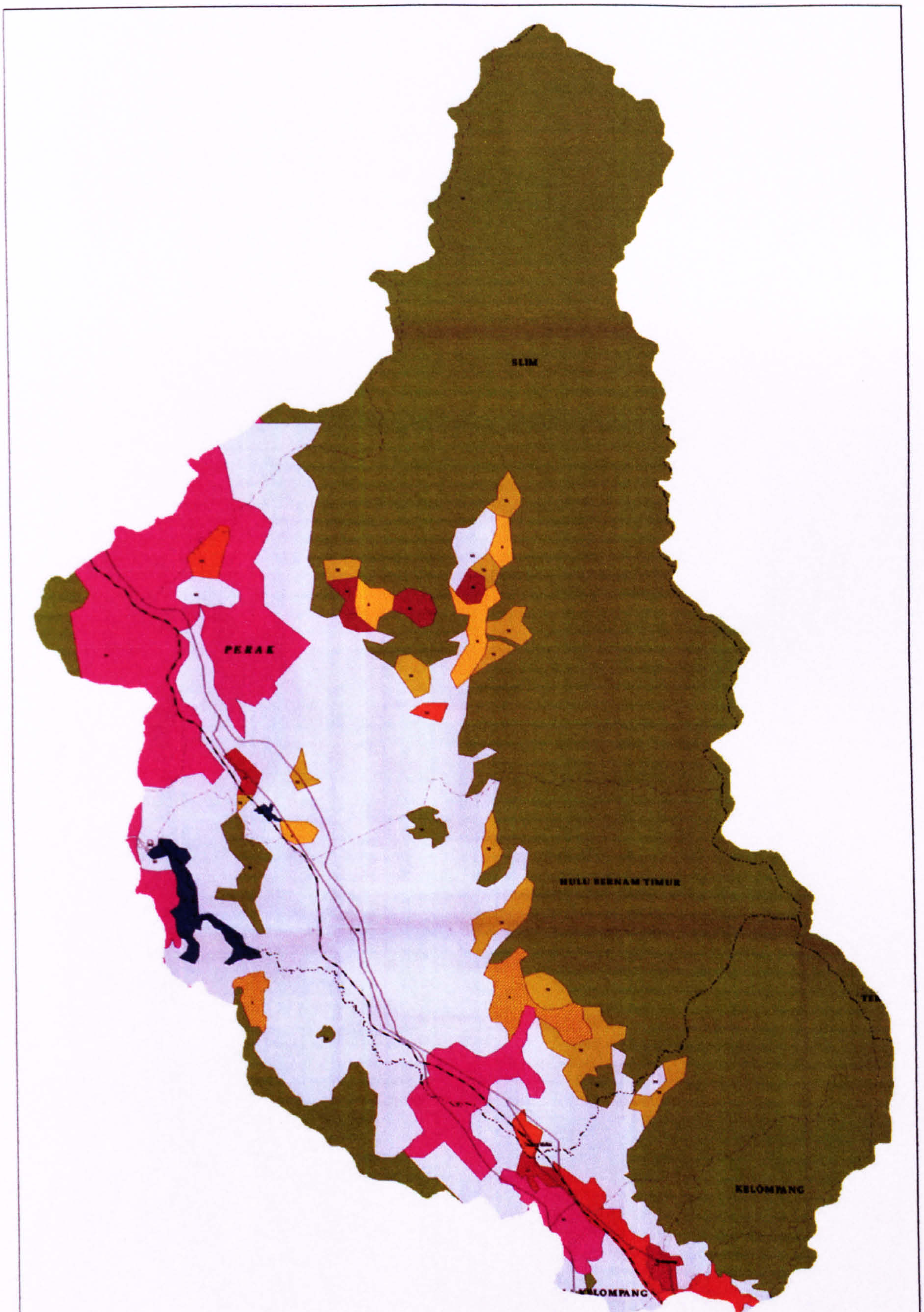


Linggi 2000

Bernam catchment



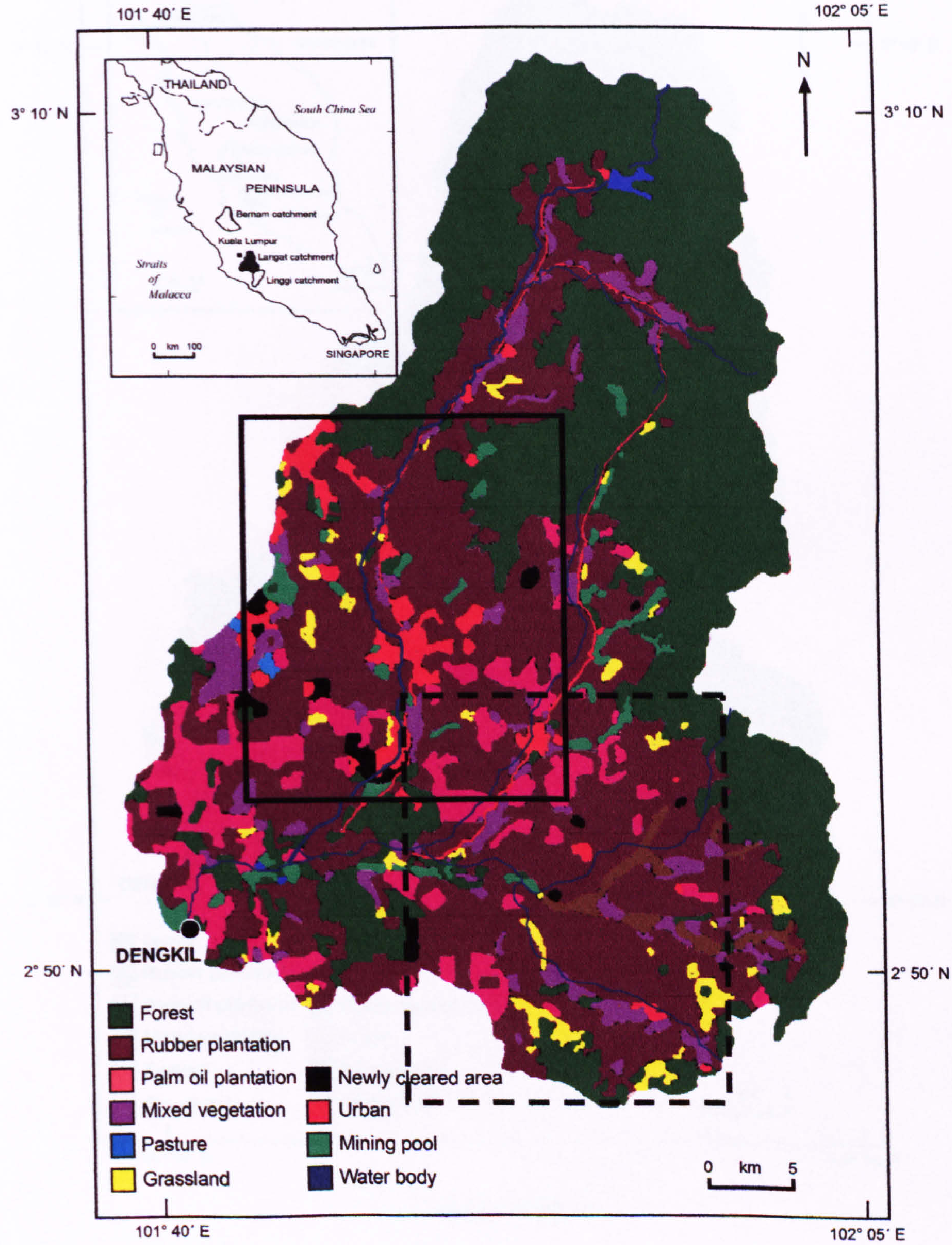
Bernam 1984



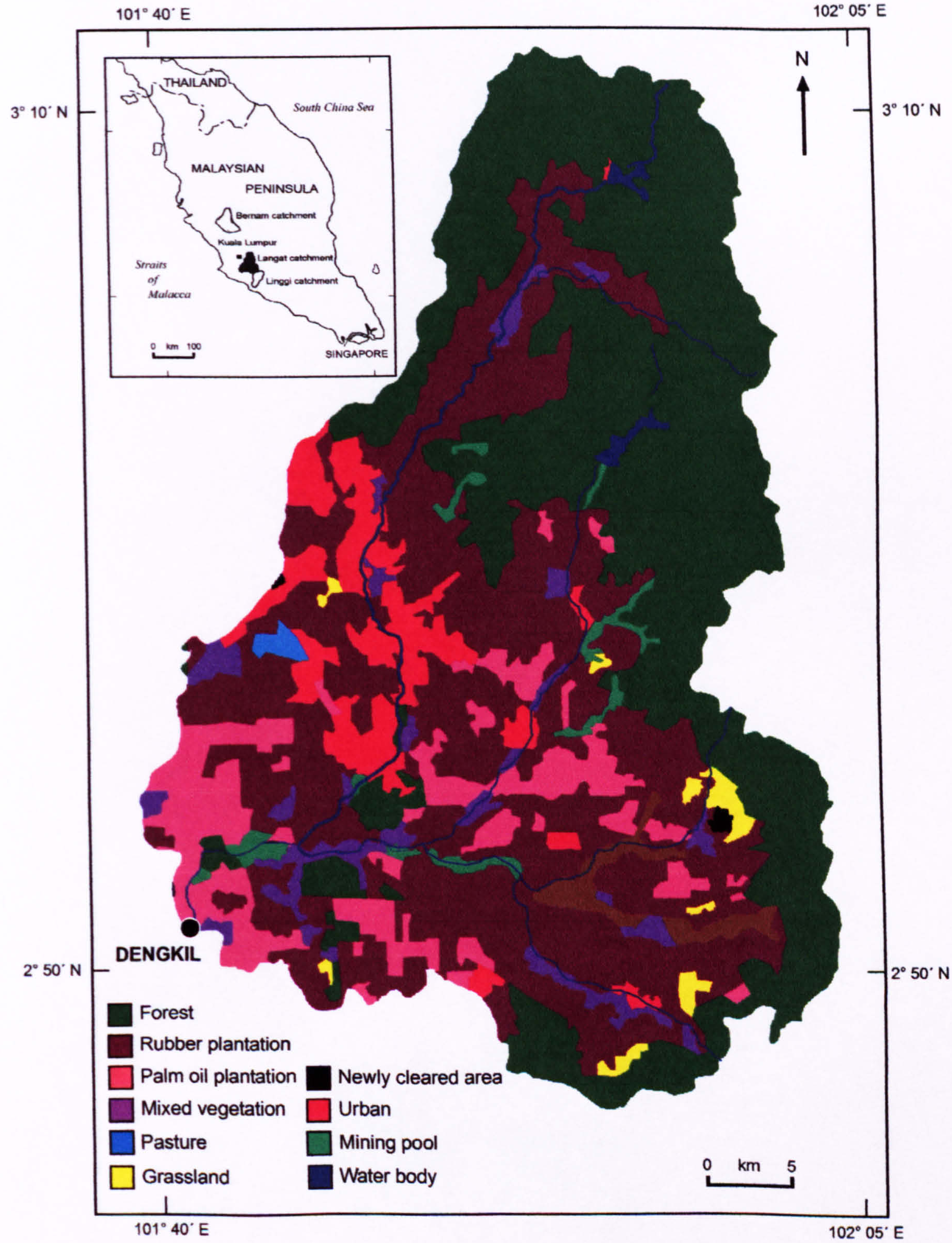
Bernam 1990

Bernam 2000

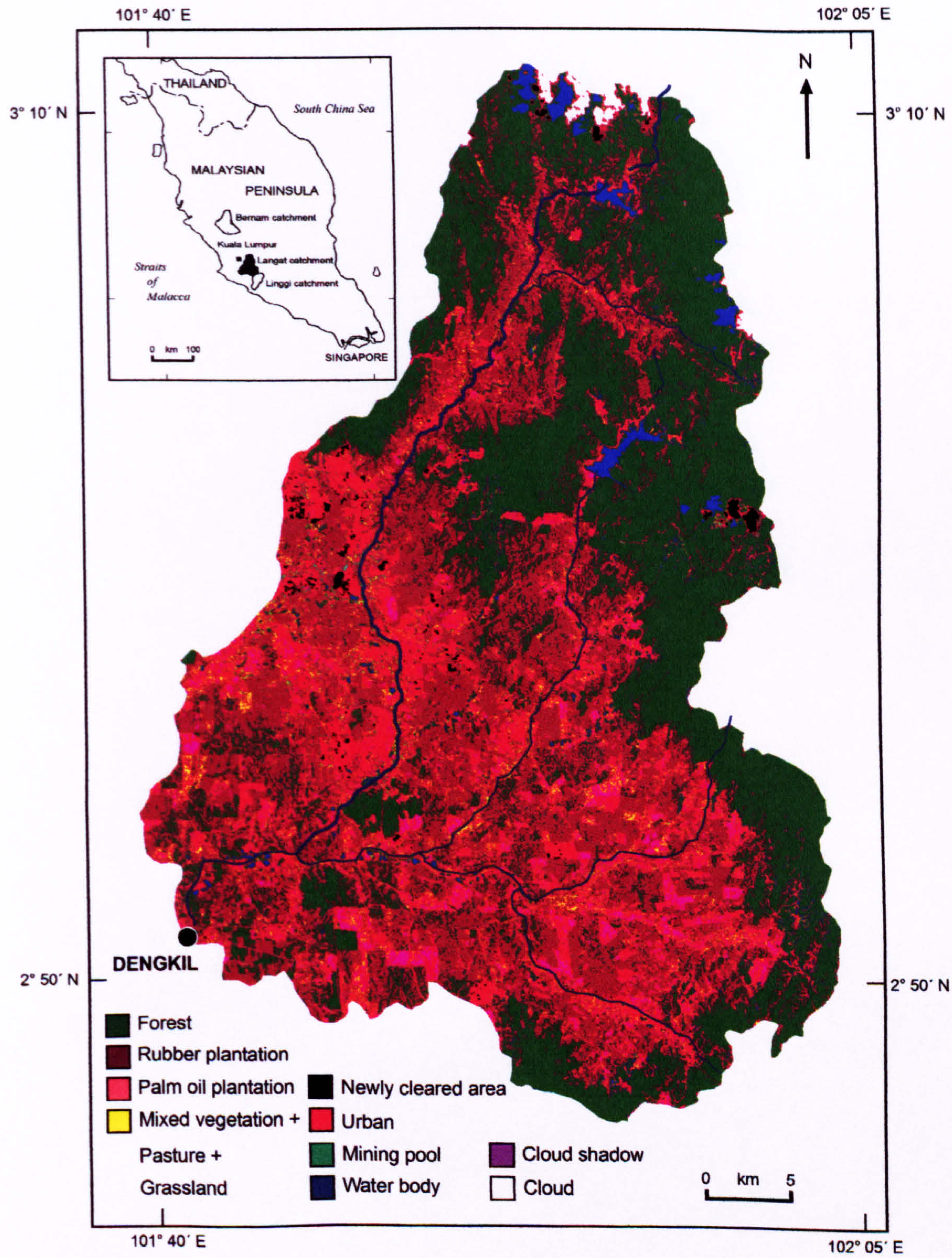
Appendix 4: Land use maps for all three catchments (based on DOA maps and Landsat – final classification)



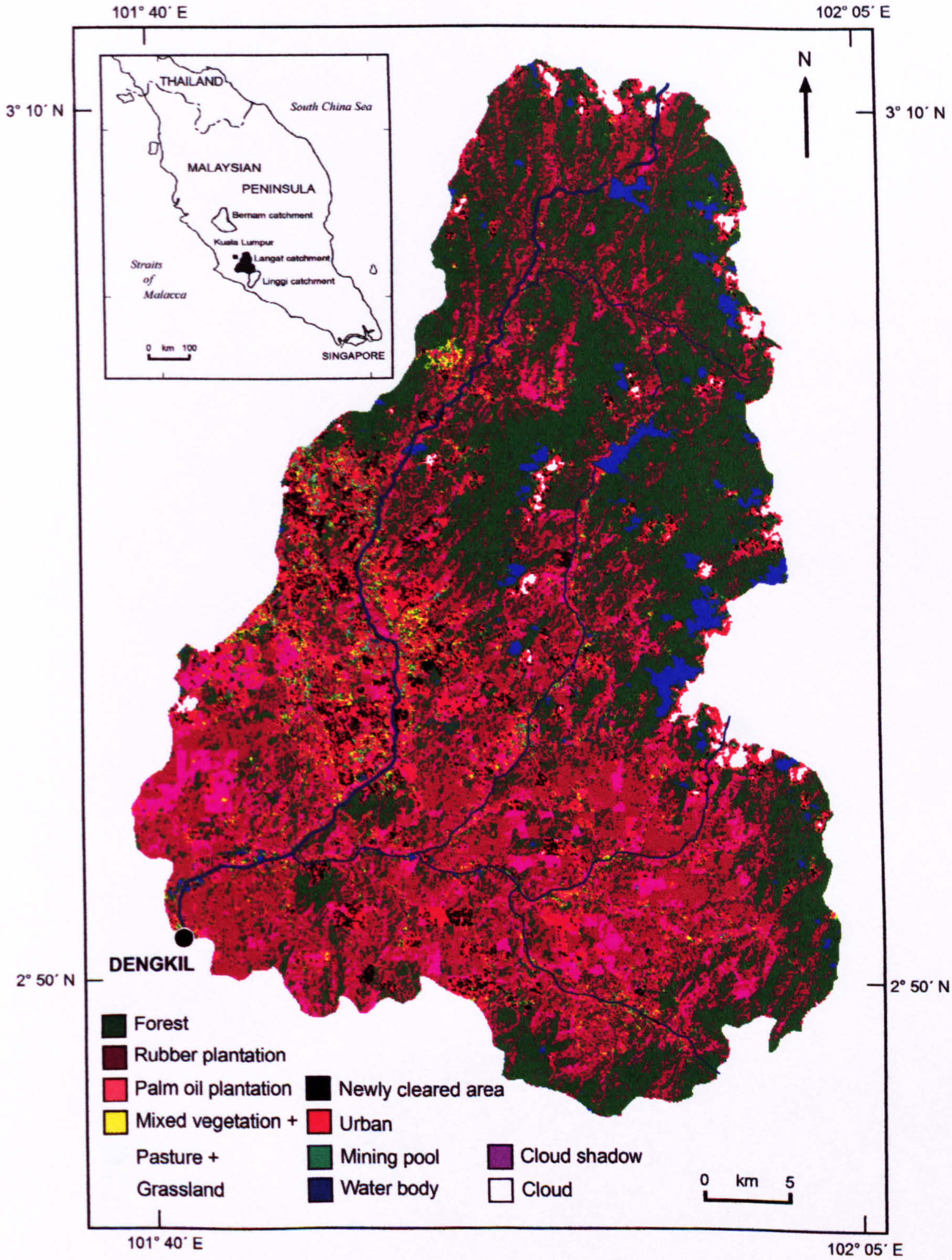
Langat 1984


101° 40' E
102° 05' E
3° 10' N
3° 10' N
2° 50' N
2° 50' N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits
of
Malacca
0 km 100
SINGAPORE
DENGKIL
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5
101° 40' E
102° 05' E

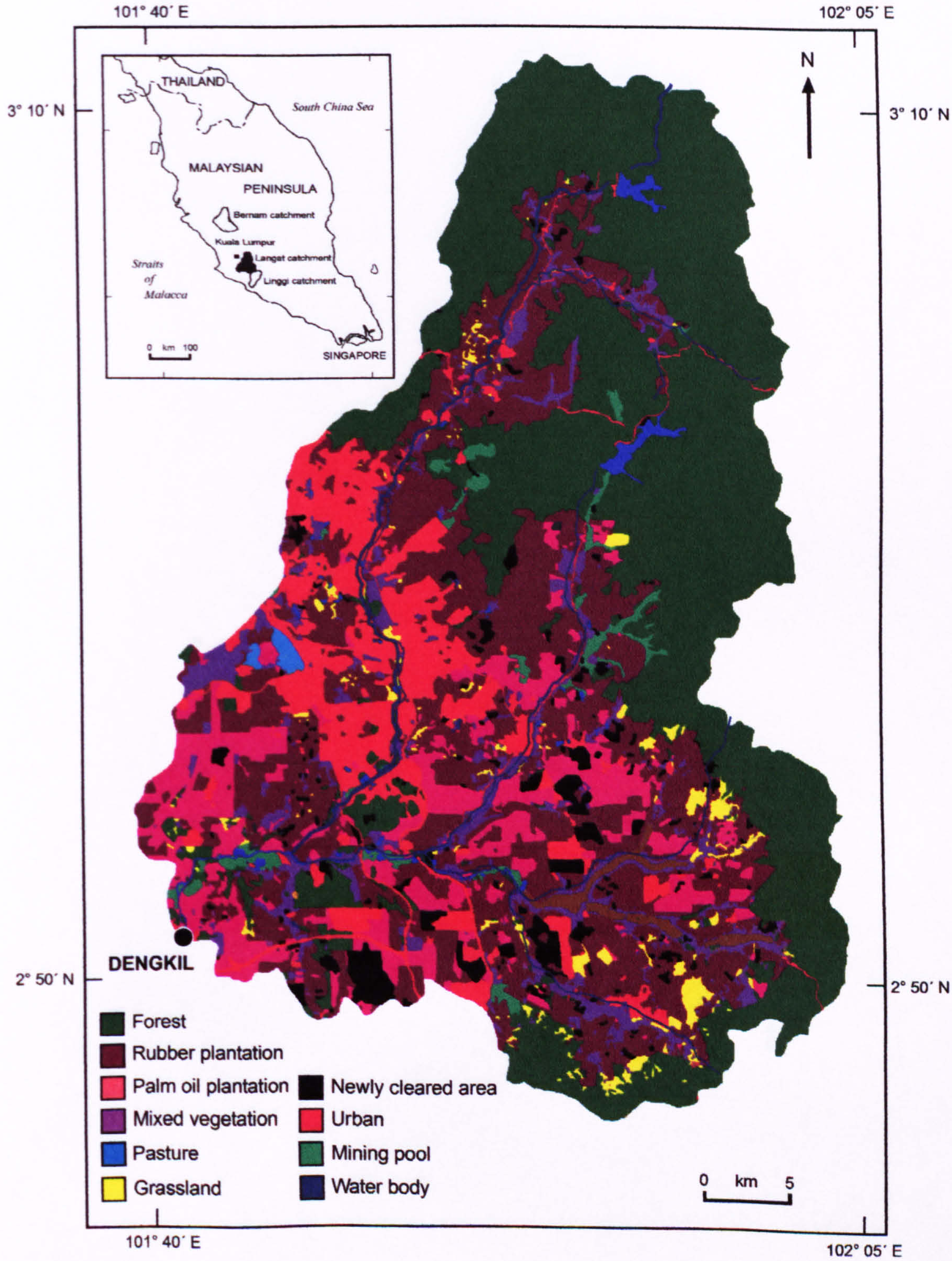
Langat 1990



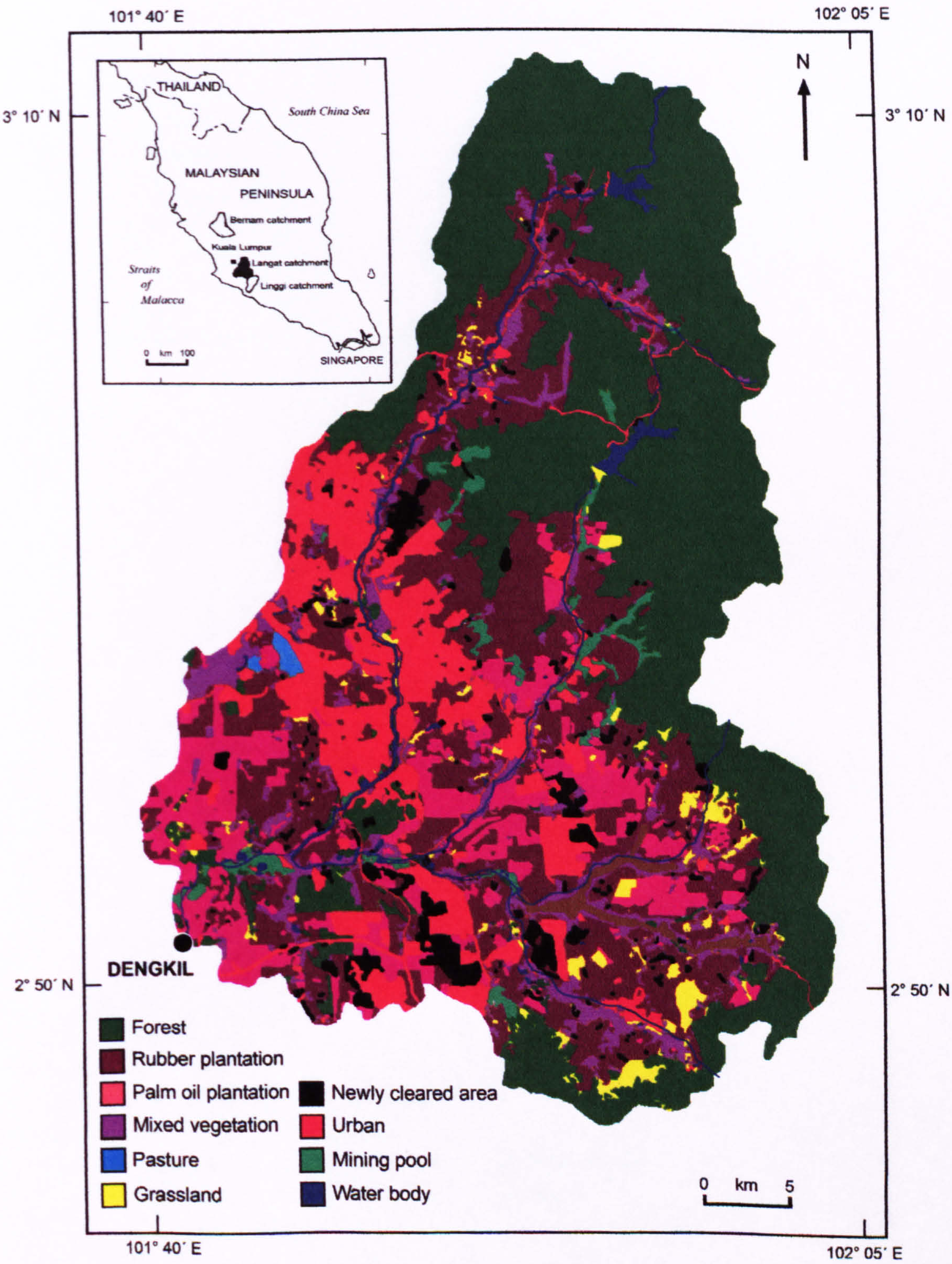
Langat 1990 -Landsat



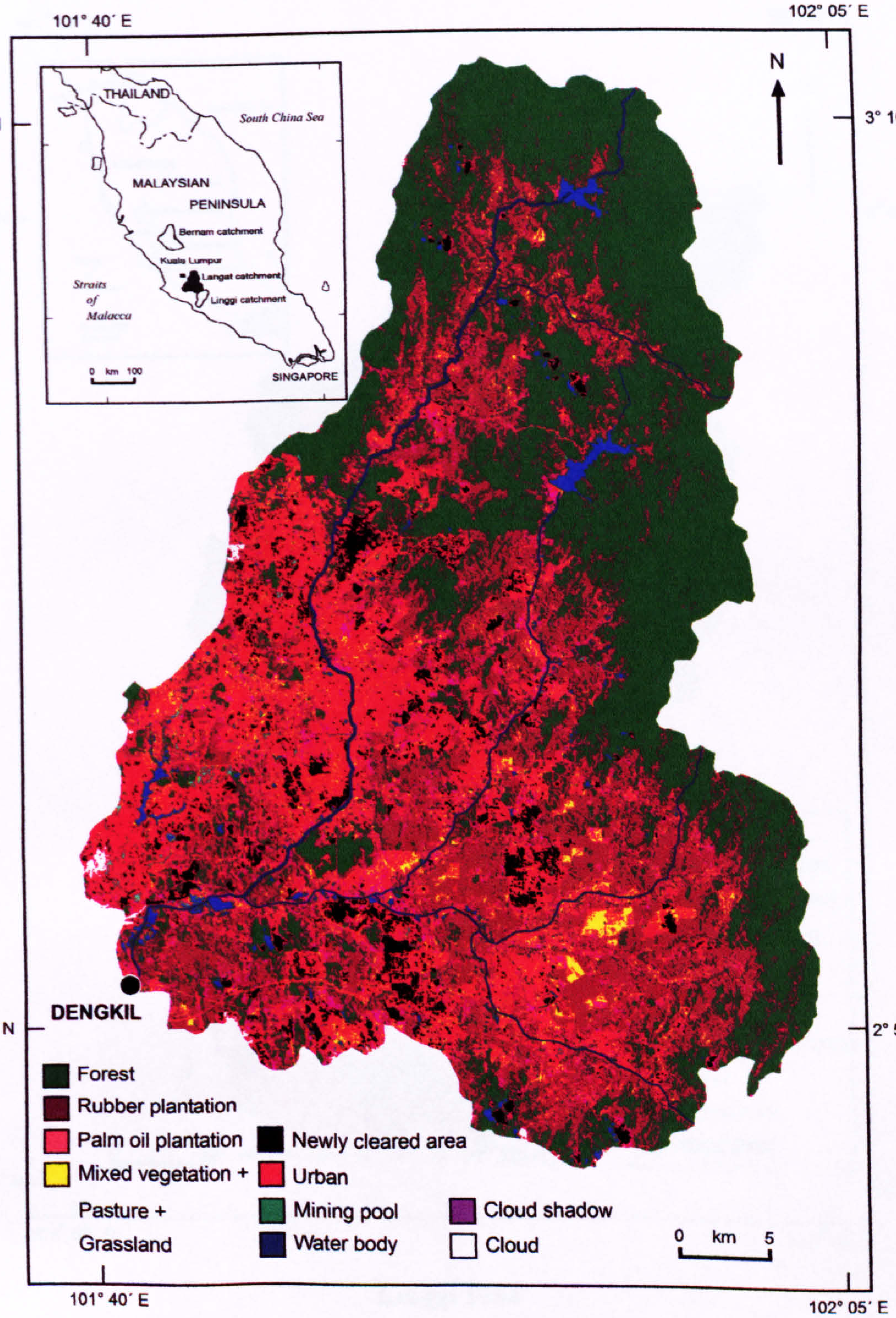
Langat 1994 - Landsat


101° 40′ E
102° 05′ E
3° 10′ N
2° 50′ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits
of
Malacca
0 km 100
SINGAPORE
DENGKIL
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5

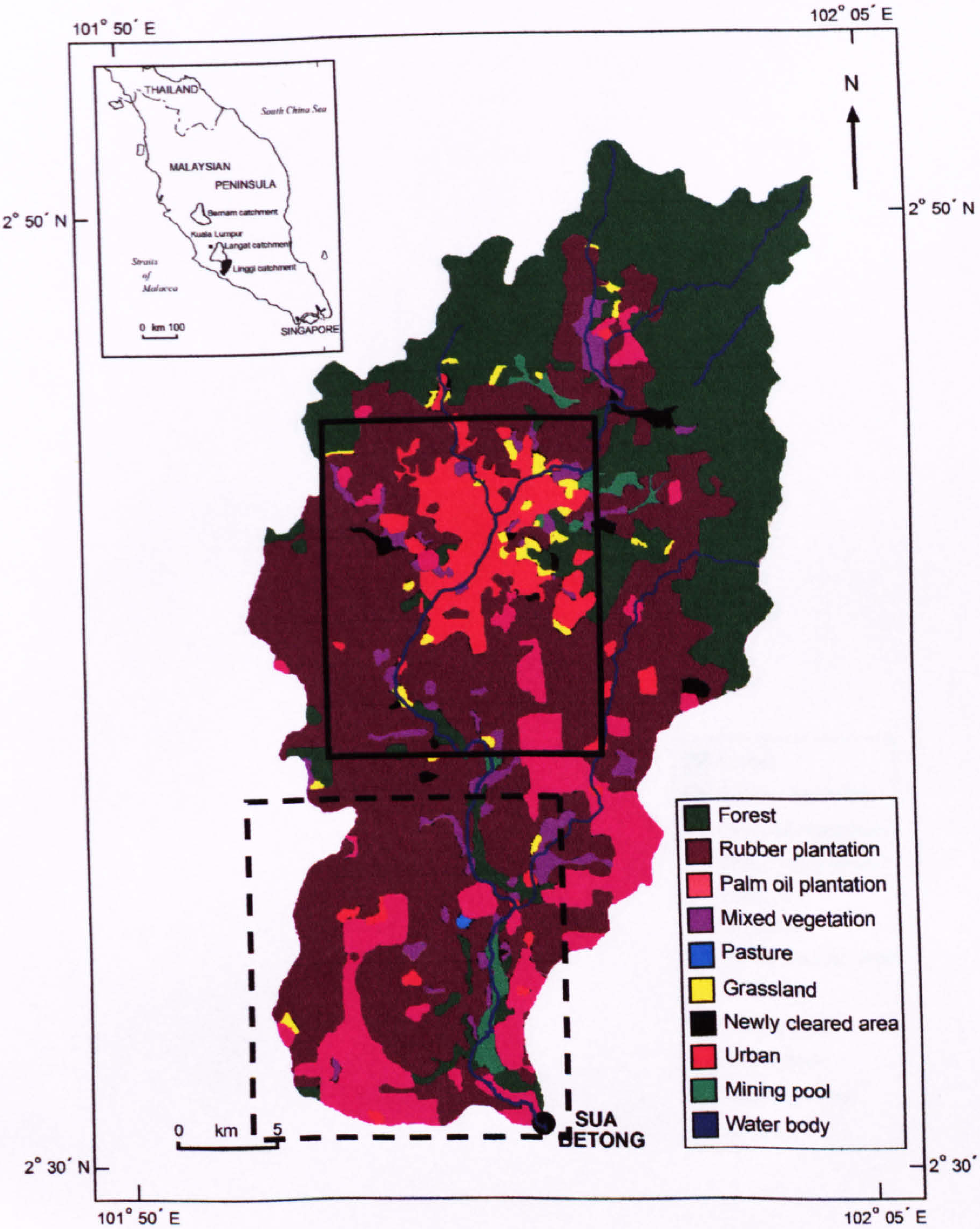
Langat 1997


101° 40′ E
102° 05′ E
3° 10′ N
2° 50′ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits of Malacca
SINGAPORE
0 km 100
DENGKIL
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5

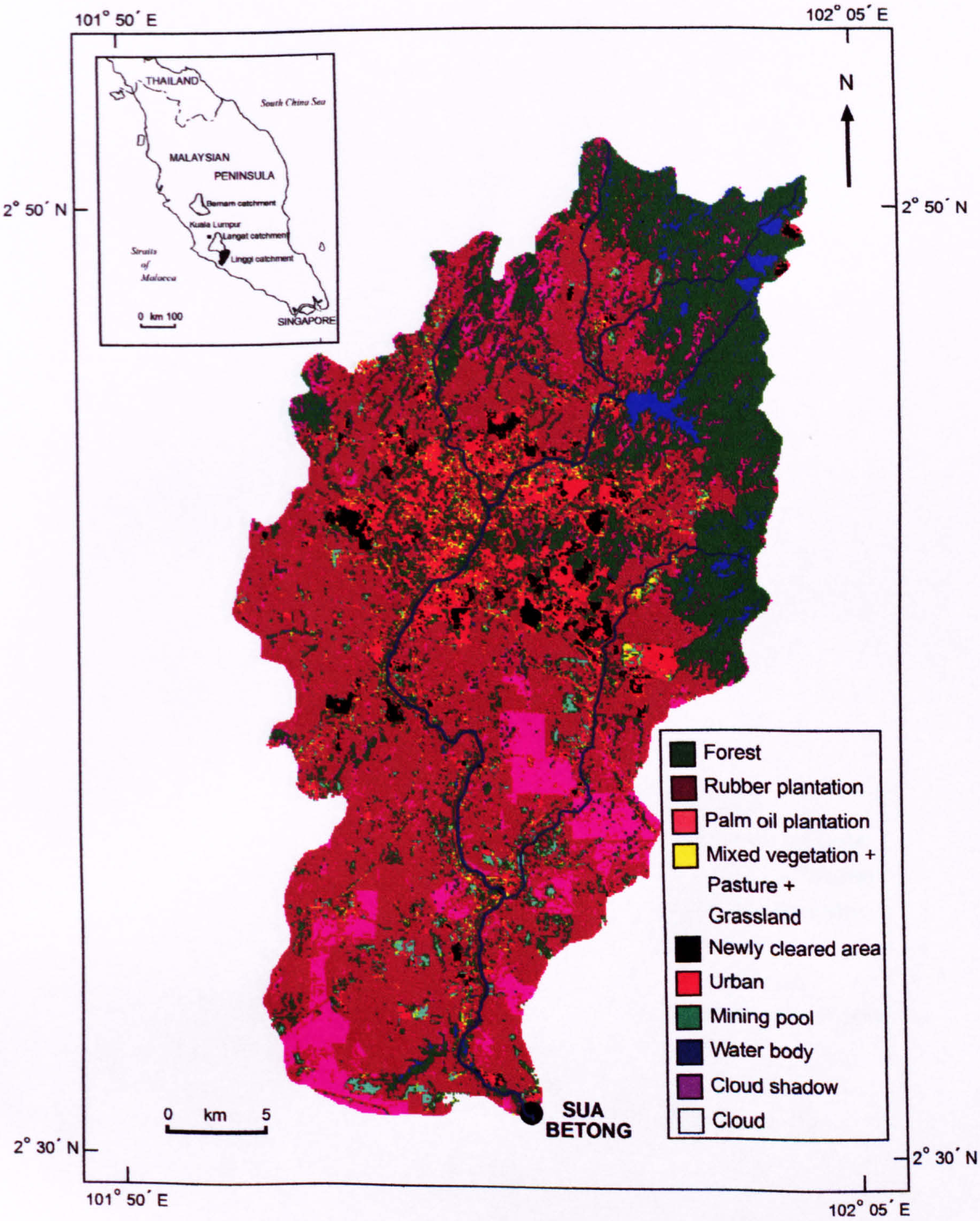
Langat 2000



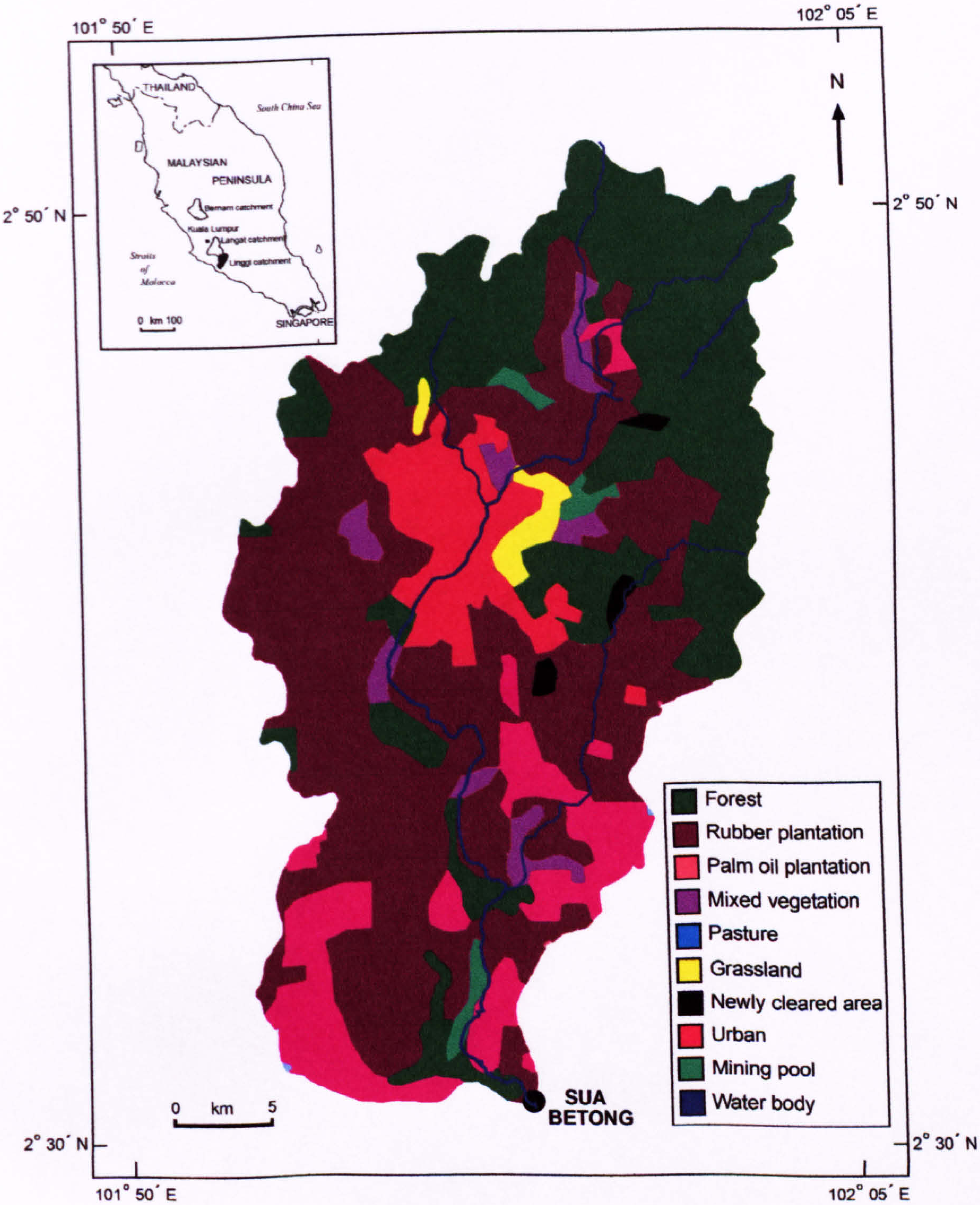
Langat 2001 - Landsat


101° 50´ E
102° 05´ E
N
2° 50´ N
2° 50´ N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits of Malacca
0 km 100
SINGAPORE
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5
SUA BETONG
2° 30´ N
2° 30´ N
101° 50´ E
102° 05´ E

Linggi 1984

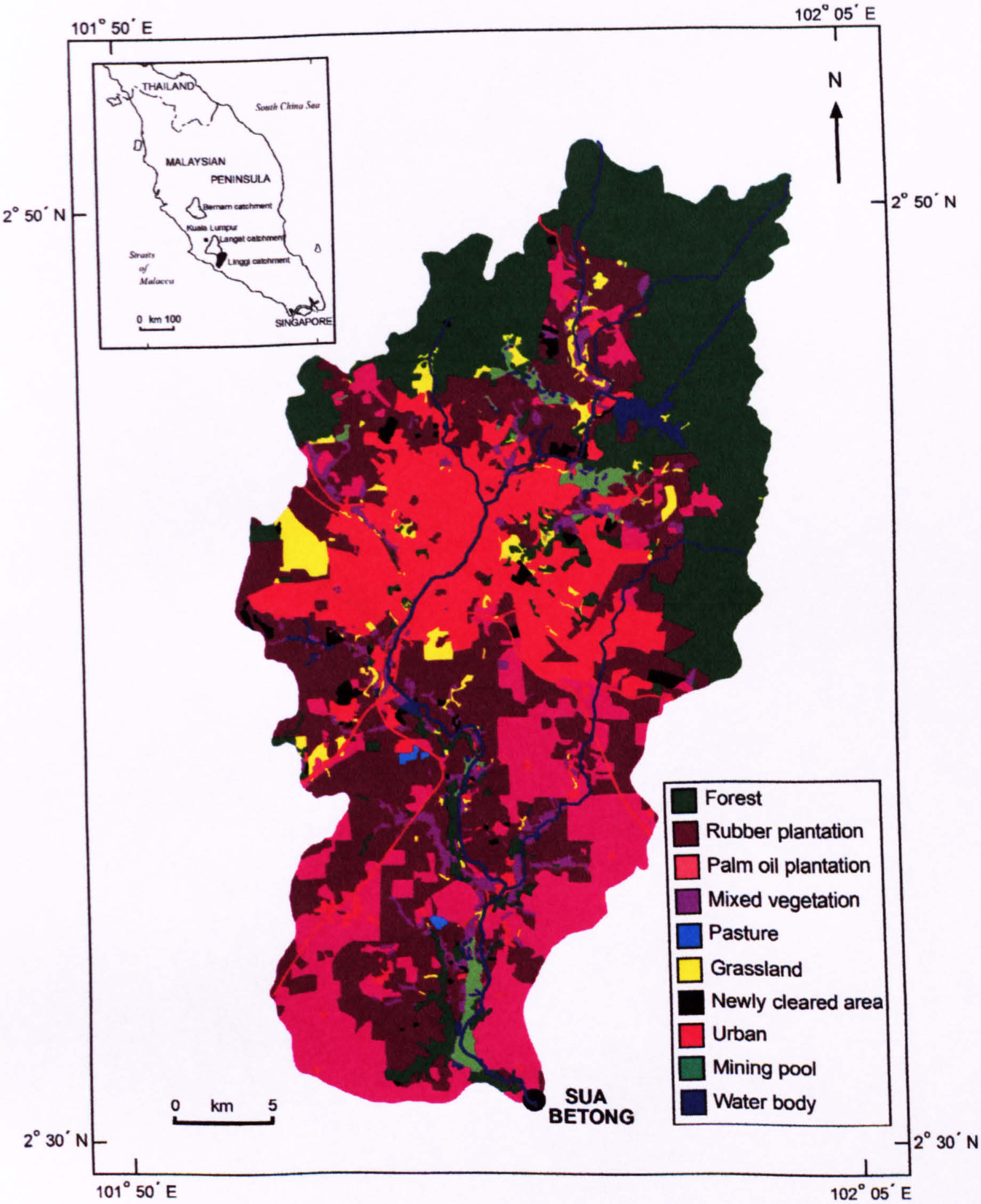


Linggi 1988 - Landsat

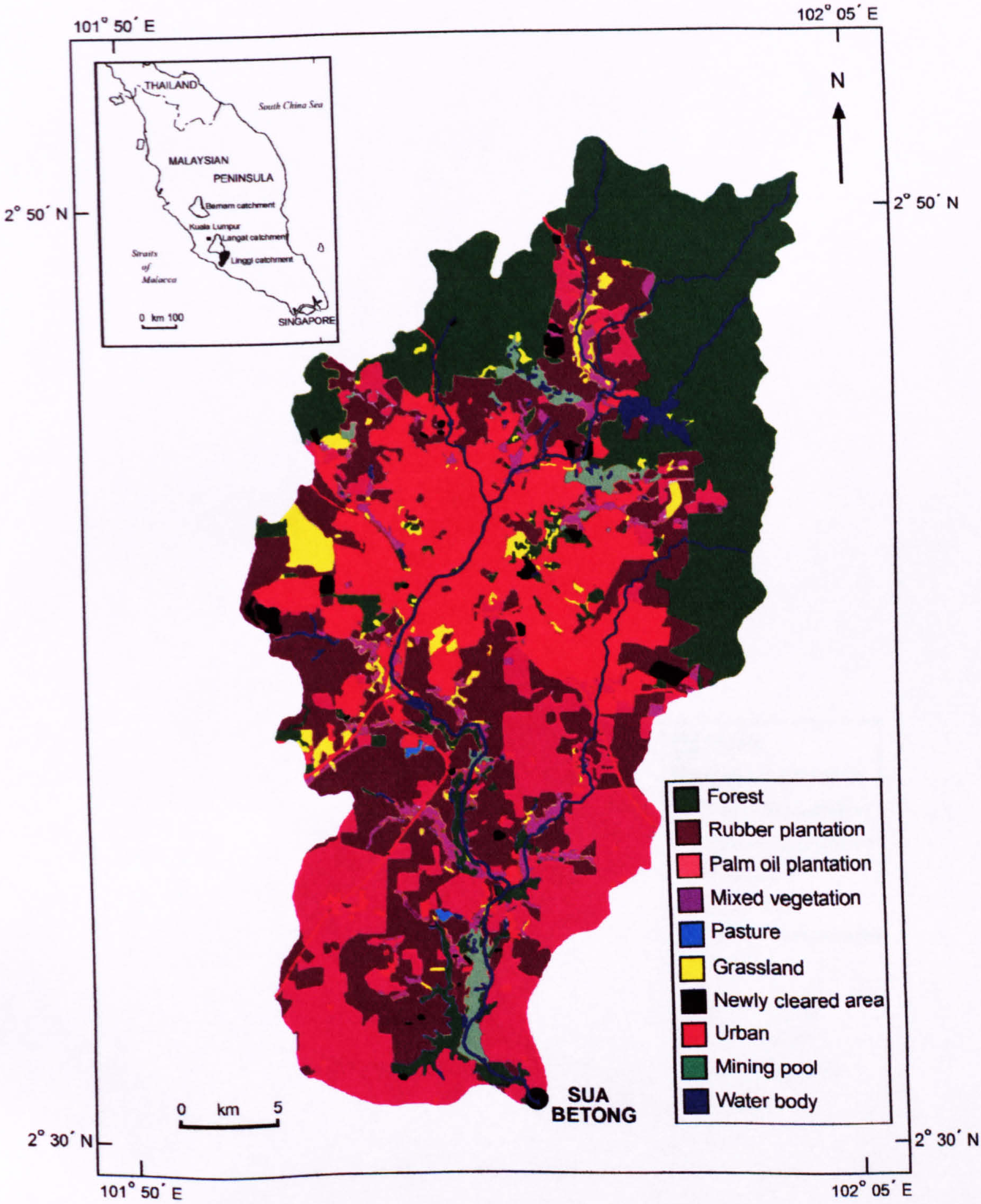


101° 50´ E
102° 05´ E
2° 50´ N
2° 30´ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits of Malacca
0 km 100
SINGAPORE
0 km 5
SUA BETONG
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body

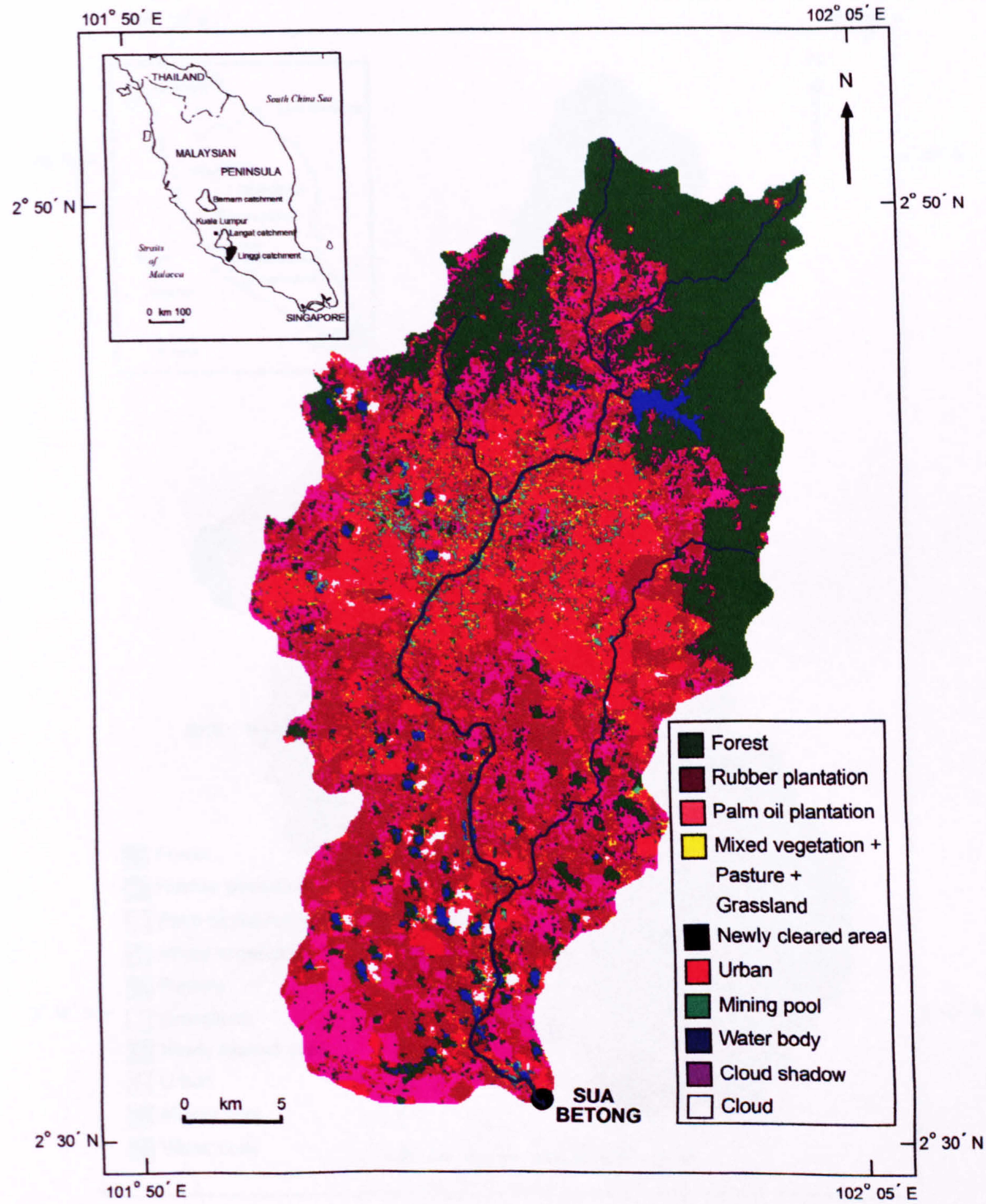
Linggi 1990


101° 50′ E
102° 05′ E
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits
of
Malacca
0 km 100
SINGAPORE
N
2° 50′ N
2° 50′ N
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5
SUA
BETONG
2° 30′ N
2° 30′ N
101° 50′ E
102° 05′ E

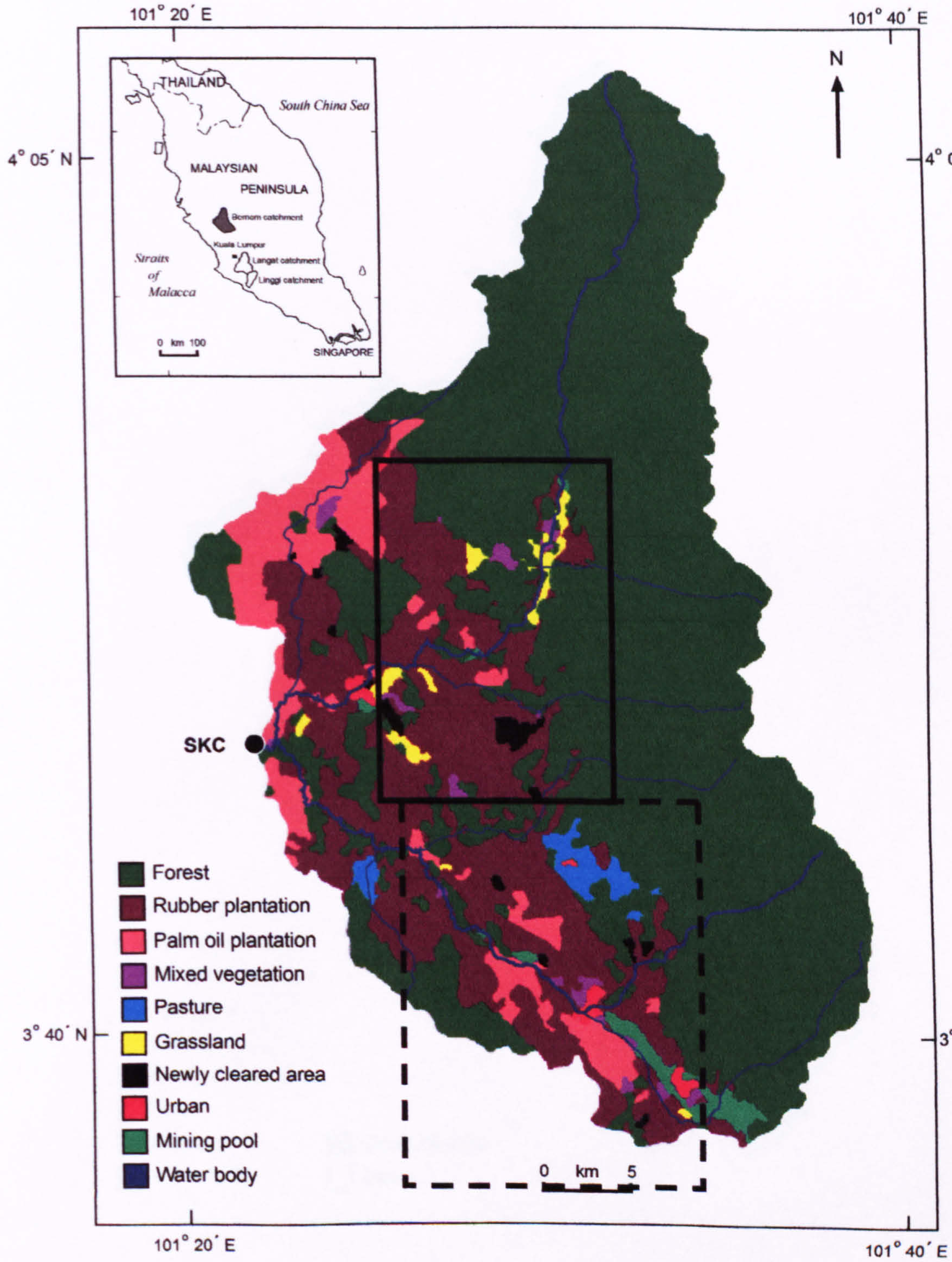
Linggi 1997


101° 50´ E
102° 05´ E
2° 50´ N
2° 30´ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits of Malacca
0 km 100
SINGAPORE
SUA
BETONG
0 km 5
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body

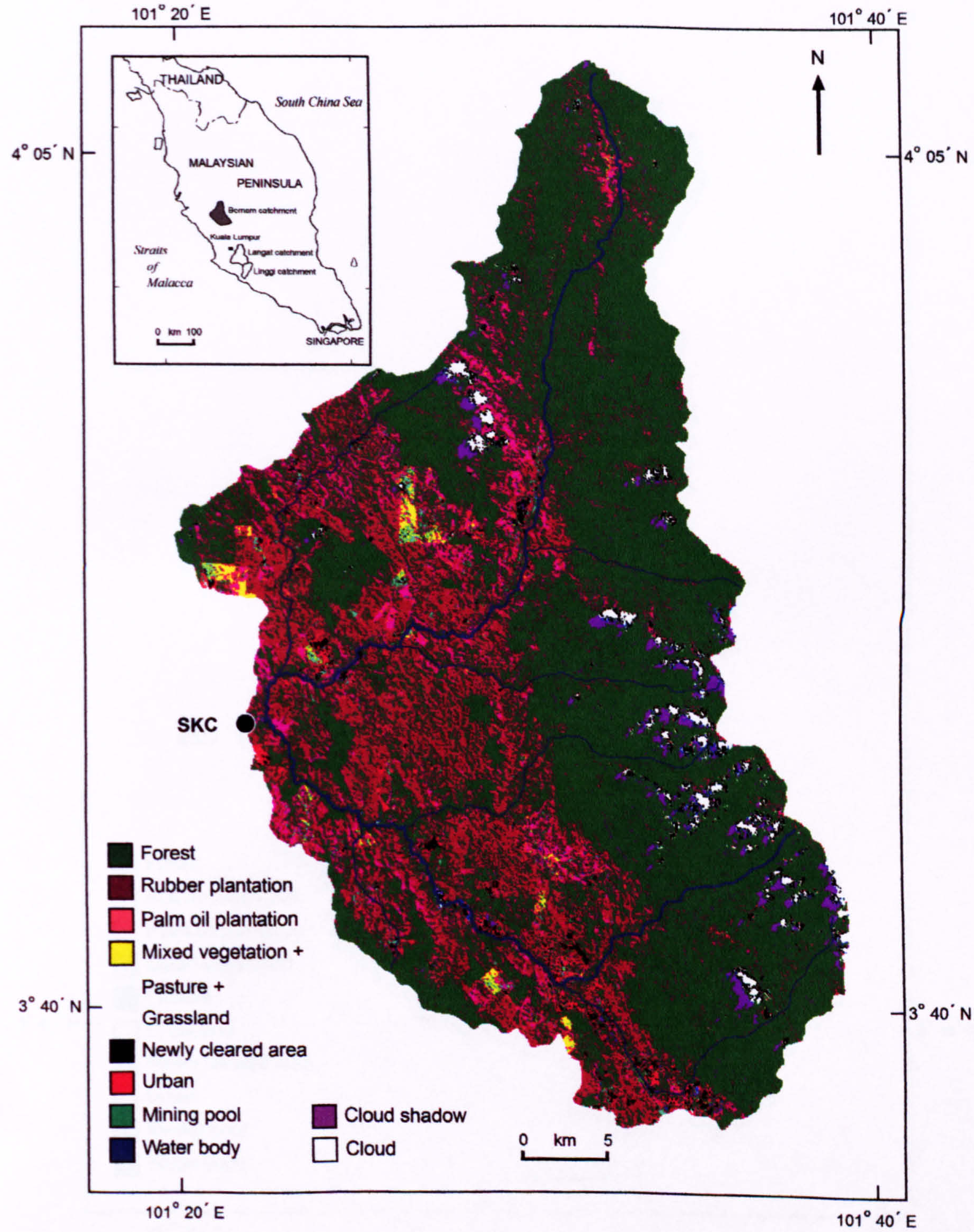
Linggi - 2000



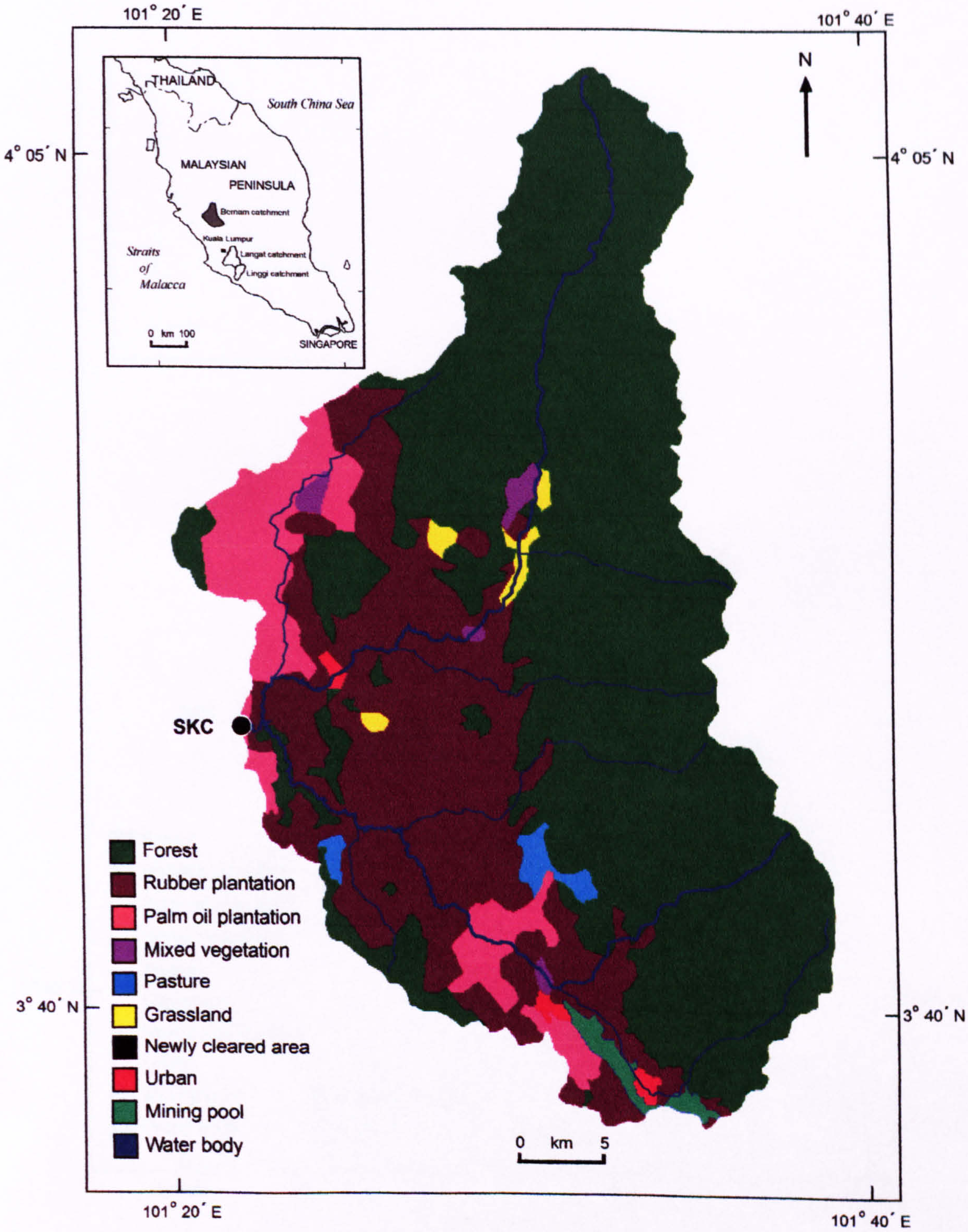
Linggi 2001 - Landsat


101° 20´ E
101° 40´ E
4° 05´ N
4° 05´ N
3° 40´ N
3° 40´ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Straits
of
Malacca
SINGAPORE
SKC
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5

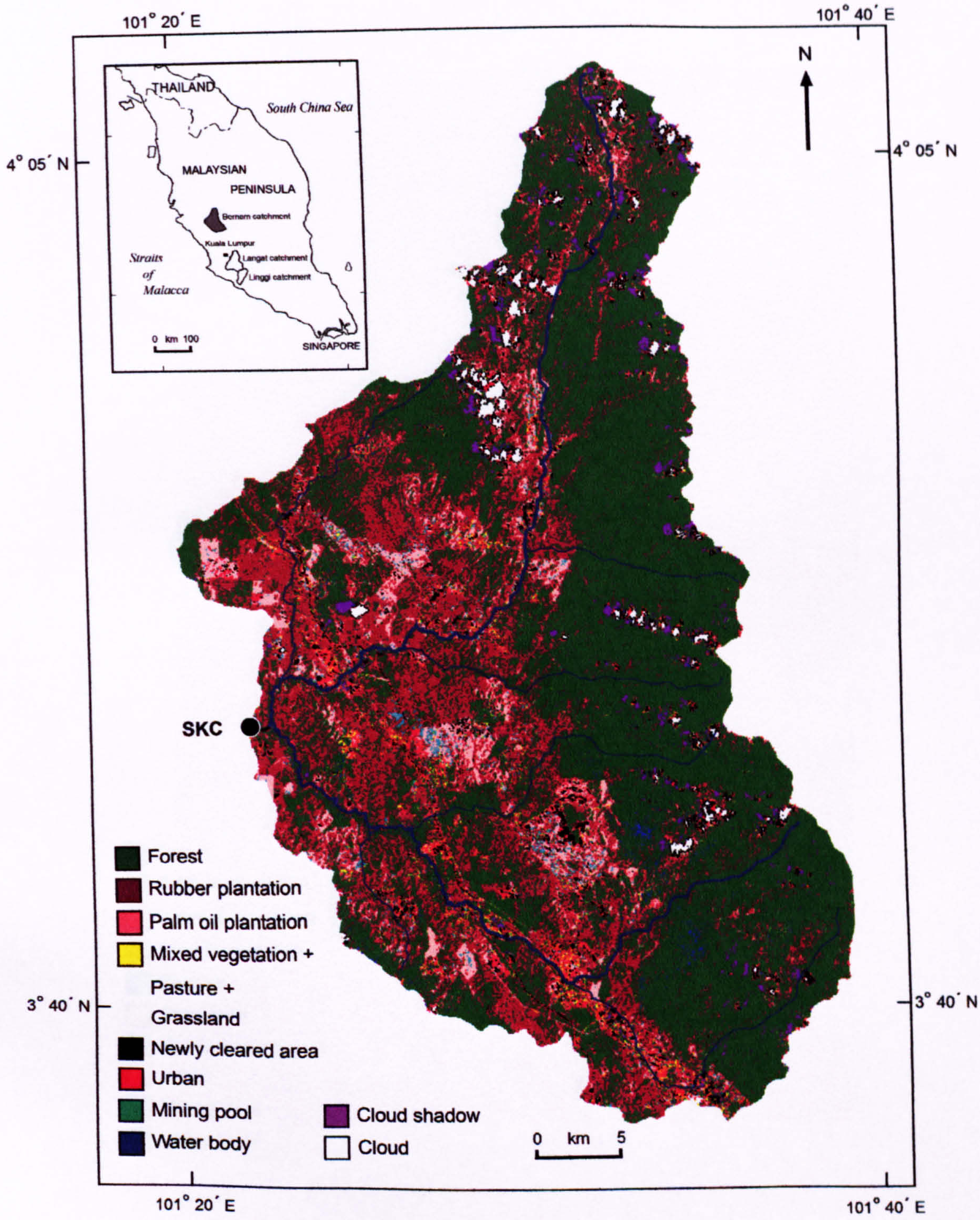
Bernam 1984



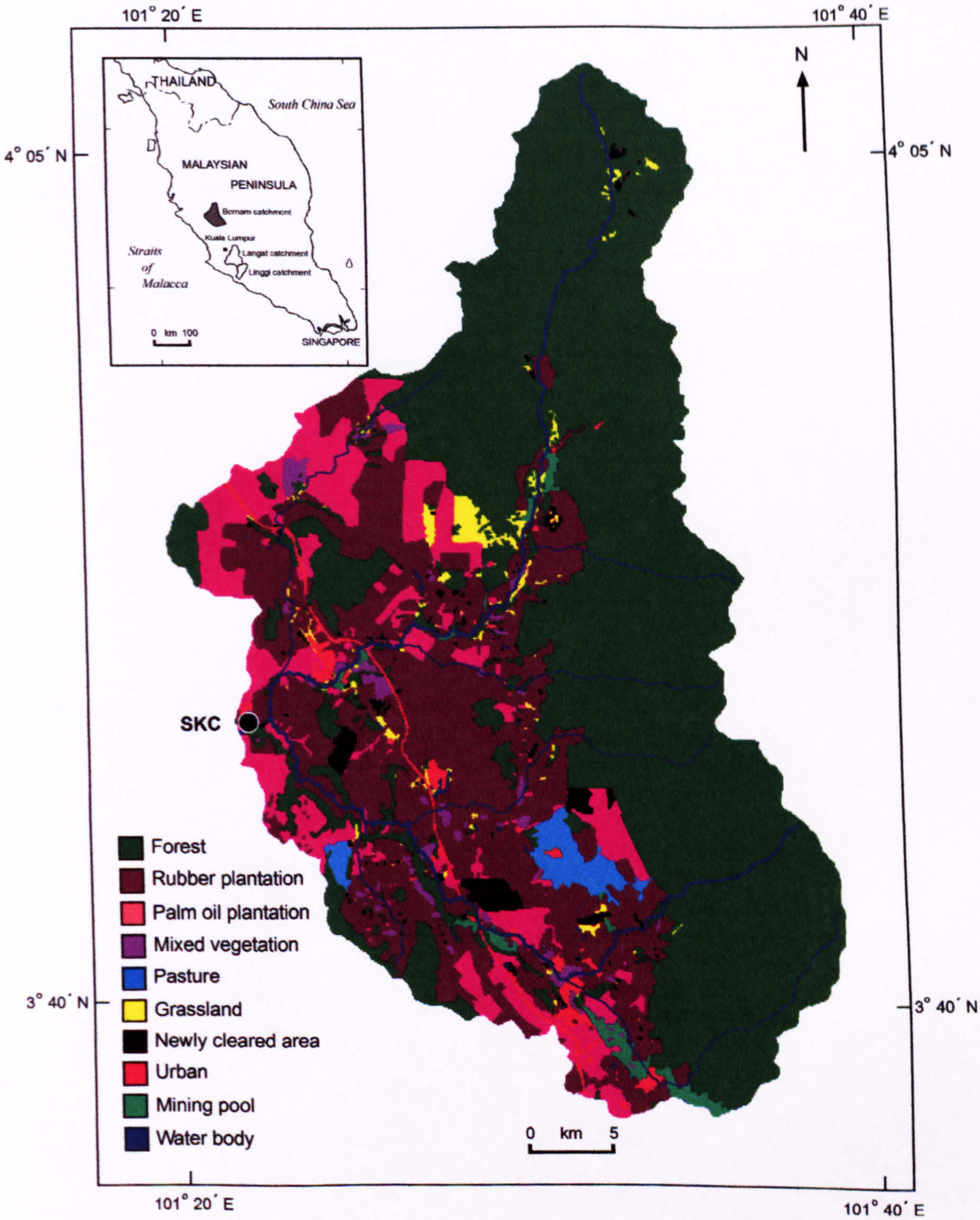
Bernam 1989 - Landsat


101° 20´ E
101° 40´ E
4° 05´ N
3° 40´ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits
of
Malacca
0 km 100
SINGAPORE
SKC
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5

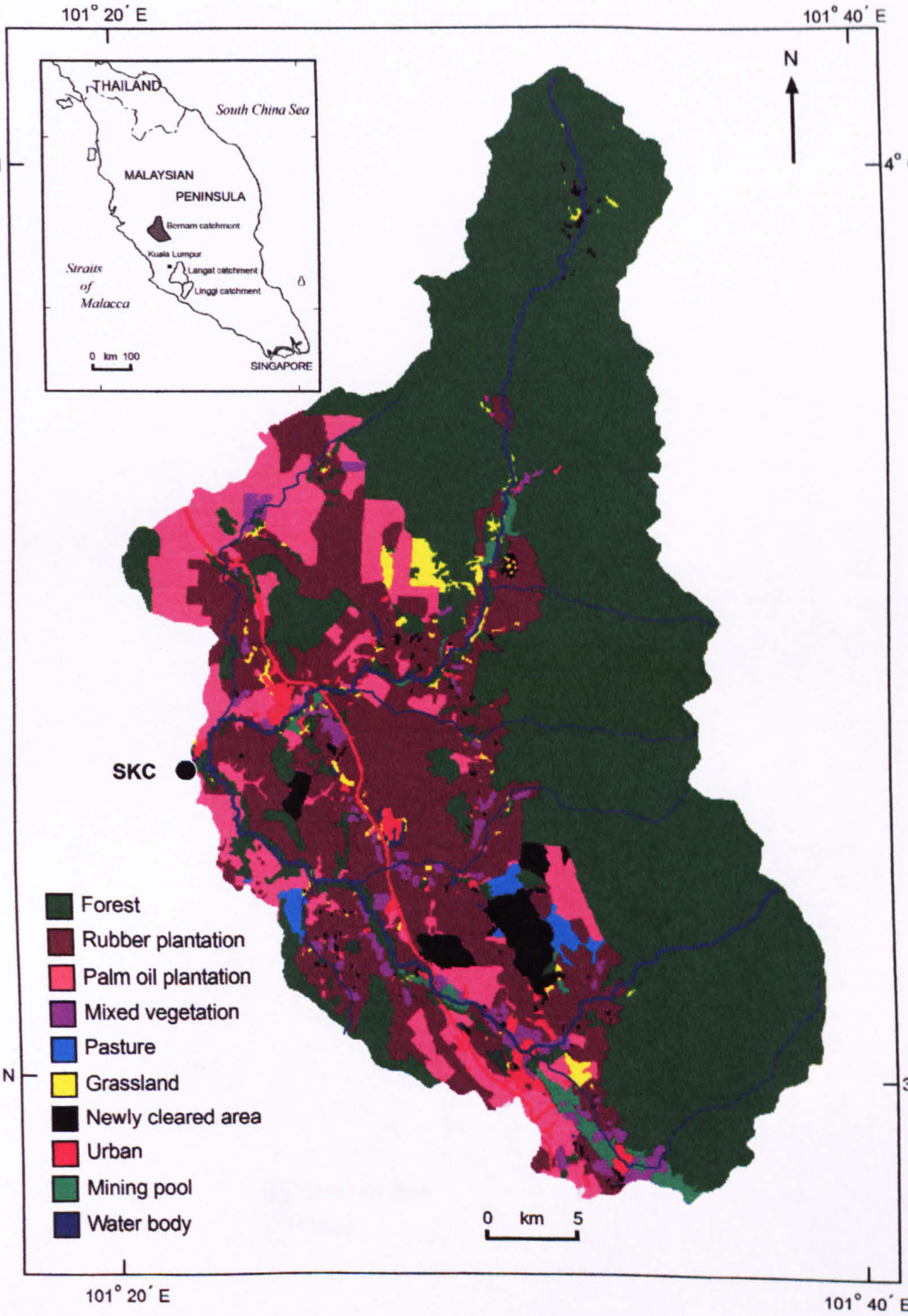
Bernam 1990



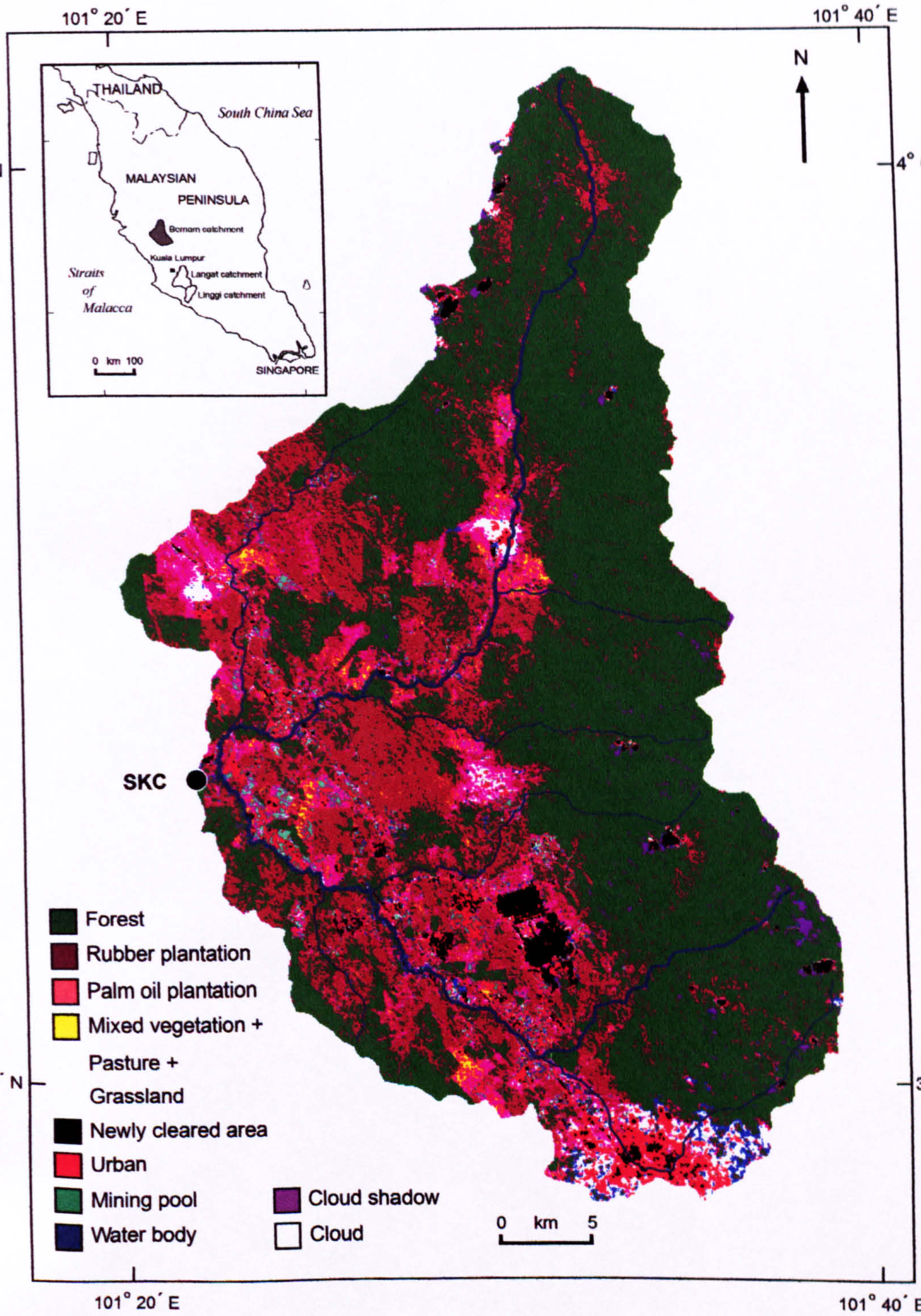
Bernam 1995 - Landsat


101° 20´ E
101° 40´ E
4° 05´ N
3° 40´ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Langat catchment
Linggi catchment
Straits
of
Malacca
0 km 100
SINGAPORE
SKC
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5

Bernam 1997


101° 20´ E
101° 40´ E
4° 05´ N
3° 40´ N
N
THAILAND
South China Sea
MALAYSIAN
PENINSULA
Bernam catchment
Kuala Lumpur
Straits
of
Malacca
Langat catchment
Linggi catchment
0 km 100
SINGAPORE
SKC
Forest
Rubber plantation
Palm oil plantation
Mixed vegetation
Pasture
Grassland
Newly cleared area
Urban
Mining pool
Water body
0 km 5

Bernam 2000



Bernam 2002 - Landsat