Development of a geographic information system (GIS)-based tool for timber harvesting planning for a Malaysian tropical forest.

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Development of a Geographic Information System (GIS)-based tool for timber harvesting planning for a Malaysian tropical forest

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the degree of Doctor of Philosophy in the Swansea University.

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Abstract

Managing a very complex ecosystem such as a tropical forest sustainably is very challenging. The challenge has increased in the recent years in timber producing countries like Malaysia due to increased demands and environmental pressures that need forest managers to make crucial and quick decisions. At present, forest management not only deals with harvesting but also conservation and rehabilitation. These normally involve large volumes of data and analysis, which have been mostly carried out manually in most tropical countries. As a result, the efficiencies and effectiveness of the decisions implemented are limited. To overcome this difficulty, this study proposes the development of a GIS-based tool for timber harvesting planning for a tropical forest in Malaysia. Timber harvesting is chosen in this study because it is the most sensitive environmental activity in tropical forests. The GIS-based tool for timber harvesting planning presented in this thesis consists of three research components, 1) the determination of net production area and identification of the harvestable trees, 2) prediction of soil erosion and its flow direction, and 3) the optimisation of forest road network. The development of the timber harvesting plan by using GIS should improve forest management.

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Chapter 1

Introduction

Overview This chapter introduces the research question that underpins the thesis and presents some justifications as to why GIS-based research is needed in the efficient and effective management of tropical forests in Malaysia. To understand the Malaysian tropical forest scenarios better, some background on the forestry issues in Malaysia, such as resources, policy, management, harvesting and conservation, are also presented. Apart from refining the research question by suggesting the development of a GIS-based timber harvesting plan, this chapter also discusses the aims and objectives of the research.

1.1 The need for GIS-based research in forest harvesting

Malaysia is rich in natural resources and its' traditional economic strength lies in commodities. Today, it is still an important source of tin and rubber, and produces more than half the world's palm oil, as well as being a net exporter of oil and gas (Commonwealth Secretariat, 2006). Forestry is also one of the most important economic resources in Malaysia. In 2003, the value of timber exports was equivalent to more than RM16 billion or US$4.21 billion, which equates to 5 % of the Country's total export revenue. Of this total, the furniture manufacturing sector produced a significant export value of almost RM4.7 billion or US$1.24 billion, while the value of timber exports amounted to

5.1 million m^3 in 2004. According to the Malaysian Timber Council (MTC), Malaysia's total export of forestry products in 2004 comprised logs (RM2.1 billion or US$550 million), sawn timber (RM2.3 billion or US$600 million), plywood and veneer (RM4.4 billion or US$1.15 billion), mouldings (RM600 million or US$156 million), medium density fibreboard (RM0.98 billion or US$258 million) and wooden furniture (RM4.7billion or US$1.23 billion) (Jumat, 2004; International Tropical Timber Organization, 2004a; Malaysian Timber Council, 2004). Among the Asian countries, Malaysia supplied 61 % of the tropical sawn timber to international trade in 2000 (Anon, 2001). Malaysia is also the world's second largest tropical-timber exporting nation, after Indonesia, for all categories of tropical timber products. The importance of the forestry sector to the Malaysian economy is best reflected by the fact that it contributed RM16.31 billion or US$4.29 billion to the national revenue in 2003; the third highest among commodities after petroleum and palm oil, and the sector employs a significant workforce (about 3 % of the total labour force in the Country).

Malaysia has been managing her forests for economic purposes for many decades. The primary aim of forest management has been to sustain the yield production of timber products. In the last three decades, however, due to growing concerns and awareness globally of the need for environmental care and conservation of the forests, Malaysia has implemented a number of measures to ensure that its forests are managed sustainably, both for economic and environmental reasons. This is reflected in the implementation of the National Forest Management system.The Malayan Uniform System (MUS) which was developed in the 1950s was substituted by the Selective Management System (SMS) in the late 1970s. Since then, Malaysia has been actively involved in promoting and practicing the awareness of environmental and conservation imperatives, and has demonstrated a commitment to international conventions and agreements, such as those initiated at the 1992 Rio de Janeiro United Nations Conference on Environment and Development (UNCED) and the International Tropical Timber Organization (ITTO) Year 2000 Objective. Today, considerable attention is given to overall sustainable forest management practices in Malaysia with multiple objectives, including meeting changing societal needs (International Tropical Timber Organization, 2004b).

Forests, as a renewable resource, should be managed sustainably to ensure that their benefits are maximized, taking into account the needs of the present and the future. For almost three decades, Malaysia has implemented an SMS which is principally designed to manage the Hill Dipterocarp forests. The determination of optimum cutting-limit regime in the SMS, which specifies the type and size of trees that can be felled, is set with both the needs of environmental conservation and the demands of the timber market in mind. The objective of optimized sustainable forest management can only be accomplished, however, if precise and up-to-date information on forest resources is available and is readily accessible by forest managers and planners. Bearing in mind these considerations, it is essential to carry out an inventory of forest resources in an area, in the context of the SMS, before it is harvested (Forestry Department, 1997). The forest resource assessment, which results from the forest inventory, produces data on the status of the forest and various trends in the forest resources. This information is used by the forest managers in their decision-making process, enabling them to manage the forests sustainably. Consequently, reliable data on the forests provides policy makers and politicians with essential information to develop and align forestry policies and programmes. To date, a rather conservative approach has been adopted, based on experimental data and experience gathered over many years. This approach is often preferable because the environmental risks associated with more radical attempts to manipulate the function and structure of forest ecosystems are reduced. Modern information technology, such as remote sensing, GIS and modeling, however, offers the potential to provide more detailed, precise and up-to-date analysis of the forest environment than the general analysis which is now broadly used and, hence, opens up a range of new possibilities for forest management. In a different forest environment, Kellomaki (2000) developed a forest ecosystem model for assessing the effects of climate change on the functioning and structure of boreal coniferous forests under the assumption that temperature and precipitation are the basic dimensions of the niche occupied by any one tree species.

Reliable information on the status and condition of the forest, and its changes over time, is a prerequisite for good forest management (Noss, 1999). Existing data sets, however, are often rather outdated and may include important errors. As a result, inaccurate analysis, conclusions and decisions about forest development may be derived, based on incorrect or insufficient information (Thuresson, 2002). Huge quantities of data relating to the characteristics of the forests and their hinterlands are normally compiled in various forms. These data are collected, processed, stored, analyzed, retrieved, summarized and tabulated by forest resource managers. In order for the managers to prepare reports on the state of the forest, all these sources of information have to be made available and readily accessible, and be regularly updated in a comprehensive Relational Database Management Systems (RDBMS). The RDBMS can then be used to predict the ecological, economic, social and cultural effects of the implementation of various management activities in the forest (Whyte, 1999). The RDBMS could be further enhanced by introducing scientific knowledge into the management processes (i.e. some form of expert system/knowledge-based system) and by incorporating numerical simulation models, both of which would assist the development of knowledge-rich practices to minimize the costs and environmental risks related to forestry. Experimental findings can be integrated to the simulation models to assess the long-term effects of the proposed management practices on the processes and productivity of the forest ecosystems (Kellomaki, 2000). Data on the status and trends of the forest, as well as information on their health and vitality and their socio-economic and environmental functions and values, are crucial to assist decision-making related to forest and land-use policies, and resource allocations (Food and Agriculture Organization, 2006b).

In the implementation of forest policies and management, it is rarely the case that the forest managers and the academic researchers interact closely on a regular basis, but this could be made possible by using the spatial database management system in such as way that the managers could use the researchers' knowledge in a clearly explained, step by step, procedure tailored to their specific needs and circumstances. Therefore, a spatial database management and decision-support system. which is divided into a set of relatively discrete sub-systems, but which is fully integrated, is a desirable and timely objective. Thus far, although a lot of research has been undertaken to model individual aspects of harvest planning, this has not yet been performed in a comprehensive and integrated way, especially in connection with the needs of strategic, tactical and operational planning. Such a methodology is needed, however, to meet the long-term objectives of sustainable forest management. There is a large body of evidence in other fields of environmental management, such as soil and water management, which demonstrates the success of this approach, but few relating to forest inventory (Whyte, 1999).

To ensure that forest ecosystems are sustainably managed, researchers and managers need to provide objective evidence, especially in the context of harvesting. Several things have to be considered, such as the structure of the integrated forest inventory and the monitoring and interactive modeling systems, where clear and rational objectives for every part of the management process are defined. Moreover, the interactions between the needs of the managers and the priorities of the researchers could be enhanced through a management information system in which context changes to the forest ecosystems can be clearly understood. Hence, these will promote organizations to have their own programmes of monitoring operational performance and the state of ecosystems, in addition to auditing and certification by independent outsiders (Whyte, 1999). In relation to these matters, improved management procedures are needed, and they must be developed to maintain the continuity of production levels in managed forests (Bawa and Seidler, 1998).

The tropical rainforest involves a complex set of interactions between tree species, which are resilient and, given sufficient time, will regenerate to a level that allows the next harvest to be performed at a given volume of standing timber. Assessment of the factors of time and the quality of the forest, which run through this general statement, is strongly dependent on the quality of the information obtained about the dynamics of the restructured forest. Uncertainties introduced by natural- (e.g. climatic variability) or human-induced problems introduce corresponding uncertainties in the outputs from models and management systems, making it more difficult to plan sustainable harvesting. Time also means that the resources that are provided to regenerate and manage forests may fluctuate and change with priorities of the government policies (International Tropical Timber Organization, 2004b). Therefore, methods for inventory and monitoring the forest management information system need to be developed and reviewed regularly in a forum that brings together researchers and managers, and which takes into account the most up-to-date forest science to ensure that the production of the forest managed in a sustainable manner. Advances in technology, including Information Technology, such as remote sensing, GIS and Global Positioning System (GPS) can and should be utilized in the forest management system to produce factual and precise results, complete and detailed explanations, and speedy conclusions in a form that can be readily implemented by the forest managers and harvesters. Hence, a GIS-based timber harvesting plan for a Malaysian tropical forest reserve is proposed for this study.

1.2 Forestry in Malaysia

Forests are complex and dynamic ecosystems, which interact with the physical factors surrounding them, such as the incident solar radiation and other climatic/weather conditions (e.g. rainfall), and other environmental controls, such as topographic and edaphic factors. The relationships among these factors are constantly changing and this is an important key to the successful management of forests ecosystems. This is due to the fact that suitable and appropriate manipulation of forest dynamics will not only increase timber production, but will also affect a range of environmental variables relating to the forest (Kellomaki, 2000). Moreover, poor forest management, deforestation and degradation help to accelerate the release of carbon from the various stores in the forests, while sustainable management, planting and rehabilitation of forests can increase carbon sequestration.

Forestry is traditionally one of the most important economic sectors in Malaysia, and it has evolved over time in response to a range of social and economic factors. Under both of these pressures, large areas of virgin forest have been turned into commercial and residential district over the past few decades. Similarly, timber has been extracted from the forests for economic purposes. Taken together, these factors gradually change the character, status and function of the forests. In turn, this has the potential to affect the socio-economic situation in Malaysia because there is a functional feedback system between natural and human/economic resources. Recently, the ecological and climatological function of forests has been emphasized, because of widespread concerns about global climatic change and environmental degradation. Therefore, forests, which are public as well as private property, represent a significant resource both locally and globally and must be managed sustainably to ensure inheritance by future generations.

1.2.1 Forest Resources

One of the key variables for decision making for forest policies and forest sector investment is the extent of the forest resources. The total extent of world's forest cover in 2005 was estimated to be 3952 billion ha, equivalent to roughly 30 % of the total land area. More than one-third of the world's forests are primary forests (i.e. forests of native species) in which there are no indications of human activity and where ecological processes are not significantly disturbed. Although the rate of deforestation amounted to about 13 millionha$\cdot$yr^{-1} during the period 1990–2005, this loss is significantly offset by forest planting, landscape restoration and natural expansion of forest. (Food and Agriculture Organization, 2006b).

Tropical rainforests cover roughly 7 % of the world's land mass, representing about 1.7 % of Earth's surface; it has been estimated that they contain more than half of the flora and fauna in the world and is an important factor in the conversion of carbon dioxide to oxygen. While tropical rainforests are found in 85 countries around the world, 90 % of these forests are concentrated in just 15 countries, each of which has more than 10 million ha of forest and remain among the few heavily forested tropical countries (Food and Agriculture Organization, 2001). Among this subset of countries, a huge amount of the world's tropical forests is found in Malaysia. In 2000, for instance, Malaysia's tropical forests represented 19 million ha out of the 3.9 billion ha of the forested areas globally (World Resources Institute, 2006).

In 2003, the total area of forests in Malaysia was estimated to be 19.2 million ha, or 59 % of the total land area. Of this forested land, 0.25 million ha were timber plantation forests (excluding rubber plantations), while the other 19.27 million ha comprised natural forests, peat swamp forests and mangrove forests. In Malaysia, a total of 14.39×10^6 ha, or 43.8 % of total land area, was designated as Permanent Forest Estate (PFE) in 2003. Peninsular Malaysia, which represents 40 % of Malaysia's land area, is 44.7 % forested (International Tropical Timber Organization, 2004b). Much of the forest consists of dipterocarp forest (89 %); the remainder is peat swamp forest (7 %), mangrove forest (3 %) and planted forest (1 %) (Chan, 2002b). With a large area still covered by forests, the biodiversity, environmental and economic values of these areas is increasingly important.

1.2.2 Forest Policy

In Malaysia, forest-based industries have been the backbone of the national economy for many decades, hence it is understood that the sustainable management of forest resources is major concern for Malaysia. It is presumed that the mis-management of the present forest resources will result in a decrease in the volume and value of future timber production. Moreover, many values and products other than economic can be accrued from the forest, such as recreational and environmental values, as well as non-timber products and services, such as bamboo, rattan, medicinal plants and home and food sources for the indigenous people and wild animals.

In its forest policies, Malaysia subscribes to and implements the principles of Sustainable Forest Management (SFM) to maximize the social, economic and environmental benefits of the forests to the Country. The SFM of tropical forests as defined by ITTO is:

> "…. the process of managing permanent forest land to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue undesirable effects on the physical and environment." (van Bueren and Blom, 1996 pg. 18).

Under Malaysian Law, forests fall within the jurisdiction of the state governments. The powers of the state governments include the ability to enact forest laws, to formulate forest policies and to undertake management responsibilities independently. The role of the federal government is only to provide advice and technical assistance, maintaining experimental and demonstration stations, training and research activities. In order for the forest to be administered and managed efficiently, and also to coordinate between the federal and state governments, Malaysia has established a National Forestry Council (NFC). The NFC is the forum within which SFM policies and implementations between the two governments are discussed and agreed upon. A National Forestry Policy (NFP) was formulated in 1978 by the NFC, which was amended in 1992 due to the concerns about the conservation of biological diversity, sustainable utilization of forest resources, ecological and environmental stability, as well as the role of local communities in forest development, compared to the traditional approach of forest management, which focused mainly on timber production. The amendment was carried out to ensure a common approach to forestry management between the separate state governments and to maintain the forest stability while providing the required economic, social and environmental benefits (Enters and Leslie, 2002).

The NFP is a strong statement of the intentions and direction of the both federal and state governments in forestry management. It notes that the principles of sound forestry management are to be applied, and stresses the need for efficiency in the production and utilization of forest resources. Sound forestry management was changed to SFM in later revisions to reflect the current expression. The objectives of the NFP are to conserve and manage the forests based on the principles of sustainable management and to protect and conserve its important roles in biological diversity, genetic resources, research and education. The policy also mentions specifically the need to increase the production of non-wood forest products through scientific and sustainable management practices, to supplement local demands and the requirements of related industries. The key foundation of the NFP is the dedication of sufficient areas of strategically located forests classified as Permanent Reserved Forest (PRF), in accordance with the concept of rational land use. The PRF will be managed and classified under four major functions:

1. Protection Forest for ensuring favourable climatic and physical conditions in the Country; the safeguarding of water resources, soil fertility, environmental quality, preservation of biological diversity and the minimization of damage by floods and erosion to rivers and agricultural lands.

2. Production Forest for supplying all forms of forest produce (in perpetuity and at reasonable rates) that can be produced economically within the Country and are required for agricultural, domestic and industrial purposes, and export.

3. Amenity Forest for the conservation of adequate forest areas for recreation, eco-tourism and public awareness.

4. Research and Education Forest for the conduct of research, education and the conservation of biological diversity.

The PRF is one of the concepts later enshrined in the ITTO Objective 2000. ITTO is an intergovernmental organization promoting the conservation and sustainable management, use and trade of tropical forest resources. Its 59 members represent about 80 % of the world's tropical forests and 90 % of the global tropical timber trade. As a producing member of ITTO, Malaysia is committed to achieving the ITTO Year 2000 Objective, where all member countries agreed to implement the procedures required to achieve SFM. Once certified, a country has the evidence that a SFM system has been implemented in its forests and that its timber can be traded to the international market. Malaysia hopes that with certification, exports of timber products will be increased as demanded by the international market (Malaysian Timber Council, 1997). The demand for certified forest products comes from the wood business chain (i.e. wholesalers and retailers), but not yet from the final consumers. Despite recent moves towards more cooperation between certification schemes, a lack of mutual recognition between schemes may confuse consumers. The adoption of Chain of Custody (CoC) certification to trace forest products back to their source is expanding. Several initiatives are underway to assess certification schemes and increase transparency. The national and local government procurement policies in some countries increasingly influences wood consumption and require that wood products come from sustainably managed forests (International Tropical Timber Organization, 2004a). The effort and active implementation of SFM certification, promotion of the SFM concept at the international level, and adaptation to the Kyoto Protocol are among the most important issues debated both domestically and internationally (Fujisawa, 2004). Hence, Malaysia has taken the appropriate moves to ensure that this objective is successfully accomplished. Malaysia has developed its criteria and indicators based on those developed by the ITTO to ensure sustainable tropical forest management and known as Malaysian Criteria, Indicators, Activities and Management Specifications for Forest Management Certification (MC&I). Some of the forestry practices listed under *Criteria, Indicators, Activities and Management Specifications for Sustainable Forest Management* are already being carried out but there are more to be adopted. To ensure its consistency, it is paramount that the MC&I be reviewed against the ITTO guidelines and other internationally-agreed principles of forest management.

Malaysia is also one of the few countries in the world that has established its own national timber certification scheme, developed by the Malaysian Timber Certification Council (MTCC) in 1999. The task of the MTCC is to develop and operate a voluntary national timber certification scheme, as well as to play a coordinating role by being the Secretariat for the multi-stakeholder consultative process, which led to the development and adoption of forest management standards. Currently, the standard used for forest management certification under the MTCC timber certification scheme is the MC&I 2001, which is based on the ITTO Criteria and Indicators (C&I). For the next phase of its scheme beginning 2005, the MTCC will use a new standard, MC&I 2002 which is based on the Principles and Criteria (P&C) of the Forest Stewardship Council (FSC) (International Tropical Timber Organization, 2004b).

Malaysia was among the first producer-member countries of ITTO to commit to the implementation of the ITTO *Guidelines for the Sustainable Management of Natural Tropical Forests and its Criteria for the Measurement of SFM*. Related to this, in 1994, a National Committee on SFM was formed, consisting of representatives from various agencies in the Malaysian forestry sector. The task of the Committee is to manage the process of implementation of the ITTO C&I. The Committee has formulated a total of 92 activities and 27 indicators to operationalize the ITTO C&I at the national level and 84 activities at the level of the forest management unit level. The activities cover forest resource security, continuity of flow of forest products and services, socio-economic effects, community consultation and an acceptable level of environmental impact including the conservation of biological diversity (Malaysian Timber Council, 1997).

Among the most difficult issues faced in managing forests sustainably is determination of the Annual Allowable Cut (AAC). AAC is the amount of timber permitted to be harvested in the forest within a one year period to ensure the sustainability and productivity of the forests. At present, the AAC is determined through a technical process based on forest inventory, which is a good scientific methodology. Then, with other relevant data, the AAC is extrapolated from lower to higher range values of incremental growth of the forests. The AAC is the key operational process for implementing SFM. The NFC discusses which values should be used to determine the AAC. If a lower value is used, this would result in a smaller volume of timber being harvested, which would affect the economic income; however, a higher value would correspondingly result in a larger volume of timber extraction and might decrease the environmental value of the forest. The process of determining the AAC for each State is approved at the NFC, so that a figure can be derived that balances both the development needs of forestry revenue of the States and the national and international responsibility of the country. No doubt, the AAC could be further refined through research discussions (ie workshops or conference and regular investigation), because the determination of the AAC is critical to ensure the sustainability of harvest.

1.2.3 Forest Management

In general, the management of forest resources is aimed at simulating the ecological processes that control the regeneration and growth of tree populations. Proper management is, therefore, related to the patterns of the disturbance controlling forest regeneration. Forest management consists of a set of silvicultural operations used to control the functioning and structure of the forest ecosystem over time (Kellomaki, 2000). In ensuring the sustainability and conservation of her forests, Malaysia has implemented an SFM policy. This involves Reduced Impact Logging (RIL), which, in turn, involved the implementation of a series of pre-logging and post-logging guidelines designed to:

1. protect future regeneration from injury;
2. minimize soil damage;
3. prevent unnecessary damage to non-target species; and to
4. protect critical ecosystem processes.

Most RIL guidelines call for at least the following measures:

- pre-harvest planning of the routes of skid trails and the locations of log yards;
- directional felling to facilitate timber yarding and protection of potential crop trees;
- restrictions on the movements of ground-based yarding equipment on steep slopes and during wet weather; and
- post-logging closure operations to drain roads and skid trails and to remove potential impediments to stream flow (Putz et al., 2000).

The silvicultural systems used in Malaysia are designed to promote natural regeneration after logging (Dawkins and Phillip, 1998), but modern mechanized extraction leads to considerable damage of natural regeneration (Brown, 1998). Since the 1950s, under the MUS, it has been mandatory to prepare and implement forest management working plans in the PFE. In the late 1970s, however, the logging procedures followed a system called SMS which was introduced in Peninsular Malaysia in 1978 and later replaced the MUS. The MUS was originally developed for lowland tropical rainforest in Malaysia and is no longer being implemented in Malaysia. Recent additional guidelines under the SMS have been set by the forestry departments to incorporate volume and area control, such that harvesting is based on joint consideration of area, volume and silvicultural conditions. The SMS uses pre-F inventory data to select a harvesting regime based on a 30-year cutting cycle. The SMS is also the mandated forestry system used throughout Peninsular

Malaysia (Forestry Department, 1997). In relation to this, the extractable timber volume for a specific area is based on a pre-F forest inventory, offering various cutting options. The actual logging volume is then supervised at forest checking stations, which check the volume of timber harvested against the specific licenses. To ensure accountability, a sophisticated tree-tagging system has been implemented.

The implementation of the SFM provides the basis for the forest certification in Malaysia through the MTCC, which was created in 1999. In fact, timber certification in Malaysia has gone beyond the motivation of ensuring market access in environmentally-sensitive areas. The Forestry Department (FD) are the custodian of the forests, which are an asset for the Nation. In this context, the MTCC administers a fund for forest management auditing under the MTCC scheme on a routine basis. This arrangement, which is implemented in Peninsular Malaysia, is unique globally in the world of forestry certification.

Peninsular Malaysia has recently adopted the RIL guidelines, which were published in 2004. The RIL guidelines are an amalgamation of the individual guidelines found in various documents of the Forestry Department Peninsular Malaysia (FDPM), which were implemented previously. In Sabah, for instance, RIL is specially used to guide timber harvesting. The techniques involved in RIL include:

- climber cutting before logging,
- marking of trees for directional felling,
- a planned network of roads and skid trails aligned according to the location of the trees and terrain conditions and
- a halt to harvesting during rainy periods.

The last of these is already in practice due to the inherent dangers to the operators in wet conditions. Cable logging is used on steep slopes and undulating terrain to reduce further the impact of logging. To reduce impact on the soil, skidders are not allowed to use their blades when hauling logs. All of these techniques are implemented to keep logging damage to a minimum. Old skid trails are used, whereever possible, to minimize the impact on soils caused by the creation of new skid trails; this practice is now being implemented widely. This does not preclude opening new skid trails where there is a clear justification and approval by the Forestry Department. The re-use of old skid trails is also prevalent in Peninsular Malaysia and Sarawak. Areas with low stocking of commercially valuable species are surveyed for regeneration and rehabilitation. Climber cutting is carried out to enhance growth in commercial species. The latter activities are also standard in Peninsular Malaysia and Sarawak.

The Forest inventory of Peninsular Malaysia forms the basis for allocating extraction volumes. A peninsula-wide National Forest Inventory (NFI) was conducted in Peninsular Malaysia between 1970 and 1972 under the Food and Agriculture Organization (FAO)/United Nations Development Programme (UNDP) Forest Industries Development Project. This inventory was used to determine the forest resource availability, especially timber resources in Peninsular Malaysia. The inventory was updated in the second and third NFI (Peninsular Malaysia), which were conducted between 1981 and 1982 and between 1991 and 1993, respectively. A follow-up forest management level inventory is now planned for each of the Forest Management Unit (FMU). The fourth NFI is currently under way. This peninsula-wide inventory is complemented by the pre-felling and post-felling inventories for every timber concession (International Tropical Timber Organization, 2004b).

1.2.4 Forest Harvesting

Harvesting inevitably affects the environment. With careful planning and sound operational practices, however, the disturbances to the forest can be minimized. With continuously improved felling techniques, improved overall forest management, innovative harvesting methods, and robust downstream processing coupled with commitment from timber producing companies, sustainable harvesting can be achieved (Ludwig et al., 2001). Most of the production forest is confined to the hillslopes, where the terrain is rough and the slope is steeper. Therefore, harvesting and transporting timber out of the forests necessarily results in some damage to the residuals and young trees owing to the heavy machinery employed. Moreover, the soils also become severely eroded and compacted as a result of frequent heavy vehicle movements. Studies on soil erosion, water quality and nutrient dynamics suggest that there are serious problems with the rate of recovery of the forest soils (Appanah, 2001).

Determination of sustainable cutting cycles and annual allowable cuts is crucial to prevent further degradation of tropical timber resources (Ludwig et al., 2001). Clear-felling of tropical rainforests disrupts the interrelated life cycles of very many indigenous species. The conversion of a diverse natural forest to agricultural land, or to a tree monoculture and short-rotation forestry, may also introduce severe risks of erosion and nutrient leaching. These negative aspects must be taken into account when logging operations are planned, particularly since the effects of tractor tracks can persist for many years (Hogberg and Wester, 1998).

The impact of harvesting on biodiversity depends upon both the intensity of logging (i.e. the number of stems extracted per unit area) and the amount of care and planning that goes into the extraction process. Although there is an extensive and expanding literature on the effects of logging on the distribution and abundance of plant and animal species, most of these studies describe the effects of mechanized, commercial logging operations. The immediate effects of a logging operation in a primary tropical forest consist of significant alterations to the physical structure of the forest (Bawa and Seidler, 1998). Removal of as few as 3.3 % of the trees in an area can reduce canopy cover by 50 % (Johns, 1988; Uhl and Vieira, 1989), and disturbance to the forest canopy of up to 75 % is not uncommon (Cannon et al., 1994). The resultant opening of the canopy can result in changes to the biophysical conditions of the forest, including the soil. Soil structure can be modified by compaction and drying, which may in turn have negative effects on the recruitment rates of trees (Malmer and Grip, 1990; Johnson and Cabarle, 1993). Where RIL techniques are employed during logging of lowland tropical forests, the amount of damage to advanced regeneration and soils is generally reduced by about 50 % relative to conventional logging procedures John et al. (1996); Pinard and Putz (1996); Winkler (1997). Employing RIL techniques is not the same as sustainable forest management, but in many forests it constitutes an important step toward this coveted goal (Putz, 1994). At present, innovative methods to fell trees and transport logs are being tested in various parts of the Country in an attempt to reduce the environmental damage of logging. Various types of damage, and uncontrolled management implementations, result in decreased wood quality, habitat disruption, water pollution, increasing sediment quantities. For these reasons, spatial constraints are often imposed upon harvesting activities on forest stands or harvest units adjacent to those that have been recently felled (Baskent and Keles, 2005).

In Malaysia, the SMS is a framework that is generally applied to forest management and conservation. The SMS was designed for logging operations in forested hill areas. In the 25 to 30 year cutting cycle, selective felling is carried out. For dipterocarps, the cutting limit is over 60 cm DBH, and for non-dipterocarps it is over 45 cm DBH. The treatment which is applied to logged-over forests is dependent on stand condition, securing an economic cut and determining the most feasible way in which the stock may be replenished either naturally or through enrichment planting. Within this context, the preparation and implementation of a Forest Management Plan (FMP) is compulsory, and is currently adopted and implemented by each of the States in the Country. The FMP outlines the AAC, silviculture prescriptions for harvested forests, the minimum cutting limits for harvestable species, and specifies the species that can be removed. At the operational level, information on which species and which particular trees are allowed to be felled is provided by a pre-F inventory, based on a 10 % sample, rather than a full inventory. This sample size is considered adequate in most instances; in any case, a full inventory would be too time-consuming and costly. The larger trees which are under the cutting limit are left as residual trees and will form the next crop, and smaller diameter trees will form the crop during future cutting cycles. In general, only 7 to 12 trees are felled per hectare but there are local variations. The constant factor is that 4 mother trees per hectare, which produce seeds or also known as seed trees, are left standing and undamaged. There is no requirement, however, to ensure that equitable numbers of different species of mother trees are left after logging, although there are guidelines for selecting the number and quality of mother trees per hectare. The guidelines for the selection of mother trees stipulates that the composition of mother trees should reflect the original stand composition of commercial timber species, based on the result of the pre-F inventory.

Constant monitoring and changes in the cutting cycle may be required if regeneration is not as good as initially predicted. A post-felling (post-F) inventory is carried out to determine the prescription for silviculture, and to determine infractions against the procedures and licensing conditions. Enforcement is carried out routinely by FD staff to prevent infractions against the procedures and licensing conditions.

1.2.5 Forest Conservation

Roughly 11 % of the world's forests are designated for the conservation of biological diversity. These forests have increased in area by an estimated 96 million ha since 1990 and are mainly located within protected areas. The conservation of biological diversity was reported as one of the management objectives (primary or secondary) for more than 25 % of the forest area (Food and Agriculture Organization, 2006b).

Many ecological research studies have been carried out to examine the biodiversity of the rainforest (He et al., 1996; Hubbell, 1979; Hubbell and Foster, 1983, 1987; Kochummen et al., 1991; Newberry et al., 1986; Poore, 1968; Wyatt-Smith, 1987). The diversity of a community usually refers to species richness, abundance or a combination of various diversity indices in a community (He et al., 1996). It is regarded as the result of species interaction, or community adaptation, to the environment over time (Rice and Westoby, 1982). Therefore, it is important to ensure that this sensitive and stable environment be maintained, especially after harvesting activities have taken place. Among the features stated in the SMS is the need to maintain the original species composition of the forest, to sustain its biological diversity. Silvicultural treatment is carried out to improve the stocking and growth of preferred trees in the residual stands by means of thinning and enrichment planting immediately after harvesting. In these activities, the heterogeneous character of the forest is maintained.

Deforestation and forest degradation are probably the most significant factors impacting on the survival of species. Deforestation probably poses the most direct threat to biodiversity. This imposes a tremendous challenge to ensure that the desired distribution and types of habitat, and the consequent levels of biodiversity, are given some form of protection from conversion, or are given the highest level of protection by designating areas as totally protected areas. Tropical deforestation releases more than 1.5 billion metric.tons of carbon into the atmosphere every year, though in some years, like the 1997-1998 el Nino year when fires released some 2 billion tons of carbon from peat swamps alone in Indonesia, emissions are more than twice that. There are difficulties in interpreting the results of past studies on the biodiversity of the forest. First, there are major differences between these studies in terms of the ecological conditions examined independent of logging events, in the spatial and temporal scales examined, in the scientific methods employed, and in the characteristics of the logging operations studied, which make it difficult to predict with great confidence how timber harvesting may affect biodiversity of a specific area (Bawa and Seidler, 1998). What is evident, however, is that the overall effects of logging are likely to vary with the size of the area being harvested and the extent to which the area is embedded in a natural, undisturbed forest matrix (Boyle and Sayer, 1995). Second, the sustainability of natural forest management cannot, in principle, be rigorously evaluated until at least three cycles of harvest are completed (Poore et al., 1989). On the other hand, it has been argued that almost all of a tropical forest's biodiversity could be conserved if the number of stems extracted could be kept to a strict minimum. Perversely, however, as extraction becomes less intensive, damage levels per tree rise, primarily because the extent of road building per tree extracted rises exponentially (Gullison and Hardner, 1993; Boot and Gullison, 1995).

Tropical rainforests are very much richer than the temperate forests: there are seldom fewer than 40 (often over 100) tree species over 10 cm in diameter within a single hectare of primary forest (Richards, 1996). Indeed, Malaysia's rich and diverse tropical rainforests are recognized internationally as one of the mega diversities for both flora and fauna. The forests are inhabited by over 8000 species of flowering plants, 1000 species of vertebrates, over 6000 species of butterflies and moths, an estimated 20 000 to 80 000 invertebrates and an unaccounted number of insect species and other lifeforms. Therefore the forests must be managed carefully in accordance with the principles of SFM to achieve a balance between development and conservation, so that forest products and services can be obtained in perpetuity (Chan, 2002b). More generally, it is noted that there are over 300 species of mammals (27 endemic), birds (736 spp., 11 endemic), reptiles (268 spp., 69 endemic), amphibians (165 spp., 57 endemic), freshwater fishes (449 spp.), invertebrates (more than150 000 spp.) including 12 000 species of moth, and 1200 species of butterflies. Of flowering plants, there are over 15 000 species, of which orchids account for over 3000 spp., (more than 2000 species endemic), palms (more than 250 spp., of which over 100 species are endemic), ferns (more than 750 spp.), fungi (more than 500 spp.), mosses (more than 450 spp.). According to the International Union for the Conservation of Nature and Natural Resources (IUCN) 2002 Red List, Malaysia has one extinct animal, with 143 species under threat from a variety of sources, including habitat destruction, logging, forest conversion, hunting and trade. Since 1948, around 170 species of flowering plants endemic to Malaysia have become extinct, including *Shorea cuspidata* (Dipterocarpaceae), *Impatiens cryptoneura* (Balsaminaceae); *Piper collinum* (Piperaceae); and

Ridley's staghorn fern - *Platycerium ridleyi* (Polypodiaceae). A further 199 species are classified as critically endangered globally. In addition, the forest is rich in species that are used in traditional medicine and as a source of pharmaceutical drugs, for ornamental purposes (orchids and palms), fruit trees, traditional technology (rattan and bamboo) and other minor forest produce (International Tropical Timber Organization, 2004b).

One of the salient properties of the tropical rainforest is its high species diversity. A tropical rainforest in Sarawak, East Malaysia, was found to contain over 1000 tree species within an area of approximately 50 ha (Condit et al., 2000), and a 50 ha plot in Pasoh, Negeri Sembilan, Peninsular Malaysia was found to consist of 825 species (He et al., 1996). Dipterocarp forest constitutes over 85 % of the forested area in the Country, mostly concentrated in the lowland regions, below about 1200 m above sea level. In the lowlands, for dipterocarp forest alone, a total of 820 species of trees over 1 cm DBH were recorded in a 50 ha area (Anon, 1999). This indicates that the forest types in Malaysia are biologically very diverse. Therefore, it is important to maintain the ecological and environmental values of the tropical forest to ensure of the sustainability of its biodiversity.

The role of forestry in providing environmental services such as watershed protection, biodiversity conservation and species management have also gained recognition, and this is enshrined in the NFP 1978 (revised 1992), which is applicable to Peninsular Malaysia only.

1.3 A role for GIS technologies as a part of the solution

Most countries in the Asia-Pacific region assess the extent of their forest areas on a regular basis. The area of natural forests is usually known, although area assessments may not necessarily be completely accurate. In some countries, data on logging are also available and post-harvesting inventories determine the needs for silvicultural treatments. Once the forest operators leave the forest areas and road conditions deteriorate, however, regular inventories cease. As a result, knowledge of the status of logged-over forest areas is scant, and the implicit assumption is often made that previously logged forests will be ready for re-entry, although this assumption is frequently based on inadequate knowledge of forest stand volumes and composition. In fact, there is a widespread concern that many production forests are now degraded and will yield, during the second harvest, substantially lower commercial volumes than during the first harvest. The knowledge gap is a major concern, since wood-based industries rely on a continuous flow of raw material. In many countries, all the old-growth production forests have been, or will soon be, exploited and wood supply will have to rely on logged-over, or second-growth, or even third cycle or residual forests. Assessing the status of logged-over forests in terms of expected volumes, species composition and timber quality is, thus, a high priority.

Sustainable and holistic planning and management of forest resources requires the integration of large volumes of disparate information from numerous sources (Sugumaran, 2000) and demands efficient tools for assessment and evaluation to permit broad, interactive participation in the planning, assessment and decision-making processes. There is no single method or technique that can address all these requirements (Fedra, 1995). However, modern technologies such as remote sensing (earth observation), GIS, and numerical (simulation) modeling, combined with simple graphical user interfaces, relational database management systems and intelligent knowledge-based systems have the necessary power and flexibility (Densham, 1991; Fedra, 1994) to solve the planning and management problem.

A forest inventory with relatively low sampling intensity, high accuracy in measurements and known random errors in the estimates can give estimates for the most important and sought-after variables on the country level, although the level of precision does not permit breakdown into smaller areas or classes (Thuresson, 2002). International Union of Forest Research Organizations (IUFRO) guidelines for designing multi-resource inventory systems have been drafted by Lund (1998). An important aspect outlined by Lund

(1998) deals with taking advantage of modern technologies such as GIS, georeferenced databases, electronic measurement and data recording. Forest managers and researchers may not be able to interact very often on one-to-one basis, but today there are templates and knowledge-based systems in which managerial users of researchers' knowledge can be clearly explained step-by-step on how to proceed, in ways suited to individual circumstances (Whyte, 1999).

In Malaysia, at the compartment level, which typically equates to between 300 ha and 1000 ha, field operations are planned, implemented and recorded for harvesting, rehabilitation, silviculture, and resource accounting to note changes in growing stock and quality of timber stand. The records are analyzed at the end of each planning period and changes are made for the next planning cycle. For concessions within PRFs, the following plans and activities are generic steps that have to be followed:

1. Pre-harvesting planning
2. Harvesting planning and operation
3. Landing point / *batau* / log pond
4. Stumping point / checking station
5. Mill

The concessions have to prepare a forest management plan. This is followed by a harvesting plan, a fire management plan where applicable, an annual work plan, tree markings, and so on. Tree markings are categorized for felling and for protection. Each is checked by the FDs to ensure that the documentation and markings are correctly carried out. Harvesting is usually supervised by a forest ranger. In Sabah and Peninsular Malaysia, tags are attached to each log felled, as well as to the stump. Hence, it should be possible to detect any infractions or deviation from the license conditions, plans and laws, at some stage of the operation, or after the fact, and to impose the appropriate fines. The inadequate number and quality of staff and their deployment, as well as similar limitations in terms of equipment, can give rise to reduced performance in field and supervisory capacity. Some of these constraints are addressed through efficient and regular reporting, especially in several important areas, notably infrastructure (including roads condition) form, environment (including erosion), and monthly harvesting reports, which could give early warning if there is a degree of over-harvesting or illegal harvesting (International Tropical Timber Organization, 2004a).

Cost and reliability are important considerations when designing an inventory. Forest inventories can involve large areas and a 100 % inventory is often not possible and for most purposes is unnecessary unless for a specific research requirement. Complete inventories are expensive, tedious and as a result, non-sampling errors such as incorrect recording of tree diameters, heights and quality tend to increase. For this reason, sampling has been introduced, which if properly done, provides reasonable estimates of the true population. It is crucial to select a sampling method or combination of sampling methods that allows for the most efficient collection of data.

In Peninsular Malaysia, information based on preliminary investigations and observations indicate that most residual forest stands have not regenerated according to assumptions and will not be ready for commercial harvesting on a sustainable basis at the end of the cutting cycle as expected. The effects of poor harvesting practices and illegal logging on forest conditions remain unclear. Due to the large extent, high variability and inaccessibility of many natural forests in the region, conventional forest inventories are extremely costly. Alternative assessment tools are needed, which allow for the rapid appraisal of stand conditions. This thesis provides an account of a methodology that can be used for assessing logged-over forests rapidly at the broad management level. For operational level inventories, the design and intensity of sampling will be different (Samsudin et al., 2003).

The rapid expansion and development of Malaysia's forestry sector over the last few decades has led to a rapid increase in forestry activities and tremendous growth in data collection. For instance, in addition to existing statutory and routine requirements, forest management practices now have to be evaluated against prescribed sustainable forest management criteria. The manpower allocated to data collection is therefore increasingly over stretched in keeping up with the volume of work and this has affected the timeliness, accuracy and quality of statistics. Computer use in information management, GIS and remote sensing applications in Malaysia has developed rapidly since the 1970s. In the case of Peninsular Malaysia, efforts prior to 1996 to computerize data processing met with limited success. There was no single integrated system, but a number of systems and applications operating in isolation. Their use was complex and their relationships poorly structured or non-existent. Different systems frequently required identical information and the same data were often entered several times, resulting in inconsistencies and inefficient use of scarce staff time. Therefore, development of a unified GIS-based timber harvesting plan is suggested in this thesis so as to manage the forest more sustainably and efficiently.

1.4 Research Aims and Objectives

In SMS, the collection of pre-F inventory data is mandatory before any harvesting can be carried out. These data are then used to prepare the timber harvesting plan, which assists the forest managers in making decisions on the volume of timber to be extracted from a particular forest area. The determination of the net production area and the optimization of the forest road network also need to be based on the inventory data. However, harvesting effects on the environment such as soil erosion must also be considered. At present, these procedures are carried out manually. The aim of this study, therefore, is to develop a GIS-based tool for timber harvesting system using tropical forest inventory information and to analyze spatially the results with the available ground data after the harvesting has been carried out on the field. With the development of a GIS-based timber harvesting system, the expectation is that a more sustainable, reduced-disturbance harvesting system can be produced. This aim can be achieved through the following sequence of steps:

- Determine the net production area in a forest concession
- Select suitable trees to be harvested
- Anticipate the soil loss before harvesting
- Predict the soil loss flow direction
- Optimise the forest road network in the net production area

More specifically, this thesis examines the drawbacks, problems and inefficiencies in the forest management method and harvesting system in Malaysia (Chapter 2). Chapter 3 describes the study area and the data sets used, along with information on the data collection, data formats, software and methods employed in the research. The preparation of timber harvesting plan and the selection of the trees to be harvested is covered in Chapter 4. Chapter 5 discusses the prediction of soil erosion and its flow direction before harvesting in the study area. The road alignment options required to transport the timber out of the forest are discussed in Chapter 6. Validation and comparison of results from this study and the ground data is analyzed in Chapter 7. Discussions, final conclusions, recommendations and future work can be found in Chapter 8.

Chapter 2

GIS and Forest Management

Overview Some background information and literature related to the study are presented in this chapter. The main emphasis of the review is placed on the application of GIS technologies to forestry. Since the practical component of this study comprises three main research components (i.e. the determination of the net production area and identification of the harvestable trees; the prediction of soil erosion and its flow direction; and the optimization of forest road network), the research literature in each of these domains is also discussed. In addition, the research design is also presented.

2.1 Introduction

This chapter reviews previous studies that have applied GIS technologies to forest management, including those conducted in Malaysia, especially the application of GIS technologies to timber harvesting planning. It also discussed any weaknesses in the approached previously adopted. Since timber harvesting plans comprise several different component parts, and bearing in mind the time constraints imposed on this study, three of the most important component elements are examined in detail here, namely,

- the determination of the NPA and selection of tree to be harvest based on the SMS requirements,
- the prediction of soil loss and the soil loss flow direction, and
- the optimum alignment of the forest road network to transport out the harvested timber.

The principal aim of this review is to establish the need to develop a more effective timber harvesting plan using pre-F forest inventory data, based on GIS technologies. In carrying out the review, the application of GIS in other domains in Malaysia is also considered, as well as its integration with related spatial data technologies, such as remote sensing (earth observation), GPS and numerical (simulation) modeling. The problems of applying these techniques to forestry and their potential for minimizing the inefficiencies involved in the implementation of Malaysia's timber harvesting plan are also discussed.

2.2 Application of GIS technologies to forestry

Research into the application of GIS technologies to forestry has been considered in various application domains around the world. For instance, a GIS-based assessment was carried out by Zhang et al. (2006) to examine the vulnerability of the Congo Basin's forests, taking into consideration population growth, road density, logging concession and forest fragmentation. The assessment indicated that the forests will continue to shrink towards the interior over the next 50 years. The study also showed that integrated GIS assessment of tropical deforestation can be used to predict the future distribution of forests and provide a tool to address the broader implications of social and economic development for tropical deforestation. In north-west Spain, to understand the Galicia region's forestry dynamics and to predict its future tendencies, Marey Perez et al. (2006) developed a Forest Geographic Information System, called 'SIFGa'. SIFGa was used to examine the necessary variables describing the environment, population tendencies, land tenure and forest management, at both council and parish levels in a single database.

GIS is also being increasingly used as a tool to improve efficiencies in planning, development and management in Malaysia. Several GIS-based studies had been carried out since 1990 (Yaakup et al., 1990), not only in the conventional areas such as mapping (Baban and Yusof, 2001a), assessment (Adeel and Pomeroy, 2002), change detection (Jusoff and Senthavy, 2003; Jusoff and Setiawan, 2003; Hanson et al., 2004), management (Adeel and Pomeroy, 2002; Ali et al., 2003) and monitoring (Rowshon et al., 2003), but also in other fields of application, such as urban area monitoring (Yaakup et al., 1990; Ahris et al., 2003; Yaakup et al., 2003; Narimah, 2006), environmental assessment (Chan, 1998), engineering studies (She et al., 1999), construction projects (Li et al., 2005), agricultural studies (Rowshon et al., 2003), and in forestry (Ditzer et al., 2000; Jusoff and Senthavy, 2003; Jusoff and Setiawan, 2003; Safiah Yusmah et al., 2003; Phua and Minowa, 2005). The environmental studies include one focusing on soil erosion (Baban and Yusof, 2001b), landslides (Sharifah et al., 2004; Lee, 2005; Lee and Talib, 2005), biomass changes (Brown et al., 1994), Environmental Impact Assessment (EIA) (Sayed Jamaludin, 2002) and health (Sharma, 1997). Some of these studies had been integrated with other geospatial technologies, such as remote sensing (Baban and Yusof, 2001a; Jusoff and Setiawan, 2003; Samsudin et al., 2003; Lee, 2005; Safiah Yusmah et al., 2003), GPS (Li et al., 2005) and environmental modeling (Brooks et al., 1993; Ditzer et al., 2000; Baban and Yusof, 2001b; Huth et al., 2005; Lee, 2005; Phua and Minowa, 2005). In forestry, the scope of research carried out is quite diverse. There are studies on rehabilitation (Safiah Yusmah et al., 2003), mangrove ecosystems (Adeel and Pomeroy, 2002; Sulong et al., 2002) and forest fires (Iwan et al., 2004). The most frequently studied field in forestry research centres on the impacts of harvesting; for example, on saturated hydraulic conductivity (Ziegler et al., 2006; Gomi et al., 2006; Huth et al., 2005), forest structure (Ho et al., 2004), genetic diversity (Chan, 2002a), sediment and wood accumulation (Gomi et al., 2006), erosion and surface roughness (Clarke and Walsh, 2006) and soil hydrology (Malmer and Grip, 1990; Brooks and Spencer, 1997). In the simplest GIS research in forestry applications in Malaysia, the studies carried out deal with the detection of land use changes, the effect of deforestation, and conservation purposes (Naoki et al., 2001; Jusoff and Senthavy, 2003; Phua and Minowa, 2005).

However, recently GIS-based forestry research has been broadened through integration with more advanced models and forms of analysis. For instance, Ditzer et al. (2000) used a stand growth model, FORMIX 3-Q, in a GIS environment to simulate tropical rainforest growth at the FMU level in the Deramakot Forest Reserve (DFR), Sabah, Malaysia. The harvesting scenarios were simulated for stands on different sites and the effects on forest structure and the implications for sustainable forest management were analyzed. Different stand types were determined based on a classification of site quality (three classes), slopes (four classes), and present forest structure (four strata). The effects of site quality on tree allometry (height-diameter curve, biomass allometry, leaf area) and growth (increment size) are incorporated into FORMIX 3-Q. Allometric relations and growth factors for different site conditions were derived from the field data. Climax forest structure at the stand level was shown to depend strongly on site conditions. Simulated successional pattern and climax structure were compared with field observations. Based on the existing management plan for the DFR, harvesting scenarios were simulated for stands on different sites. The effects of harvesting guidelines on forest structure and the implications for sustainable forest management at Deramakot were analyzed. Based on the stand types and GIS analysis, undisturbed regeneration of the logged-over forest was also simulated in the DFR at the FMU level. The simulations predicted slow recovery rates, and regeneration times far exceeding 100 years. Similarly, Huth et al. (2005) used another rainforest growth model, FORMIND, and Multi Criteria Decision Making (MCDM) analysis to evaluate tree-harvesting scenarios (minimum cutting diameter, logging cycle, method and intensity) and to identify the optimum ones by applying a stochastic extension of the PROMETHEE method in a dipterocarp lowland rainforest stand in Sabah, Malaysia. PROMETHEE is a ranking method which is simple in conception and application compared to other methods for Multi Criteria Analysis (MCA) (Brans and Vincke, 1985). The simulation results include harvest yields and the impact on forest structure (canopy opening and changes in species composition). Almost all optimum scenarios used reduced-impact logging. High cutting limits or low logging intensities could not compensate for the high damage caused by conventional logging techniques. Five scenarios proved to be optimum for a wide range of priorities concerning different forest functions. They all use reduced-impact logging and long logging cycles (60 years), either with a minimum cutting limit of 50 or 60 cm stem diameter, or with medium logging intensities. Although these two studies by Ditzer et al. (2000) and Huth et al. (2005) relate to SFM by using harvesting scenarios and GIS, they are different from this study because they used forest growth model to assess the impacts of forest harvesting. In other words, they concluded that the recovery rates of the logged-over forest is slow and the regeneration times exceeds 100 years. Among the implications of their studies is the existing cutting cycle should be prolonged to ensure that the forest is sustained. However, practically and economically, the prolonged cutting cycle up to 100 years is impossible. Whereas this study aims to implement SFM by ensuring the harvesting is being carried out efficiently and sustainably. This could be done by applying GIS in the preparation of a timber harvesting plan. As the timber harvesting plan is usually carried out for a specific area of forest, the results are precise and implementable.

Another GIS-based MCDM was carried out for forest conservation planning at the landscape scale to enable decision-makers to evaluate the relative priorities of conserving forest areas based on a set of preferences, criteria and indicators for the area; this study was carried out by Phua and Minowa (2005). Their study reveals that riparian vegetation is an important aspect to forest conservation and the legislation to protect riparian zones should be strengthened. Similar methods are also used by Iwan et al. (2004) to identify and map peat-swamp-forest fire hazard in Pahang, Malaysia. Peat-swamp-forest fire has becoming a major threat recently, especially during the dry season; therefore, this model and map provide valuable information about the areas most likely to be affected by fire. It is also a useful tool in forest fire prevention and management in order to minimize wildfire hazard. In developing a methodology to model disaster risk for flood risk management and for peat-swamp-forest fires, Shattri et al. (2004) integrated high spatial resolution remote sensing data within a GIS using multi-criteria analysis to assist in providing decision-support systems for emergency operations and for disaster prevention.

Several research studies have been carried out on pre-F inventories, such as those by Potts et al. (2005) and Samsudin et al. (2003), although neither of these applied GIS techniques or were GIS-based studies. By contrast, Hill-Rowley et al. (1996) used a grid-based GIS in the inventory of trees to examine ecological relationships among species of flora and fauna within the Pasoh 50 ha research plot in Negeri Sembilan, Malaysia. This study focused on ecological matters, however, rather than operational harvesting. Similarly, Nezry et al. (2000) applied GIS techniques, together with forest structure models and advanced remote sensing techniques (e.g. SAR and optical), to estimate standing timber volume in Sarawak, East Malaysia, although the use of the analytical capabilities of the GIS in this study is minimal. A more closely related study was suggested by Khali Aziz (2001), who used remote sensing, GIS and GPS in the management and at an operational level to implement precision-forestry practices to achieve ecologically and environmentally sound forest management objectives. The study suggested that a forest resources database should be developed in a GIS format at the highest management level, in which spatial information is continuously updated with the assistance of remote sensing input and where these data are employed at the operational level.

It is evident from these studies that a detailed analysis of the timber harvesting plans using GIS has not yet been conducted in Malaysia. There is, therefore, an urgent need for such a study, which is also vital and timely because the implementation of SFM requires precise planning and rapid decision-making by forest managers. As the GIS-based timber harvesting plan study implemented in this thesis consists of three major components, the review of literature is further divided into three parts, which will be discussed in sections 2.2.1, 2.2.2 and 2.2.3, below.

2.2.1 Net Production Area (NPA) and tree harvesting

Operational level of forest management planning involves the determination of the forest harvesting area, or the NPA, and forest operations activities, which includes both tree harvesting and access road construction. Determination of the NPA based on SFM requirements has been implemented for some time in Peninsular Malaysia. For instance, Thang (1987) reported the evolution of a forest management system and the implementation of SFM in the late 1970s. Methods to improve the techniques used to quantify the forest resource and its management have been discussed and advocated ever since (Sist et al., 2003).

In MUS, the minimum diameter cutting limits applied in mixed dipterocarp forests of the Malaysia region has led to high felling intensities. Such extraction rates create substantial stand damage (as much as 50 % of the remaining tree population can be affected), which has a negative impact on the regeneration and growth of many harvested dipterocarp species. As such, the minimum diameter cutting limit approach is not compatible with SFM. However, the selective logging approach applied in SMS is based on the criteria that different minimum diameter cutting limits can and should be applied to different tree species; where the basic ecological characteristics of the commercial species are considered in timber harvesting prescriptions, mixed dipterocarp forests appear to capable of producing sustained timber yields, that are compatible with habitat conservation, as well as providing a range of other goods and services. Sist et al. (2003), for example, presents the main silvicultural systems developed in mixed dipterocarp forests of Western Malaysia and then reviews current knowledge of dipterocarp biology to develop guidelines aimed at improving the ecological sustainability of production forests in Western Malaysia.

Chappell et al. (2006) applied what they refer to as Data Based Mechanistic (DBM) modeling to land-use change scenarios in a rainforest catchment in Malaysia. They suggest that the majority of the stream behaviour over a 7-year period after selective logging, is sensitive to the skid-trail densities associated with RIL and clear-fell systems largely because of the relative insignificance of the overland flow pathway and the fact that changes in this pathway are predicted to occur on the rising stage of stream hydrographs, rather than at the more critical peak. The study also supports the idea that most of the soil protection should be located in the stream-side areas in the form of buffer zones. Stream buffer zones, or riparian reserves, appear to minimize the impacts of logging on streams, even though Gomi et al. (2006) discovered that more sediment was found in a tributary channel with a 20 m buffer than in an unlogged channel because some of the nearby roads and skid trails were connected to the stream. The study examined the effects of logging and riparian buffers on sediment and wood accumulations in the Bukit Tarek Experimental watershed, Peninsular Malaysia. On the designation of the buffer or protection zones, Chappell et al. (2006) first identified the location of returning sub-surface waters using measurements of the topsoil moisture content and the first-order stream-head location, then evaluated a topographically based index to predict the location of both the channel heads and the wet soils. Their study recommended that more research be conducted into return-flow to, among other things, provide a hydrological basis for the objective definition of a riparian forestry buffer.

Apart from adequate buffer zones that should be reserved beside permanent watercourses (rivers), some of the standard of performance indicators in the MC&I include the prevention of logging activities in areas with slopes greater than 40° for soil and water protection purposes. An example of this practice is demonstrated by Khali Aziz (2001) at Temenggor Forest Reserve (FR), Perak, Malaysia, using GIS techniques, where 31 % of the total area falls within the river buffer zone and 2 % is categorized as very steep terrain (i.e. greater than 40° of slope). Altogether, therefore, a total of 33 % of the forest areas in the study zone need to be reserved for protection purposes. The study by Khali Aziz (2001) also showed that GIS techniques are capable of identifying and mapping the extent of the affected area, information on which is needed by forest managers involved in forest harvesting planning.

2.2.2 Soil erosion and flow direction

Soil erosion research in humid tropical rain-forests has been carried out for several decades in Malaysia, especially in relation to the role of the rain-forest hydrology and the related processes of soil erosion (Douglas, 1969). Various methods have been applied, ranging from traditional field experiments to a more advanced techniques and models. For example, Brooks et al. (1993) modeled slope processes and soil erosion in Sabah, East Malaysia and went on to explore the full range of hydrological properties and considered in detail some of the consequences of changing hydrological behaviour for an area in Sabah, East Malaysia, which was undergoing extensive logging (Brooks and Spencer, 1997). A comprehensive study of steep slopes on the east coast of Peninsular Malaysia, where the rainfall pattern is monsoonal, was conducted by Ghulam et al. (1995) who measured the rates of rainfall, runoff, and soil loss from four large forested plots ($1000\,m^2$) and a smaller ($20\,m^2$) bare plot using various instruments, computer hardware and software for data processing and analysis. Because of the gradient of the land (about 10°) and the existence of large well-defined flow pathways, high chemical enrichment ratios were noted, which has important implications on the reduction of soil quality through nutrient and organic matter losses.

In Danum Valley, Sabah, Malaysia, hydrological investigations conducted over a period of ten years were analyzed by Douglas et al. (1999) to examine the long-term role of extreme events in the erosion of primary and selectively logged catchments. They also examined the pattern of hydrological recovery following selective logging over a period of eight years in catchments of differing size. To investigate the recovery process from first selective harvesting, Chappell et al. (2004b) monitored surface discharge and turbidity from 15 contributory areas of a 44 ha catchment and found that although some sediment sources recover from the impacts of forest road construction and harvesting, the collapse of road-fill materials and local log-culvert failure persists for several years after harvesting. They also suggest that sustainable forestry guidelines that do not focus on improving these regular instabilities may not significantly mitigate the geomorphological impacts of conventional, selective harvesting.

In relation to the application of GIS and remote sensing technologies to studies of soil erosion in Malaysia, Sharifah et al. (2004) have used these approaches to create thematic maps to assess and estimate landslide hazards in the Pos Slim-Cameron Highlands, Peninsular Malaysia. They generated a DEM, which was used to produce a slope risk map, an aspect risk map and a height risk map from which a simple algorithm was created to classify the area into different soil erosion risk zones. A final hazard map was produced by overlaying each of the hazard maps. Ruslan (2004), on the other hand, compares the effects of slope information derived from three different pieces of GIS software on the sediment yield estimated using the Agricultural Non-Point Source pollution (AGNPS) model, developed by Young et al. (1987), in a small watershed at Penang Hill, Malaysia. The three GIS software packages considered are IDRISI^{TM} for Windows^{TM}, ERDAS Imagine^{TM} and ArcView^{TM}. Rather worryingly, the results of the study clearly demonstrated that the different software produced different slope information and maximum slope occurrence, which impacted on the estimates of sediment yield. Therefore, in order for results to be comparable and for their extrapolation from one region to another, it is important that methodologies be standardized (Lal, 1994).

2.2.2.1 Modeling soil erosion

Over the years, there has been considerable research and development into the most appropriate erosion models for the prediction of soil loss and sediment delivery. Such models vary in scope and application from relatively simple empirical models, which are based primarily on observation and statistical relationships, to physically-based models, also known as distributed parameter models. The latter group of models are intended to represent the essential mechanisms controlling soil erosion, including the complex interactions that exist between the various controlling factors, and their spatial and temporal variability. Overall, the value of erosion models lies in their use as predictive tools for assessing soil loss for conservation planning and increasingly for setting guidelines and standards for regulation purposes (Croke and Nethery, 2006). However, their application needs some necessary precautions and reliable input data. Moreover, their applications have to be subjected to pre-evaluation and necessary calibrations, if they are applied in areas different from places where the equations were originally developed. In other words, the USLE and its versions are useful for the description of soil erosion and sediment yield at different scales and land uses, but even with perfect knowledge of erosion-determining factors, a considerable amount of variation and a directed error have to be expected. At larger scales, the accuracy of input data decreases rapidly. In addition, erosion-determining processes change with scale and easy-to-use models such as the USLE and its versions are not able to easily cope with this (Sadeghi et al., 2007).

Since the establishment of the USLE in 1970s, it has been by far the most frequently used and globally applied technique to predict soil erosion (Jurgens and Fander, 1993; Morgan et al., 1997; Montoro et al., 1988; Safiah Yusmah, 1998). The USLE was pioneered by Wischmeier and Smith (1978) and was developed specifically to calculate soil erosion rates in agricultural areas as a function of rainfall, topography, management and cover factors. It has since been modified to suit different environments and applications. The USLE was one of the three erosion models used by Croke and Nethery (2006) in the application of models of varying complexity and design to predict runoff and soil erosion from logged forest compartments in south-eastern Australia. The other models employed by Croke and Nethery (2006) are the Water Erosion Prediction Project (WEPP), and TOPOG, a physically based hydrologic modeling package. The models were evaluated in terms of general ease of use, input data requirements and accuracy of process understanding and prediction. The results suggest that the USLE overestimated soil loss, and has the limitation that it does not predict sediment yield or sediment redistribution for specific storm events. When used at the hillslope scale, WEPP and TOPOG have predicted runoff and soil loss reasonably well, particularly on disturbed surfaces such as skid trails. On less disturbed surfaces such as the general harvesting area, both models performed less accurately, generally under-predicting soil loss and sediment yield, notably on sites with low observed values. The complexity and data requirements of WEPP and TOPOG limit their usability as a general-purpose, erosion hazard predicting tool. The USLE has been the tool of choice for erosion prediction and conservation planning, but is being replaced by a more accurate and flexible Revised Universal Soil Loss Equation (RUSLE) in 1985 with a number of changes (Renard et al., 1991). These include: revisions to the R factor values; the development of a seasonally variable K factor; modifications to the LS factor to take account of the susceptibility of soils to rill erosion; and a new procedure for computing the C factor value through the multiplication of various sub-factor values (Morgan, 2005). This technology is available as RUSLE 1.04 software from the Soil and Water Conservation Society. RUSLE 1.04 has weakness, primarily related to its USLE-like structure. A new version (RUSLE 2) corrects these and provides a friendlier state-of-the-art interface. This allows better erosion science, permits faster calculations, and lets users with different languages and measurement units share hillslope descriptions (Yoder and Lown, 1995). In terms of process understanding, none of the existing models accurately depict the nature and extent of sediment redistribution quantified in the rainfall simulator experiments. In order to advance the application and accuracy of modeling tools in forestry environments, this redistribution process should be considered integral to the refinement and redevelopment of future models. Although there are many models developed, the USLE continues to be applied in different environment and under different land use and activities because of its simplicity and the availability of a well documented parameter set which has allowed it to be used in environments where input parameters are not readily available. The major limitation of the model is that it does not predict deposition or sediment yields from gully and channel erosion. Likewise, it was not developed, and is not accurate for, single storm analysis, and provides no time distribution sediment yield or particle size analysis. Until recently, the most widely used model for erosion and sediment deposition simulation was the USLE and the revised USLE (RUSLE). However, there are various other models and techniques carried out on estimation or prediction of soil loss globally or locally. Among the techniques used were the Unit Stream Power Erosion and Deposition (USPED) model which was used to predict where erosion and associated deposition was likely to occur in a watershed (Mitasova et al., 1998), the Non-point Source Pollution (NSP) simulation model which is basically a simplification of surface water and subsurface water balance that include rainfall-runoff transformation processes and water quality measurements using defined mathematical equations (Novotny and Chesters, 1981). Other process-based models which have been applied in the past for rainfall-erosion modeling are Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Moehansyah et al., 2004), Water Erosion Prediction Project (WEPP) (Croke and Nethery, 2006), Agricultural Non-Point Source (AGNPS) (Ruslan, 2004), Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS), etc. The USLE has also been extensively used in Malaysia, coupled with other technologies and methods to predict soil erosion. For example, integration of satellite remote sensing and GIS technologies with USLE parameters is employed by Roslinah and Norizan (1997) to predict annual soil loss in the catchment area of the Bakun Dam. The analysis was done in MICSIS^{TM} (Micro Computer Spatial Information System), an image processing and GIS software package developed specifically for erosion modeling. The current and potential erosion risk maps of the study area generated by Roslinah and Norizan (1997), were useful for planning the land clearing activities at Bakun and for estimating the severity of soil sedimentation in the dam area. Their study also used a three-dimensional animation package to model the extent of water inundation and the volume of water storage at three flood levels. Roslan et al. (1997) used a colour infrared interpretation key coupled with Landsat Thematic Mapper (TM) to determine the combined land-use management factor, *CP*, required by the USLE. Their study was carried out in the Cameron Highlands, Perak, Malaysia, where much of the forest has been converted to agricultural farms. However, the high cost of satellite images and software package in their studies make it impossible to be applied at the operational level as needed in the timber harvesting plan.

Safiah Yusmah (1998) compared the USLE, MSLE and field experiment methods to measure or predict soil loss from a forest catchment which was converted to a hill recreational area, based on different vegetative covers and slope angles. The study found that due to the way in which the values of the driving parameters, *K*, *C* and *P*, were estimated, both the USLE and MSLE overestimated the soil loss. The study, therefore, concluded that the field experimental method is the most representative method to measure soil loss. Based on the results from study carried out by Safiah Yusmah (1998), this study measured the *K* parameter using both primary data and the soil erodibility nomograph, and substituted *CP* parameters measurement with a more detailed and precise *VM* parameter estimation. This method would generate accurate and more representative results as the *VM* factor is determined in detailed by analyzing the forest through its canopy cover, mulch or ground vegetation cover and bare ground with fine roots unlike the *CP* factor in USLE which are determined by selecting the crop type and tillage method and supporting cropland practices respectively. Similarly, Baban and Yusof (2001a) produced soil-erosion probability maps under various scenarios, accounting for uncertainties in the data and in the decision rule, using the USLE, remote sensing and GIS in Langkawi Island, Kedah, Malaysia. To achieve its objectives, the Bayesian Probability Theory within IDRISI, a raster based GIS was applied. The outcomes were two continuous probability soil erosion maps: the first map, which ranges from 0 to 1 expressed the likelihood that an area would be subjected to soil erosion if the assumption were made that it would not, therefore representing a decision risk, and the second map indicates areas that have high to moderate probability of soil erosion which are concentrated mainly in the highlands (in the central, eastern, and northern regions of the island), whereas areas having a low probability of soil erosion are located in the lowland areas of the western and northern region. Assuming a 10 % risk, this impact has increased by 11.98, 11.83 and 5.741 % for high, medium and low soil erosion risk areas on the Langkawi iIsland respectively. Although the study by Baban and Yusof (2001a) used GIS in evaluating soil erosion, the software used and the landuse type of the study area is different from what is used in this study. An effort to map the mean annual erosivity for Peninsular Malaysia was carried out by Morgan (1974), based on relationship with mean annual rainfall and the result is shown in Figure 2.1. However, he stressed that extrapolating such relationships beyond the data base from which they have been derived in order to apply them elsewhere is dangerous and also the results of different researchers are not always comparable because of assumptions made when calculating the *R* value.

Despite its limitation, however, a modification of USLE has been chosen to be used in this study because Baharuddin et al. (1999) modified the *CP* factor to *VM* factor to suit the tropical forest environment (refer Subsection 5.2.4) and tested it in the Malaysian forest. This modified version is known as Modified Soil Loss Equation (MSLE). In Malaysia, where heavy and high intensity rainfall is one of the main climatic characteristics, soil erosion can be found even under undisturbed natural forests. Soil erosion is, however, further accelerated once the forest is logged, especially along logging roads and in log-landing areas. The MSLE is used to measure the soil loss in the study area for several reasons: (i) it is considered to be more appropriate to forest conditions, such as those in

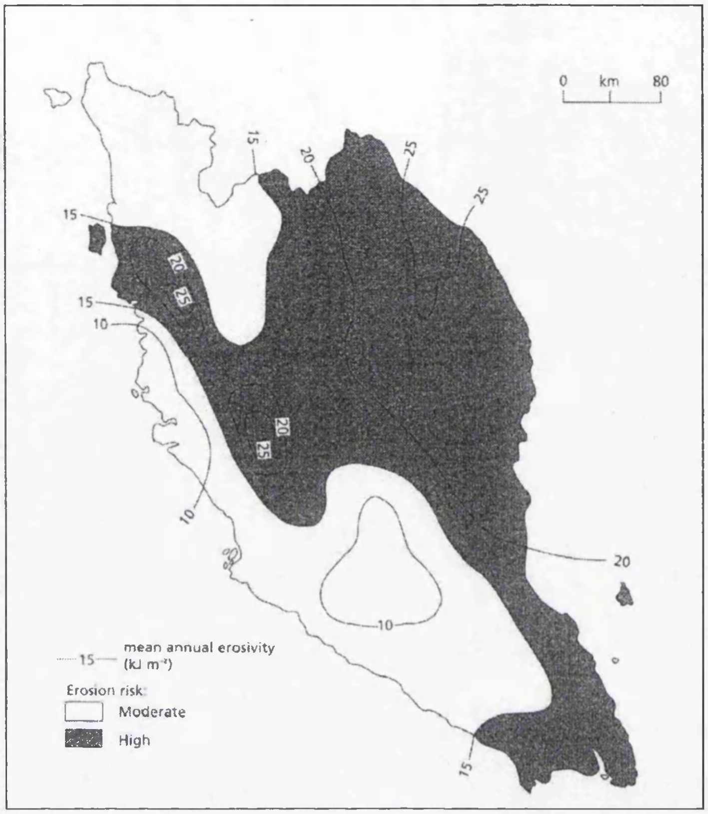


Figure 2.1: Mean annual erosivity (EV) in Peninsular Malaysia estimated from mean annual precipitation (P;mm) using the relationship $EV = 9.28P - 8838.15$ (Source: Morgan (1974)).

the study area; (ii) it has been applied in estimating soil loss at the Bukit Tarik Experimental Watershed, an area which is also under forest, in Peninsula Malaysia (Baharuddin et al., 1999); (iii) it is a simple and quick method, based on a straightforward empirical approach, which can be implemented with relative ease in ArcMap for spatial extrapolation across the study area.

The USLE was pioneered by Wischmeier and Smith (1978) and is designed to predict soil loss owing to sheet and rill erosion. It is probably the most widely used empirical model of soil erosion and has since been modified to suit different environments and applications. In the USLE, the parameters affecting soil erosion are grouped into six factors, which describe the erosive forces of rainfall, the soil erodibility, the length and steepness of the terrain slope, specific farm practices, and land management. The USLE can be used to predict the average annual soil movement. Since the prediction is meant for agricultural purposes, the USLE can be applied as a guide to select suitable conservation practices, to estimate the comparative utility of cropping systems, to determine optimum levels of cropping and maximum tolerable slopes, and to provide soil loss data for erosion mitigation needs. Wischmeier (1976) advised researchers to consider the factors that might cause the differences between average and local field conditions, as well as normal field operations. The formula for computing the soil loss in the USLE is as follows:

$$A = R \times K \times L \times S \times C \times P \tag{2.1}$$

where, A is the soil loss (metric ton$\cdot$ha$^{-1}\cdot$yr^{-1}), R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the soil cover management factor and P is the soil conservation practice factor.

By the 1970s, the USLE was broadened to enable its application to other areas, such as rangelands, constructions, recreational land,, highways and minelands. To maximize its application in forests, however, some modifications have been made to the factors to suit the complex forest environmental conditions. The soil cover management factor, C, and the soil conservation practice factor, P, in the USLE are replaced by a vegetation management factor, VM, in the modified model, which is known as the Modified Soil Loss Equation (MSLE) (Warrington et al., 1980). The vegetation management factor, VM, is evaluated based on three sub-factors, namely canopy cover, mulch or ground cover, and bare ground with fine roots. The calculation of the MSLE is as follows:

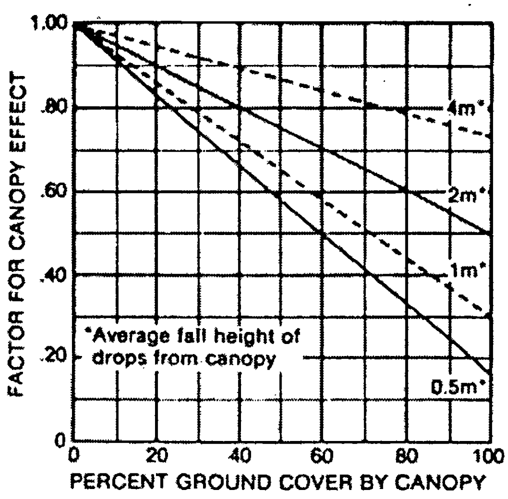
$$A = R \times K \times LS \times VM \tag{2.2}$$

where, A is the soil loss (metric ton$\cdot$ha$^{-1}\cdot$yr^{-1}), R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the slope length factor and VM is the vegetation management factor.

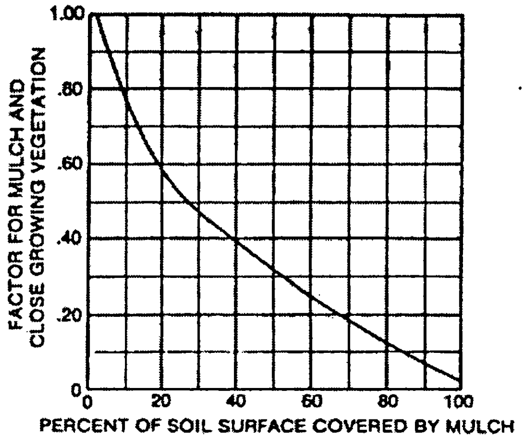
The MSLE, is considered to be the most appropriate model to be used in this study, base on the similarity of the study site to that studied by Baharuddin et al. (1999). In applying the USLE to the forest environment, Baharuddin et al. (1999) modified the cover management factor, C, and conservation practice factor, P, to produce a single vegetation management factor, VM, suitable for application in the tropical forests of Malaysia. The VM factor is a combination of vegetation cover and soil surface condition which results from three sub-factors, namely: canopy cover; mulch or ground vegetation cover which have direct contact with the soil surface; and bare ground with fine roots. Each sub-factor value can be obtained directly from Figure 2.2 while Figure 2.3 is a guide for estimating area covered by canopy, mulch and fine roots. Zero canopy cover or an open area is assigned a canopy sub-factor of 1. A forested area normally has fine roots uniformly distributed over 99-100 %.

2.2.2.2 Flow Direction

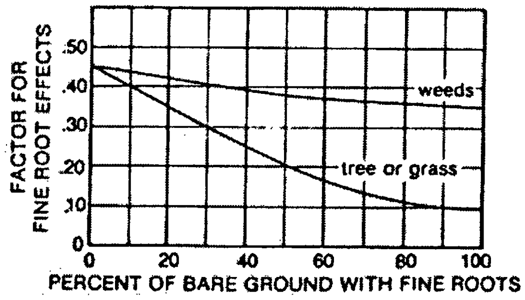
Digital Terrain Model (DTM)s and the integration of hydrological models within GIS have been widely studied. TOPography based hydrological MODEL (TOPMODEL), which was created almost thirty years ago, provides one of the few easy-to-use hydrological modeling structures that use DTM data and that has been used in a variety of applications. TOPMODEL is not, however, a single model structure that is of general applicability; rather it is a set of conceptual tools that can be used to simulate hydrological processes in a relatively simple way, particularly the dynamics of surface and sub-surface contributing areas. Many hydrological models have been developed using TOPMODEL formulations, which is based on the idea that topography is the primary determinant of the distribution of soil moisture at and within the land surface (Beven, 1997). In observations and simulations examining plant-water relations in a forested catchment characterized by strong topographic control over surface hydrology and stand structure, Engel et al. (2002) used two methods for modeling the flow of water within a catchment. The first was a



(a) Influence of vegetal canopy on effective EI.



(b) Effects of plant residues on close-growing stems at the soil structure on the VM factor.



(c) Effects on fine roots in topsoil on the VM factor. These values do not apply to cropland and construction sites.

Figure 2.2: Graph for determining VM sub-factor (Source: Wischmeier, 1975).

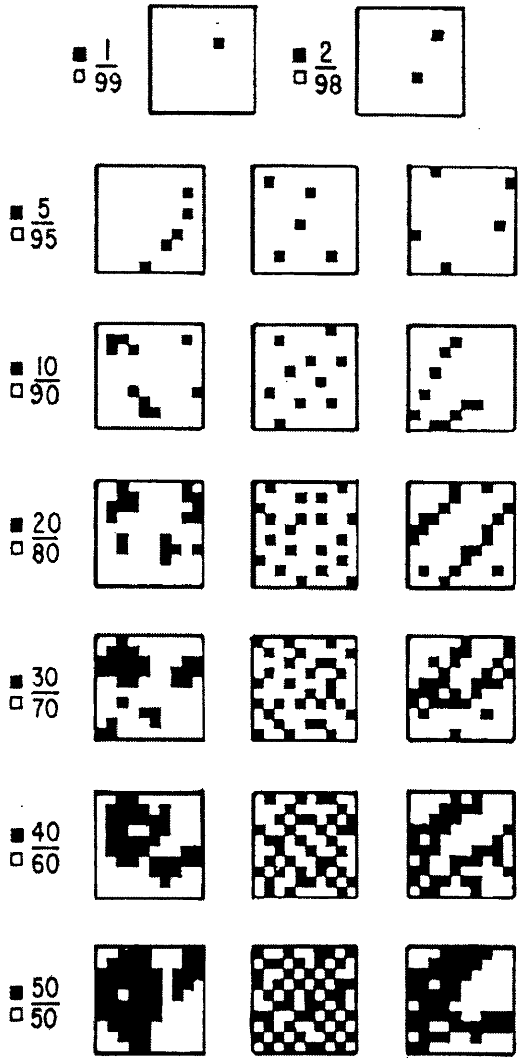


Figure 2.3: Guide for estimating density of bare soil, canopy and fine roots (Source: Dissmeyer and Foster, 1980).

soil column model that simulates the vertical movement of water and heat within the soil and between the soil surface and vegetation to the atmosphere. The second method partitioned the catchment surface into two distinct hydrologic zones, namely saturated lowlands and unsaturated uplands. Using statistical information on thetopography, the horizontal movement of groundwater was tracked from the uplands to the lowlands (a TOPMODEL approach). Combining these two approaches produced a three-dimensional picture of soil moisture distribution within a catchment. In determining the flow direction and measuring the soil gain and soil loss in this study, the concept of TOPMODEL where topography is the determinant factor is used.

Most distributed hydrological models aim better to represent the spatio-temporal variability of hydrological characteristics governing the rainfall-runoff response at the catchment scale (Beven and Kirkby, 1979; Beven, 2001; Hyung and Beven, 2007). For instance, Hyung and Beven (2007) present a new approach to multi-criteria model evaluation (MCME) to reduce prediction uncertainty in an application of TOPMODEL within the Generalised Likelihood Uncertainty Estimation (GLUE) framework. To test the proposed approach, the original version of TOPMODEL was been modified and applied to a small catchment in South Korea, where global performance measures suggest that the model fits observations of the local hydrology well.

Research carried out by Chappell et al. (2006) is more closely related to the operational level of this study. In tropical forests, rainfall infiltrates trees and the soil substrate and continues the flow before resurfacing in stream channels or at the edge of streams. As a result, the water accumulates and create wet zones by the stream which are exposed to disturbance and, hence, should be protected from forestry or agricultural activities.

Determining surface water flow directions over an interpolated terrain surface is a necessary requirement in almost all hydrological models. Water carries soil in its flow direction which gives an indication of the areas where the soil is eroded and deposited. This information is vital as it could assist forest managers in making decisions on areas to avoid when aligning and constructing roads or harvesting trees. Besides, riparian buffers could be assigned to protect the wet zones and their width could be determined accordingly.

Chappell et al. (2006) identified the location of returning subsurface waters using measurements of the topsoil moisture content and first-order stream-head location. They examined the ability of a topographically based index to predict the location of both channel heads and wet soils, and then evaluated this index to assess its utility for streamflow generation modeling and the designation of buffer or protection zones. The analysis of their study indicated that the Kirkby topographic index (λ spatial distribution) was suitable for this purpose, allowing the designation of buffer or protection zones to within two terrain pixels (each $20m \times 20m$) in the Baru catchment, Sabah, East Malaysia. Their study also verified that topography played a key role in the generation of perennial streams within this catchment, and showed that the λ spatial distribution may be useful in locating the perennial stream network on digital maps for objective 'hydrological buffer zoning'. In a further component of the same study, carried out in the Huai Pacha catchment, Northern Thailand, the authors also examined the spatial structure of 468 soil moisture content measurements by means of variogram analysis and then used this to interpolate between the observed data points. Their results show that the wet patches in the terrain coincide with areas of high topographic convergence and, more specifically, with values of the λ spatial distribution greater than $9\ln(\mathrm{m})$. The use of a threshold in the λ spatial distribution, rather than a fixed-width riparian buffer defined smaller protection zones with a higher proportion of the sensitive saturated or near-saturated soils. Consequently, the study concluded that the λ-based buffers would be more efficient, easier to justify scientifically, and allow access to more of the timber growing on less sensitive, drier soils. On the other hand, the application of a variable-width buffer zone is more difficult to convey to forest harvesters in field conditions and is arguably harder to enforce on a regional basis.

Surface flow directions are normally determined over an interpolated terrain surface, which is a necessary requirement in almost all hydrological and hydraulic models. In a raster environment, routing can be relatively simple and for each cell surface, water flow can be directed to the neighbouring cell with the steepest downslope drop. This method is commonly referred to as the Deterministic 8 or D8 method. Without modifications, however, this method is inadequate for routing flow over flat areas (flats) and through depressions (sinks). Numerous strategies to route flow through these areas have been developed and typically involve making modifications to the interpolated elevation values. Modification to elevation values can include filling of depressions, lowering of pour point elevations and imposing elevation gradients through flat areas. An alternative method to establish reasonable flow direction was described by Kenny et al. (2005), who made alterations to the flow direction grid, while leaving the interpolated elevation values largely unaltered. They developed two separate routines to utilize the known hydrological network features as boundary conditions when analyzing sinks and flats. Each sink and flat is analyzed in sequence and flow directions are resolved iteratively using both the surrounding terrain and the imposed hydrology. They found that the resultant flow direction surface provide reasonable flow directions through sinks and over flats in interpolated terrain surfaces, while retaining flow directions reflective of the morphological content within sinks.

2.2.3 Forest road alignment

Integration of GIS technologies and forest road design have been investigated in a number of studies globally, and several literatures are now available. However, there are limited studies on forest network that have been carried out in Malaysia. Studies such as optimization of forest road for timber harvesting in Malaysia as proposed in this study is, hence, timely and necessary. For instance, Yoshimura and Kanzaki (1998) developed an expert system to support decision-making for the layout of forest roads in mountainous areas in Japan based on a risk assessment. In particular, their study focused on decision-making based on the selection of passing points of forest roads using the fuzzy theory. Their study concluded that the advantage of their method is that the computer can make the decision on where to lay out forest roads automatically in a manner similar to how a human would act, but the automation of this process made it easier to plan forest roads in mountainous areas avoiding the danger that the areas considered might collapse.

A three-dimensional forest road alignment model, known as TRACER, was developed by Akay and Sessions (2005) to assist a forest road designers with the rapid evaluation of alternative road paths. The objective was to design a route with the lowest total cost considering factors such as construction, maintenance, and transportation costs, while conforming to design specifications, environmental requirements, and driver safety. The model integrated two optimization techniques: a linear programming for earthwork allocation and a heuristic approach for vertical alignment selection. The TRACER model enhanced user-efficiency through automated horizontal and vertical curve-fitting routines, cross-section generation, and cost routines for construction, maintenance and vehicle use. The average sediment delivered to a stream from the road section was estimated using the method of a GIS-based road erosion/delivery model, SEDMODL, which consider road erosion factors like geologic erosion rate, road surface type, traffic density, road width and length, average precipitation factor, distance between road and stream, cut slope cover density, and cut slope height. SEDMODL predicts reasonably the sediment delivery and defines the road segments with high sediment production. The study anticipated that the development of a design procedure incorporating modern graphics capability, computer hardware and software languages, modern optimization techniques, and environmental considerations can improve the design process for forest roads. The study by Akay and Sessions (2005) is excellent, however, they are more physically approached which is different from this study which is more managerial and operational.

In a separate study, Karlsson et al. (2006) described a decision support system, called

RoadOpt, which could be used to plan upgrades to forest roads using a GIS-based user-interface to present and analyse data and results. Road blocking due to thawing or heavy rains annually contributes to a considerable loss of profit in Swedish forestry. Companies have to build large stocks of sawlogs and pulplogs to secure a continuous supply during periods where the accessibility of the road network is uncertain. This storage leads to quality deterioration, which means loss in profit. One approach to reduce the losses due to blocked roads is to upgrade the road network to a standard that guarantees accessibility throughout the year. Two important modules used were the Swedish road database, which provides detailed information about the road network, and an optimization module consisting of a mixed integer linear programming model. A case study from a major Swedish company is presented. Although this study is a GIS-based user-interface decision support system, the study is meant for forest road upgrading which is a bit different from the objective of this study.

Forest catchments have long been recognized as a source of high quality water. Within forested areas the unsealed forest roads are the main sources of soil erosion and there is increasing concern about the impacts on water quality caused by forest road systems. This problem has been well documented in the literature over the last three decades. To predict, control and minimize soil erosion and water quality impacts, (Farabi, 2003) developed a risk-based approach using terrain attributes which also assists in the development of more effective management systems to maintain forest roads by assessing maintenance priorities for protection of water quality impacts. Among the lesson that can be learnt from the Farabi's study is the approach could be used to assist in the development of more effective management systems to maintain forest roads. This can be done by assessing the existing forest roads impacts on soil and water quality.

Sediment budget analysis require watershed scale evaluation of road erosion and delivery. The Watershed Erosion Prediction Project (WEPP) model, as developed by the USDA Forest Service, simulates sediment detachment and delivery for a road, fill, and buffer system. Time and budget constraints typically prevent a comprehensive sediment loading analysis using WEPP throughout a watershed. Hence, Brooks et al. (2006) presented an automated GPS/GIS-based approach to run the hill-slope version of the Watershed Erosion Prediction Project (WEPP) to simulate sediment detachment and delivery for a large road network. The approach can be applied to multiple road designs and climate regimes, with unique attributes for each road segment. Road attributes are acquired from GPS-assisted road surveys and mapped in a GIS. After data manipulation in GIS and Excel, the required input files for WEPP were built. Then, they applied the automated approach to the South Fork Clearwater River and concluded that the availability of analysis capabilities of the WEPP results from large road networks within GIS provides a spatially explicit tool for the management and evaluation of sediment production throughout large road networks. In this study, the sediment budget analysis are also considered because the soil gain and soil loss resulted from the soil flow direction will be examined.

The spatial pattern of land-cover change and forest fragmentation is known to affect biodiversity strongly. However, whilst many of the drivers of tropical deforestation are known, less is known about their spatial manifestation. Therefore, Arima et al. (2005) carried out a study to consider emergent patterns of road networks, the initial proximate cause of fragmentation in tropical forest, by addressing the road-building process of loggers who are active in the Amazon. In order to mimic the spatial decisions of road builders, they developed an explanation of road expansions, using a positive approach combining a theoretical model of economic behaviour with GIS software. Two types of road extensions commonly found in the Amazon basin were stimulated showing the fish bone pattern of fragmentation. They conclude that although the simulation results are only partially successful, the study brought to attention the role of multiple agents in the landscape, the importance of legal and institutional constraints on economic behaviour and the power of GIS as a powerful tool.

Many of the forest road studies carried out in Malaysia are related to physical effects of logging roads and skid trails on factors such as sediment discharge, infiltration rates and soil disturbance. Logging roads and skid trails in the tropics cause soil disturbance, compaction and decrease the infiltration capacity of soils (Malmer and Grip, 1990; Baharuddin et al., 1999; Pinard and Putz, 1996; Pinard et al., 2000). A satellite remote sensing survey conducted by Jusoff and DŚouza (1996) in a disturbed logged-over hill dipterocarp forest of Ulu Tembeling in northern Pahang, Malaysia to identify and quantify the site disturbance classes due to road construction and logging activities, showed that forest soil disturbance could be easily detected and monitored with 93 % accuracy. Six classes of soil disturbance were quantified and recognized, namely primary forest roads, secondary forest roads, skid roads, skid trails, secondary landings and primary landings. Similarly, Sidle et al. (2004) conducted study on recently constructed forest logging roads and skid trails in a small headwater catchment in Peninsular Malaysia. They found that sediment discharge from logging roads is more highly connected to the stream than discharge from skid trails. Douglas (2003) predicted road erosion rates which involved calculating rates of erosion per unit length and width of road, estimating the total road length within the catchment area, making allowances for road gradient and substrate, and calculating the potential sediment yield and comparing this with measured rates at Danum Valley, Sabah, Malaysia.

Very few studies have been carried out regarding the alignment or design of the forest road system in Malaysia. Ahmad et al. (2002), however, applied GPS and GIS to map the main logging road and road features at the Perak Integrated Timber Complex (PITC), in Perak State, in the northern part of Peninsular Malaysia. This study indicated the effectiveness of a one-time detailed mapping program to characterize the system and to identify the spatial relationships of the logging road system. A further study by Musa and Mohamed (2002) showed that GIS can be used for selecting suitable forest roads in the tropical hill forest. Their study was carried out in Ulu Muda FR, Kedah, Malaysia, using several different methods (i.e. field design, office design and best-path analysis design). Each method was compared statistically and qualitatively. Their results suggest that the best-path analysis design is the best solution for forest road network placement and provides sensitivity to rule base and input features.

The potential of DEM products to be used as a key information layer in a Forest Road Alignment Model was evaluated by Musa (2004). The study by Musa (2004) addresses the problem of accuracy assessment between DEMs produced from hypsographic data and from Radarsat Synthetic Aperture Radar (SAR) fine mode images and the implications of the differences between the two sources of terrain elevation data on the production of a road alignment map in Dungun, Trengganu, Malaysia. The study concludes that the Radarsat SAR DEM provides more accurate representation of the topographic landscape at the study site.

2.3 Research Design

Environmental problems are usually related to the way forest is managed locally. However, the results and impacts of poor management of the forest not only affect local communities, but also the global community. These conclusions are reflected in environmental problems such as global warming, sea level rise, the increasing incidence of hurricanes, tsunami, etc. In Malaysia, managing large tropical forest areas is very demanding and has becoming a great challenge to the forest managers. The procedures from acquiring data and information through inventory up to the determination of rehabilitation treatments for conservation purpose are tedious, time-consuming and labour-intensive. The forest data and information that are collected are usually kept in files which are not readily accessible. This hinders quick analysis and precise decision-making by forest managers in response to urgent environmental requests. Hence, the methods of forest management have to evolve in line with wider developments in IT, such that forest data and information can be stored, retrieved, analyzed and presented systematically, in order to ensure the sustainability of the forest. Use of computer hardware and software for this purpose should be maximized to increase the efficiencies of tropical forest management in Malaysia.

Thus, the purpose of this study is to use forest inventory data and information to develop a GIS-based plan for forest harvesting. This study is carried out in a forest compartment in Taiping, Perak, Peninsula Malaysia, to enhance and increase the efficiency of the tropical forest management therein. The plan is constructed based on the set of rules adopted from the SMS and analyzed using GIS software, specifically ArcGIS 9^{TM}. There are many harvesting-related activities that have to be considered before harvesting can take place, such as the tree growth and mortality, the effects of harvesting on the environment, the rehabilitation of the logged-over forests, the economic output per harvesting cycle and the conservation of specific trees. Nevertheless, not all of these elements can be incorporated practically and in detail in this study, hence in developing the system, three main research tasks have been chosen, namely (i) the determination of the net production area and the identification of harvestable trees, (ii) the prediction of soil loss and its flow direction, and (iii) the optimization of the road network used when harvesting.

The determination of the forest area where trees can be harvested, known as the Net Production Area (NPA), is important because it involves the delineation of protection and conservation areas, which consist of buffer zones around water bodies, on steep slopes, and in areas of high soil erosion risk area, as well as identified trees, such as seedlings, saplings, mother trees and medicinal trees. Prior to delineating the NPA, information on tree species, DBH, tree height, tree location and timber volume, as well as physical data such as boundaries, contours or slopes, rivers and roads must be collected. Once the NPA has been determined, it is possible to carry out soil erosion prediction to locate areas of high soil erosion risk, where harvesting will not be allowed.

The MSLE technique is chosen here to predict the potential for soil erosion in the study area. However, before the potential soil loss can be computed in ArcGIS^{TM}., the driving factors of the MSLE, such as rainfall (*R*), soil erodibility (*K*), length and steepness of slope (*LS*) and vegetation management (*VM*), have to be calculated. These factors can be derived from meteorological, topographical and land use data. Once these factors are stored in the ArcGIS^{TM}, the calculation of soil loss, A can be carried out. The net production area map and the soil loss risk map can then be integrated to show the areas that have to be conserved and the areas where trees can be harvested. In this way, the harvestable trees can be identified.

Knowledge on the locations of the harvestable trees, on slopes of greater than 40° and on areas with high soil erosion risk are vital and required to optimize the alignment of logging road in the area. The logging road is used to transport out the harvested trees from the forest to the timber landing areas beyond the forest. Therefore, it is important to design and to build carefully the logging roads to avoid, or at least to minimize, severe environmental problems, such as landslides and water pollution. Unnecessary cutting of trees, or even damaging trees along the roads, should also be avoided. In this study, the road should be aligned on area where the terrain slopes are less than 40° in gradient, with soil erosion risk ranging from low to medium, and as close as possible to the harvestable trees.

All three research components are presented in the form of rules taken from the SMS and implemented in the ArcGIS^{TM} software. The results are produced in the form of maps and statistical analysis of the results.

2.4 Summary

This chapter reviews some of the recent literature on the applications of GIS and geospatial technologies in the field of forestry studies, with particular reference to those carried out in the forested areas of Malaysia. This leads to the definition of as GIS-based plan for timber harvesting in the present study. The plan is constructed from three research components, namely (i) the determination of the net production area and the identification of the harvestable trees, (ii) the prediction of soil loss and its flow direction, and (iii) the optimization of the forest logging road network. The literature on these components is also reviewed. The research design for the study is also discussed. More specifically, this thesis examines the following practical issues which underpin each of these three research components:

- Can the rules embodied in the SMS pertaining to the NPA be implemented in ArcGIS 9^{TM}?
- Can the same rule set be used to decide automatically which trees should be selected for harvesting, taking into account the need to distribute the harvested trees across the NPA (i.e. so that no part of the harvested area is completely denuded of trees)?
- Can the soil erosion prediction method and its parameters used in this study be implemented directly in ArcGIS 9^{TM} and is it the most appropriate method and sufficient for the purpose of this study?
- Can ArcGIS 9^{TM} be used to generate soil flow direction and indicate location of soil gain and soil loss?
- Can the forest road network be optimized using the *Forest Road Specification 1988* as determined by FD using ArcGIS 9^{TM}?
- Are there specific aspects of the problem for which the set of available data is insufficient, and what can be done to rectify this situation?
- How can uncertainty in the driving parameters and rule definitions best be incorporated in the GIS?

Chapter 3

Data Sources, Study Area and Methods

Overview The main topics discussed in this chapter are concerned with the sources of data, the study area and the methods used in this study. Related data sources are categorised into four types, namely (i) field, (ii) forest inventory, (iii) meteorological and (iv) topographical data. Then, a detailed description of the study area is presented. Lastly, the methods used for each element of the research (e.g. the determination of the net production area and the identification of harvestable trees, the prediction of soil loss and its flow direction, and the optimisation of forest logging road network) are introduced.

3.1 Introduction

This chapter discusses three aspects of the research study: first, the data sources used in this study, including where the different types of data were collected and from where the data were obtained; second, a description of the study area; and third, the methods used to carry out the research presented in this study.

The study is divided into five major research components, namely (i) the determination of the net production area, (ii) the selection of the harvestable trees, (iii) the prediction of soil loss, (iv) determination of the soil-loss flow direction and (v) optimisation of the logging road routes. The methods associated with each of these research elements is elaborated in Section 3.4.

The production forest refers to the PFE classified for timber production. It covers the total production forest area within a state, which is subject to forest management planning. As the tropical forests are huge and dense, forest managers really need to plan day-to-day activities, monitor any changes that result from these activities, and manage and make decisions for the sustainability and conservation of the forest. Therefore, a good and manageable database will assist the forest managers in their daily tasks and achieving their goals. In doing so successfully, acquiring relevant, precise and correct data is very important for decision-making are made base on these data. Hence, sources where the data are taken, type of data and how the analysis are carried out are equally important.

3.2 Data Sources

Various types of data are required for this study. The data used are primary data such as field data and forest inventory data, and secondary data like topographical data and meteorological data. These data have been obtained from a number of different agencies, such as the FDPM, Department of Agriculture (DOA) and Malaysia Meteorological Department (MMD). However, in cases where the secondary data are inadequate and measurement of new samples are needed, the data have been collected from the field itself. For example, data on soil properties, which are needed to calculate the soil erodibility factor, K in the MSLE and which are not available from secondary sources, were derived from soil samples collected at various locations in the study area and analysed in the laboratory.

3.2.1 Field data

In this study, spatial data on various forest properties and other information, such as the administrative boundaries of FRs, compartments and logging blocks, which have been determined by the State FD, were acquired from the relevant agencies. A survey on these boundaries and the locations of the rivers within the study area was carried out by a team of Forest Research Institute Malaysia (FRIM) staff to validate the information collected from the FDPM and also to update the information on the forest. In these boundaries, existing physical features such as rivers, logging roads, skid trails and *batau* (timber landing areas), where they exist, are clearly shown. The team also collected data on trees, such as their location, family, species, local name, DBH, forest group, stand age and the compartment history.

3.2.2 Forest inventory data

A NFI is carried out for all forested lands, once every 10 years, to determine the status and composition of the forest resources in support of more effective forest management planning using a combination of ground survey, remote sensing and GIS (Naáman, 2002). Malaysia has completed three NFIs and is presently finalizing the fourth. Besides the aforementioned field data, pre-F, felling (F) and post-F inventories are also compiled. The pre-F records provide details of the forest such as the inventory plots, stand density or stocking, species group, diameter classes, number of trees, the volume and basal area for all trees above 15 cm DBH (or at 1.43 m above ground level). Records on the harvesting-limit options, climbers, timber quantities and qualities, palms, *bertam* (*Eugeisson atristis*), *resam* (*Dicranopteris linearis*), rattan and bamboo and seedlings are also available from these inventories. Information on the stand volume and the spatial distribution of the trees to be harvested is essential in order to plan harvesting activities to minimize the impact of felling and to extract the timber efficiently (Malaysian Timber Council, 1997). Existing pre-F inventory techniques can be used to estimate the standing timber volume (Potts et al., 2005). All measurements are carried out in accordance with technical standards formulated by the FD. The height to the first branch and the DBH are measured for all trees with a DBH of 15 cm and above. The SMS pre-F inventory uses a systematic sampling design with fixed-area square plots nested inside larger rectangular plots. The inventory data varies for each plot depending on the tree sizes (Forestry Department, 1997). However, for the purpose of this study, only parameters of relevant forest inventory data like inventory plots and trees are employed. For the inventory plots, plot sizes, plot locations and plot boundaries are measured. Among the tree features that are measured are tree locations, species and family names, DBH, heights, etc. Then, these values are stored in a new database created in Excel and mapped using GIS software, ArcGIS 9^{TM} by me. Besides the tree features, other spatial data acquired are such as the study area and river boundaries, rivers, contours and roads. These data are then mapped and stored in the same way as the tree features data. This enables the modification and retrieval of data for timber harvesting in the later part of the study.

Harvesting or felling records determine the trees that have been marked to be felled. These trees are identified from the pre-F records. These data are vital because logging must be planned to determine the appropriate harvesting limits and the techniques to be used within the compartment (or logging block) based on the estimated timber volume, the topography and the risk of site degradation (Malaysian Timber Council, 1997). The data are also kept in the form of a tree-marking map.

Post-F records are records collected after harvesting; basically, to gather information on residual stand volume. The post-F inventory is also aimed at identifying environmental damages and to determine the appropriate sivicultural treatments needed for the area to ensure its long-term sustainability.

3.2.3 Topographical data

RIL is aimed at minimising any environmental problems that might be caused by harvesting. However, there are still problems encountered after logging, such as soil erosion and site degradation. In quantifying these impacts, meteorological and topographic data are important, since these are required to evaluate the likely extent of the damage. Features

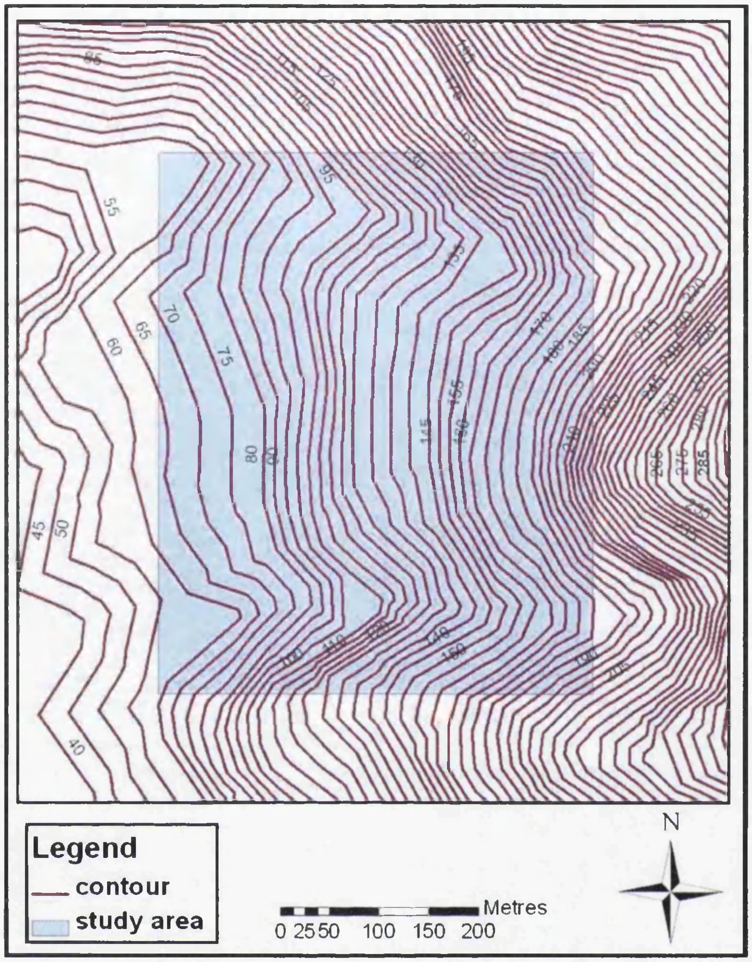


Figure 3.1: Contour map of the study area.

such as contours, terrain elevation and river courses are needed in this study. These assist in identification of high slopes and hydrological pathways. Soil samples must also be collected to investigate the soil physical properties, which are used in the soil erodibility calculation. In this study, contour data, terrain elevation and soil properties for area surrounding the study area, which cover larger area are extracted from the topographic and soil maps. However, contour for 10 ha study area was actually surveyed on the ground and is shown in Figure 3.1.

The topographic map used for this study area is Parit, Perak, Peninsular Malaysia Topo Map, Series L7030, Prints 1-PPNM and Sheet 3462. The scale is 1:50000 and the

Projection is RSO with the grid in meters. The map is published in 1987 by the Director of National Mapping. The map is prepared from the following materials:

1. Compiled graphically from sheets series L7010 - 1972
2. Additional information from Aerial Photograph - 1981 and Field completion -1984
3. Amendments to State Boundaries - 1984.

3.2.4 Meteorological data

Meteorological data on properties such as rainfall, wind speed, air temperature, relative humidity, solar radiation and evaporation, used in this study, are obtained from the relevant agencies, namely the Drainage and Irrigation Department (DID) and MMD. These data are collected not only to provide a description of the conditions in the study area, but also because of the effects they have on the environment and biodiversity of the study area. For example, rainfall due to its abundance in the tropical forest can result in severe soil erosion and may lead to landslides if the forest is already cleared.

The meteorological data were collected for the year of 2004 from Ipoh Airport station. Since this station is categorised as a principal meteorological station, the frequency with which the data are recorded is daily and because of the status, there are no gaps in the data. The total rainfall, evaporation, solar radiation and temperature for the study area are indicated in Figures 3.2, 3.3 and 3.4 respectively.

3.3 Study Area

Malaysia consists of Peninsular Malaysia or West Malaysia, which is part of mainland Southeast Asia, and the states of Sabah and Sarawak on the northern edges of the island of Borneo (East Malaysia). It is bordered by the waters of the Gulf of Thailand, the South China Sea, the Andaman Sea and the Straits of Malacca, as well as the countries of Brunei,

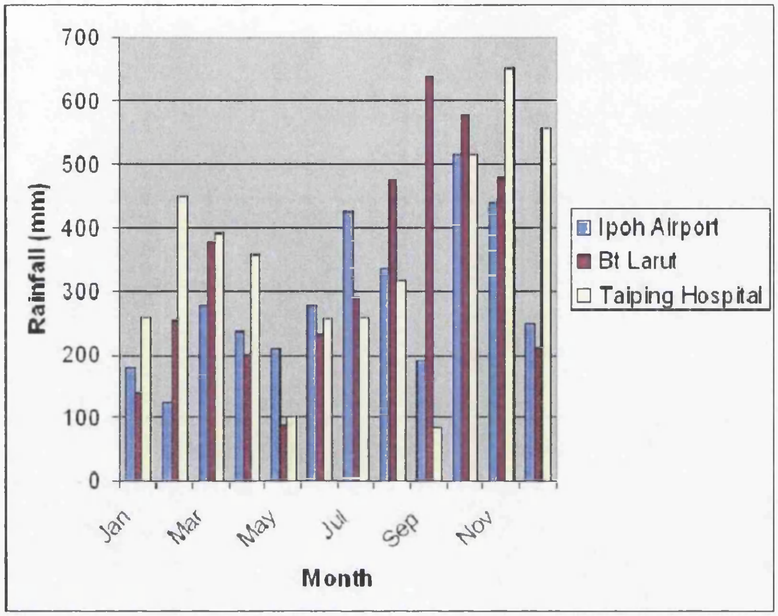


Figure 3.2: Mean monthly rainfall (*mm*) from the three rainfall stations near the study area.

Phillipines, Indonesia, Singapore and Thailand. Essentially, the coastal plains rise gently into hills and mountains, all covered by dense rainforest. The elevations in the country range, on average, between 1100 m and 1800 m, with the major exception of Mt. Kinabalu (4260 m) in the State of Sabah. Malaysia also has hundreds of very small islands scattered along its coastlines. More than two dozen rivers flow from the mountains, with the Sungai Pahang, Sungai Rajang and Sungai Sugut among the longest and most significant (CIA, 2006).

The total forested area in the Perak FMU amounts to 1 050 225 ha. Of this total, 884 205 ha are gazetted as PRF, 117 500 ha designated as the Royal Belum State Park, 7413 ha as Wildlife Reserve, while the remaining areas (41 107 ha) are categorized as Stateland Forest. The PRF comprises two main natural forest types, namely Dry Inland Forest (961 554 ha) and mangrove Forest (961 554 ha) (Anon, 2003). The dry inland forest consists of Mixed dipterocarp Forest, Hill dipterocarp Forest and Montane Forest. In

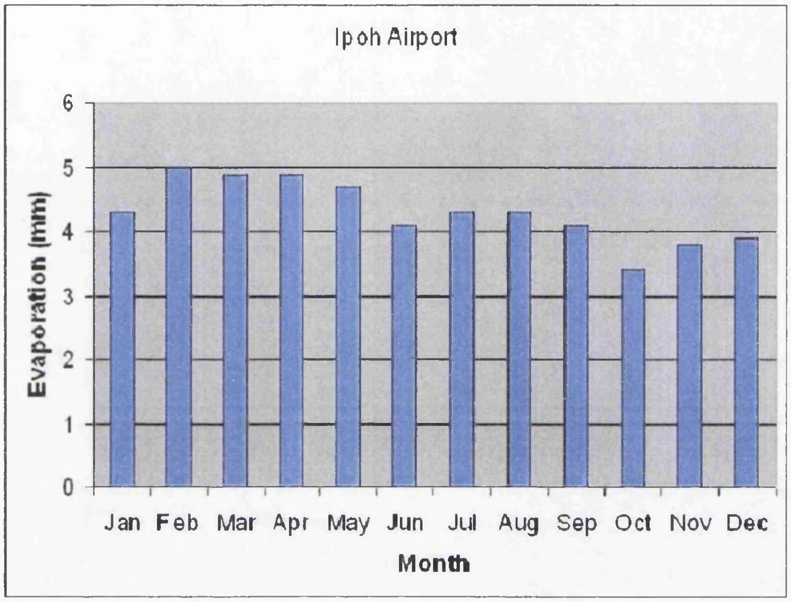


Figure 3.3: Mean daily evaporation (*mm*) from Ipoh Airport station.

the study area, although there are non-dipterocarp trees, the dipterocarp trees are more dominant in terms of physical feature and economic gain. The dipterocarps are hardwood and their size are up to 26 m height and 180 cm DBH, and are highly valuable.

3.3.1 Location

This study is focused on Block J, Compartment 65 in the Bubu Forest Reserve, Taiping, Perak, Peninsular Malaysia. The forest is a logged-over forest. The exact location of the study area is latitude 306 977°N to 307 400°N and longitude 504 247°E to 504 750°E. The Bubu Forest Reserve ranges from 60 m at the west to 180 m to the east and its altitude is 1568 m Above Sea Level (ASL). However, due to time constraints and considerations of data volume, the data for this study are drawn from a 10 ha subsection of Block J, Compartment 65. This 10 ha study area is further sub-divided in to a series of smaller inventory plots, each 20 m × 20 m in size, for data collection purposes, as shown in Figure3.5. There

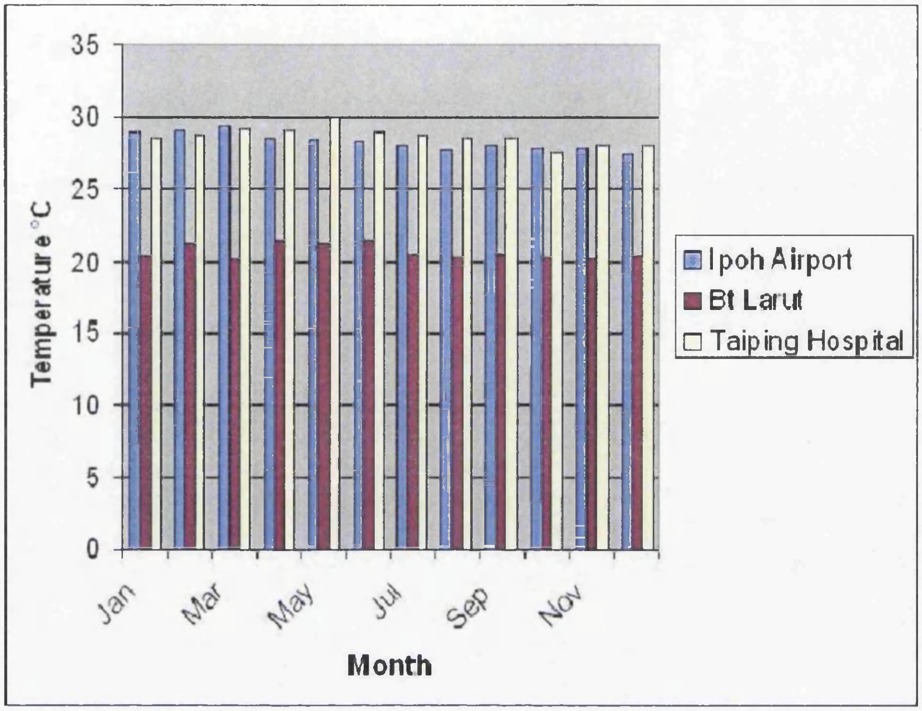


Figure 3.4: Mean temperature (^oC) from three stations near the study area.

are 291 such plots in the study. During a period of field work, all of the trees with a DBH greater than 15 cm were tagged, mapped, identified with respect to species, and their DBH measured. Thus, for each tree in this inventory, a record exists of the tree's species, DBH and its x and y coordinate within the Malaysian mapping coordinate system. Altogether 1660 trees are included in the inventory.

As has already been mentioned, the study area comprises 291 20 m × 20 m plots. Plot establishment, including climber cutting, was conducted from October 2002 to March 2002. The first measurement of the plots was carried out at the same time. Harvesting commenced in February 2005 and was completed in April 2005. The plots are further divided into 4337 sub-plots of size 5 m × 5 m in the ArcMap. These sub-plots are used to assess soil loss, as explained in section 5.2.3.

During the first measurement exercise, before logging, all trees with a DBH of at least 10 cm were recorded and marked with an individual 5 cm aluminium number tag that was buried by the base of the tree. The data recorded for each such tree included:

- tree ID
- geographical location
- the plot in which it is located
- the distance and bearing to the tree from the centre of the sub-plot
- the family, species and local name
- the DBH (measured with a tape in graduated in cm, if possible; otherwise, measured at 0.34 m above the highest buttress) and
- the height to the first branch.

Trees were identified to species level, if possible, by professional inventory rangers. The trees that could not be so identified were classified as other timbers (OT). Trees were then grouped into dipterocarps (all trees belonging to the *Dipterocarpaceae* family) and non-*Dipterocarpaceae* (all other tree species). These will henceforth be referred to as "dipterocarp" and "non-dipterocarp" trees, respectively, for the sake of brevity.

3.3.2 Drainage system

As a result of the configuration of the Country, and of the heavy rainfall that it receives, there are many rivers, which form some of the major arterial routes for trade and travel. The rivers of Sarawak and Sabah are longer than those of the Peninsula. The longest is the Rajang of Sarawak (563 km) which is navigable for small coastal steamers up to 160 km upstream. The rivers in Peninsula have historical importance, which is underlined by the

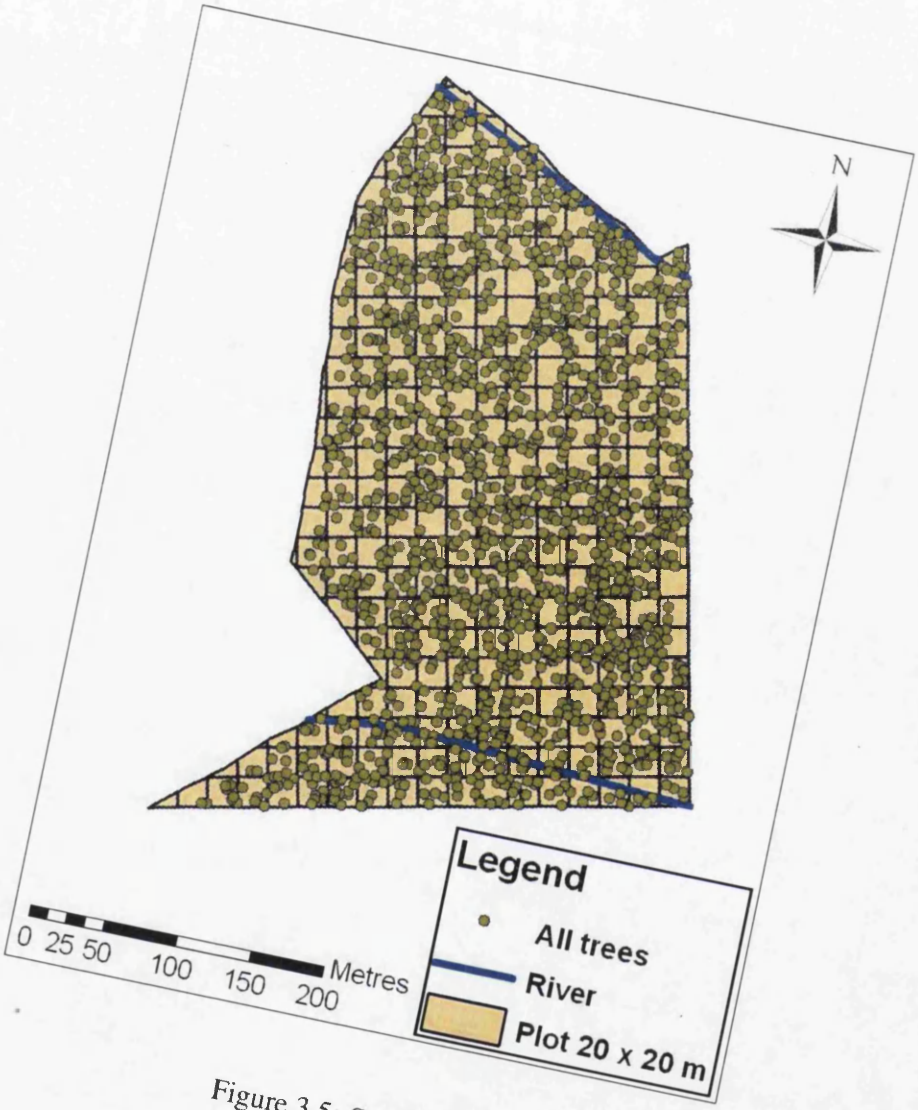


Figure 3.5: Study area

fact that nearly all of the states of the Peninsula take their names from the principal river in that state. The longest of these rivers is the Sungai Pahang (475 km), followed by the Sungai Perak (400 km).

The drainage system in the study area consists of Sungai Rotan, a tributary of Sungai Perak which flows towards north-east and splits into smaller tributary i.e. Sungai Bubu. The study area lies on the Sungai Bubu catchment. There are two smaller tributaries of Sungai Bubu that flow across the study area, one is at the top and the other at the bottom as shown in Figure 3.5.

3.3.3 Climate

The climate of the study area is humid tropical and is generally characterised by a high and uniform air temperature, high humidity, abundant rainfall and light winds. Due to Malaysia's equatorial location, it is unusual to find a day with completely clear skies or, conversely, more than a few days without sunshine. Malaysia has two main seasons, the north-east monsoon (which runs from November to March) and the south-west monsoon (which runs from May to September); these two monsoon periods are separated by two relatively shorter intermonsoon periods which are marked by heavy rainfall. The onset and termination of the monsoon varies from year to year. These dates are determined by the beginning of the rainy spell and the predominant wind direction. The south-west monsoon is a drier period for the whole country, particularly for the states of the west coast of the Peninsula, which are sheltered by the land mass of Sumatra. Periods of heavy rainfall are important because of the effects they can have on timber harvesting and road construction. Usually in Malaysia, these two activities are carried out during the drier periods to minimize erosion.

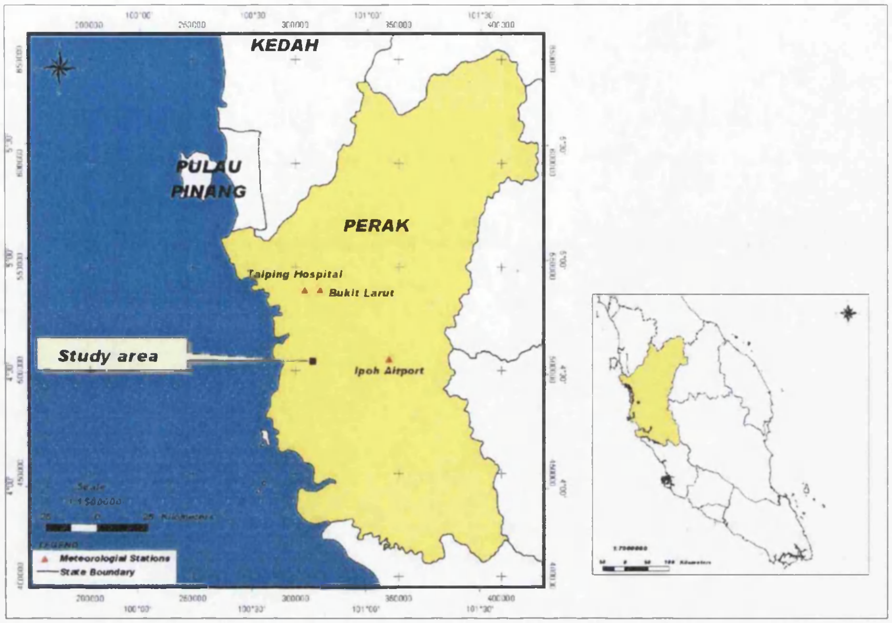


Figure 3.6: Locations of meteorological stations around the study area.

3.3.3.1 Rainfall

A major characteristic of the climate in the region is that the monthly rainfall exceeds 100 mm and the mean annual rainfall ranges from 2000 mm to 4000 mm (Whitmore, 1998). The rainfall distribution pattern over the country is determined by the seasonal wind flow and the local topographic features. Exposed areas, like the east coast of Peninsula Malaysia, western Sarawak and the northeast coast of Sabah, receive heavy rain during the north-east monsoon season. This does not happen in the inland areas, however, which are protected by the mountain ranges. The south-west monsoon, which is more powerful, brings rain to the western side of Peninsular Malaysia from April to August.

There are no rainfall stations in the study area itself, however, besides the principal meteorological station located nearest to the study site i.e. Ipoh Airport station, there are two more rainfall stations located around the study area, i.e. Taiping Hospital and Bukit Larut rainfall stations as shown in Figure 3.6.

The mean monthly rainfall in Figure 3.2 shows drier weather conditions from May

Table 3.1: Highest recorded 24-hr (one day) rainfall at Taiping Hospital and Bukit Larut stations. (Source: Author, 2007)

	Bukit Larut		Taiping Hospital
Date	Most rainfall in a day (mm)	Date	Most rainfall in a day (mm)
Jan 24	29.3	Jan 20	60
Feb 17	38.9	Feb 15	101.6
Mar 17	39.1	Mar 27	104.6
Apr 12, 18	29.7	Apr 26	50.8
May	not available	May 6	29.6
Jun	not available	Jun 6	69.8
Jul 12	117	Jul 11	64.2
Aug 2	78.6	Aug 23	60.6
Sep 26	72.3	Sep 8	22
Oct 26	99.2	Oct 25	59.4
Nov 29	54.8	Nov 27	76.6
Dec 25	50.6	Dec 26	96.3

to June and wetter weather conditions from October to December. The number of days with rainfall ranges from 150 to 200, with the heaviest rainfall in October to December. The annual rainfall is more than 2500 mm. The Taiping district where the study area is situated receives the highest amount of rainfall in the Penisular Malaysia. Besides, there are also extreme rainfall events as listed in Table 3.1, which are likely to have high impact on erosion of forest roads.

3.3.3.2 Temperature

Being an Equatorial Country, Malaysia has high and uniform temperature throughout the year which ranges from 26°C to 33°C. The annual variation is less than 2°C. The daily range of temperature is large, ranging from 5°C to 10°C at the coastal stations and from 8°C to 12°C at the inland stations. Although the days are frequently hot, the nights are reasonably cool everywhere.

The seasonal and spatial temperature variations are relatively small. Over the whole Peninsula, there is a definite variation of temperature with the monsoons, which is accentuated in the east coast districts. The highest average monthly temperature is recorded in April and May in most places, and the lowest average monthly temperature is recorded in December and January. The average daily temperature in most districts to the east of the Main Range is lower than that of the corresponding districts to the west. The difference in the average values to the east and the west of the Main Range are due almost entirely to the low daytime temperatures experienced in the eastern districts during the northeast monsoon, as a result of rainfall and greater cloud cover. At Kuala Terengganu, for example, the daytime temperature rarely reaches 32°C during the north-east monsoon and often fails to reach 27°C. On a number of occasions the temperature did not rise above 24°C, which is quite frequently the lowest temperature reached during the night in most districts. Night-time temperatures do not vary to the same extent, the average usually being between 21°C to 24°C. Individual values can fall below this at most stations, with the coolest nights commonly following some of the hottest days. The mean temperature for the study area is shown in Figure 3.4 from three nearby stations.

3.3.3.3 Relative Humidity

Malaysia has very high relative humidity due to the high temperature and a high rate of evaporation. The mean monthly relative humidity is within the range 70 % and 90 %, and for any specific area the range of the mean monthly relative humidity varies from a minimum of 3 % to a maximum of about 15 %. In Peninsula Malaysia, the minimum relative humidity normally occurs in February, when the figure is usually about 84 %, while the maximum occurs in November, when the corresponding figure is 88 %. It is also observed that in Peninsular Malaysia, the minimum relative humidity is normally found in the months of January and February, except for the east coast states of Kelantan and Terengganu, which have the minimum in March. The maximum relative humidity generally occurs in the month of November.

3.3.3.4 Sunshine

Because Peninsular Malaysia is surrounded by sea and equatorial, it receives abundant sunshine and incident solar radiation. It is extremely rare to have a full day with completely clear sky even in periods of severe drought. The cloud cover reduces substantially the amount of solar radiation received. On average, the number of hours of sunshine is between five and nine per day.

3.3.3.5 Wind

The wind over the Country is generally light and variable, however, there are some uniform periodic changes in the wind flow patterns. Based on these changes, four seasons can be distinguished, namely, the southwest monsoon, northeast monsoon and two shorter inter monsoon seasons. The wind flow during the southwest monsoon (May-September) is generally southwesterly and light i.e. below $7.7\,\mathrm{m{\cdot}s^{-1}}$ whereas during the northeast monsoon (November-March), steady easterly or northeasterly winds of $5.1\,\mathrm{m{\cdot}s^{-1}}$ to $10.3\,\mathrm{m{\cdot}s^{-1}}$ prevail. The wind during the two inter monsoon seasons are generally light and variable.

3.3.3.6 Evaporation

Two important factors that affect the rate of evaporation in Malaysia are cloudiness and temperature. These two factors are inter-related. A cloudy day means less sunshine and thus less solar radiation and as a result the temperature is lowered. An examination of the evaporation data shows that the cloudy or rainy months are the months with lower evaporation rate while the dry months are the months with higher rate. Lowland areas have an annual average evaporation rate of 4 mm to 5 mm per day. Mean daily evaporation for the study area is presented in Figure 3.3.

3.3.4 Topography

One of the most prominent mountain ranges in Sabah is the Crocker Range with an average of 457 m to 914 m, which separates the narrow lowland of the north-west coast from the interior. The Crocker Range culminates in Gunung Kinabalu (4101 m), the highest mountain in Malaysia and in Southeast Asia. Malaysia's third highest mountain, Gunung Tambuyukon (2579 m) is close by, while the Country's second highest peak, Gunung Trus Madi (2597 m) is in the same range. In Sarawak, the two highest peaks are Gunung Murud (2425 m) and Gunung Mulu (2371 m) which also boasts one of the largest natural caves in the world.

In Peninsular Malaysia, a mountainous spine known as the Main Range or Banjaran Titiwangsa runs from the Thai border southwards to Negeri Sembilan, effectively separating the eastern part of the Peninsula from the western. In the west, mangrove swamps and mudflats at the coast give way to cultivated plains. Sandy beaches lie along the east coast. A considerable part of the interior of Kelantan, Terengganu and Pahang is also mountainous and contains the highest peak in the Peninsula i.e. Gunung Tahan (2187 m).

The topography of the study area is rugged to undulating and the highest peak is Gunung Bubu (1657 m). The contour in the study area range from 70 to180 m.

3.3.5 Geology and Soils

Tectonically, Peninsular Malaysia forms part of the Sunda Shield. Its Triassic fold-mountain belt, the spine of the Peninsula, continues from eastern Burma through Thailand, Peninsular Malaysia, the Banka and Billiton Islands, and eastwards into Indonesian Borneo. All the systems, ranging from the Cambrian to the Quaternary, are represented in Peninsular Malaysia. Granites occupy almost half the Peninsula, commonly forming the topographic highs, notably in the Main Range. The Machinchang Formation in the northwest part of the Peninsula provides the oldest evidence of sedimentation.

Table 3.2: Chemical properties of samples collected in the study area. (Source: Author, 2007)

Sample no.	N (%)	C (%)	P (ppm)	K (cmol·kg^{-1})	Ca (cmol·kg^{-1})	Mg (cmol·kg^{-1})
1	0.10	0.53	7.91	0.16	0.08	0.18
2	0.07	0.43	4.97	0.15	0.07	0.17
3	0.10	0.47	1.21	0.14	0.09	0.16

Table 3.3: Physical properties of samples collected in the study area. (Source: Author, 2007)

Sample no.	Clay (%)	Silt (%)	Fine sand (%)	Coarse sand (%)	Wet pH	Dry pH	CEC (cmol·kg^{-1})
1	44	14	14	31	5.12	5.06	19.58
2	33	23	17	31	5.24	5.13	17.05
3	44	13	14	34	5.19	5.16	19.85

The soil series of Perak is Bungor series and the origin is shale. These are sedentary soils which developed on igneous and high grade metamorphic rocks. According to the FAO classification soils and Soil Taxonomy systems, these soil fall into the Acrisol group as shown in Figure 3.7 (Food and Agriculture Organization, 2006a). Three soil samples were collected from the study area and sent to the soil laboratory for analyses. Both physical and chemical properties were analysed and the results are shown in Table 3.2 and 3.3. From this analyses, it was discovered that the soil in the study area is derived from granite parent material and has coarse sandy-clay texture. Therefore, the soil nature can be classified as erodable, depending on the slope and forest cover. Minimum erosion is also expected under undisturbed forest, while serious to very serious erosion or landslides may occur if the forest is clear felled.

3.3.6 Vegetation

The forests in the study area were a primary tropical rainforest, dominated by members of the Dipterocarpaceae family, known as Hill dipterocarp forest as shown in Figure 3.8.

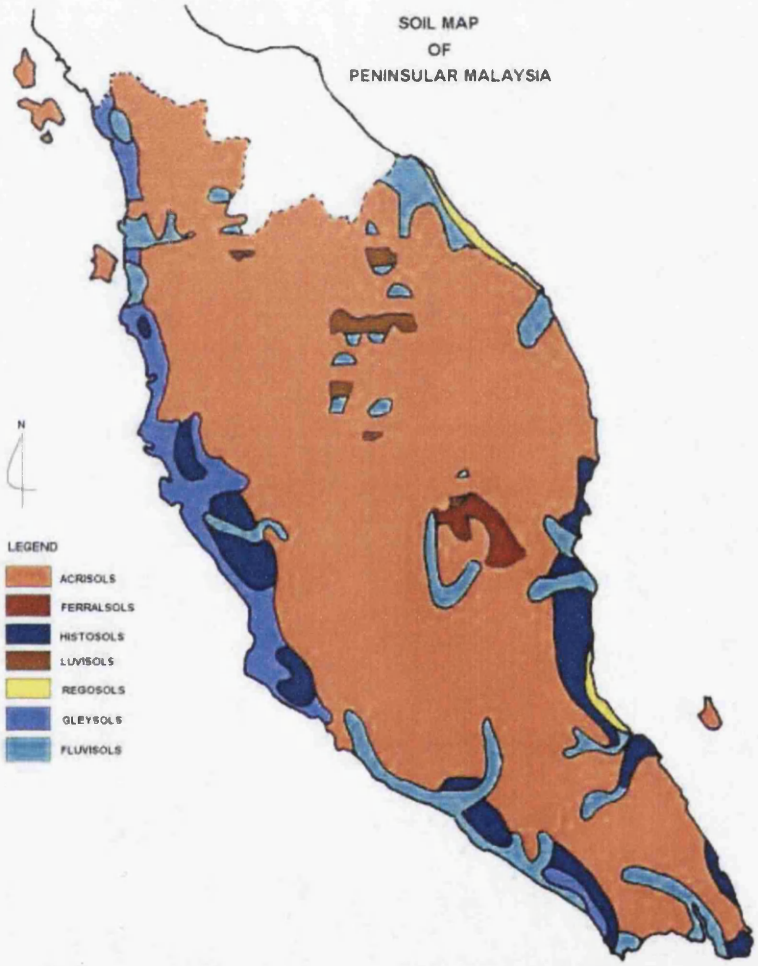


Figure 3.7: Soil map of Peninsular Malaysia (Source: FAO 2006)

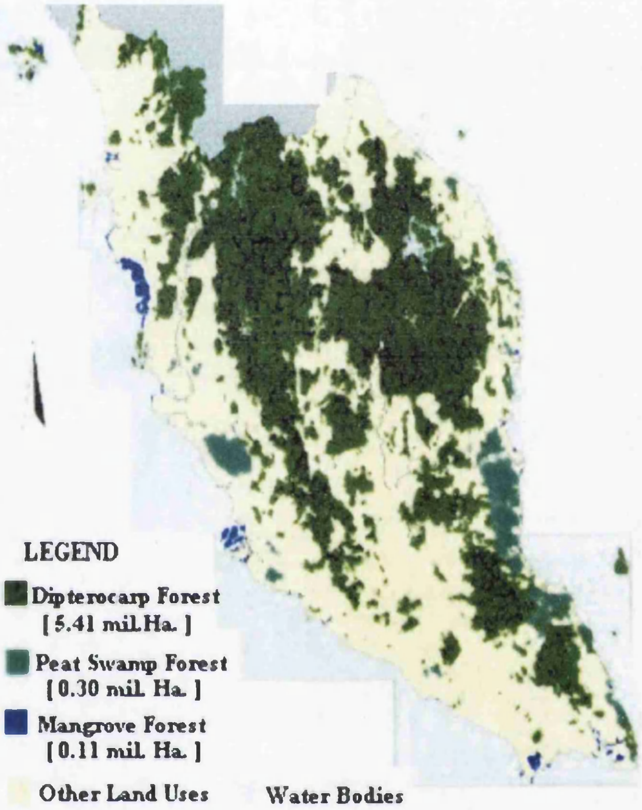


Figure 3.8: Forest cover map of Peninsular Malaysia (Source: http://www.forestry.gov.my)

The average height of the taller trees in a rainforest is usually about 46 to 55 m. However, in Malaysia, trees of 60 m and over are commonly found (Richards, 1996). In the study area, the height to the first branch of the trees surveyed is up to 26 m and the DBH is 180 cm. Altogether there are approximately 1660 trees greater than 15 cm DBH in the study area, all of which have been surveyed.

3.3.7 Land use

Dense tropical forest covers more than half of Malaysia's land area. Intensive logging and replanting operations are, however, gradually changing the form of the forest. Most cleared areas are in the north-east and west of Peninsular Malaysia. Huge tracts of Sabah's forests were felled in the 1970s and 1980s. Forests still cover 59 % of the land area, having declined at a rate of roughly 1.2 % per annum during the period of 1990 to 2000. At the present time, arable land comprises 5.5 % and permanent cropland 18 % of the total land area. The study area consists mainly of forests but these are surrounded by oil palm and rubber plantations and also some rural settlements.

3.4 Methodology

A pre-F inventory is usually performed on a compartment-by-compartment basis preceding harvesting by 6 to 12 months. A compartment is the smallest management unit in the PFE. The size of a compartment is not fixed but on average it is about 250 ha. One or more compartments make up a forest reserve with several forest reserves forming a forest management unit in Peninsular Malaysia (Potts et al., 2005).

3.4.1 Determination of net production area

The NPA is an area where forest trees are demarcated for timber harvesting. In delineating this area, many factors have to be taken into account as harvesting is the main activity affecting the ecology of the forest. Therefore, this process must be conducted in a manner that will minimize the impact to the environment. There are many regulations and techniques that can be implemented (e.g. no harvesting can be carried out on slopes greater than 40° (Malaysian Timber Council, 1997). Another important criterion is that harvesting is not allowed near a river and a buffer of 20 m of each side of the river must normally be allocated. Road buffers too must be constructed 30 m each side of any existing forest

Table 3.4: Data required for determination of standard net production area. (Source: Author, 2007)

Process	Data needed	Data generated	Spatial data sources
Contour 40°	forest reserve, compartment and block boundary contour lines and interval	slope length and steepness	topo map
River buffer >30 m	river network	river buffer	topo map

road. In ensuring the growth and sustainability of the forest, mother trees should not be harvested. Similarly, for conservation purposes, species which have medicinal value or which are in danger of extinction should be excluded. After considering all the above, it is still not the case that all of the remaining trees may be logged. For the protection and the growth of seedlings and saplings, only trees greater than 50 cm DBH for dipterocarp spp., or greater than 60 cm DBH for *Neobalanocarpus heimii* can be harvested. In the case of non-dipterocarp spp., the cutting limit is greater than 45 cm DBH. Consequently, on the basis of these accumulated rules, the net production area is demarcated. Data generated from the above requirements is summarized in Table3.4.

3.4.2 Selection of harvestable trees

During the pre-F inventory one of the most important procedures that has to be carried out is tree marking where all trees greater than 15 cm DBH are surveyed. One of the objectives of the tree marking is to obtain an up-to-date indication of the status of the forest, including the relative proportions of dipterocarp *spp.* to Non-dipterocarp *spp.*, the richness of the forest (derived from the DBH measurements and also to determine the cutting limit of the trees to be harvested. In determining the number and location of the harvestable trees in this study, the following regulations are adopted from the SMS: (i) the cutting limit for dipterocarp *spp.* is set to be greater than 50 cm DBH except for *Neobalanocarpus heimii* (greater than 60 cm DBH) and greater than 45 cm DBH for the non-dipterocarp *spp.*; (ii) 32 sound commercial trees per hectare between 30 and 45 cm

Table 3.5: Data required for selection of harvestable trees. (Source: Author, 2007)

Process	**Data needed**	**Data generated**
NPA trees	NPA, tree location	NPA trees
Conservation trees	NPA, tree location	Conservation tree map
Cutting limit trees:	tree spp., DBH, tree location	Cutting limit trees map
dipterocarp >50 cm DBH		
Neobalanocarpus heimii >60 cm DBH		
Non-dipterocarp >45 cm DBH		
Residual trees	tree spp., DBH, tree location	Residual trees map
Proposed cutting limit trees	tree spp., DBH, tree location	Proposed cutting limit trees map
Percentage of dipterocarp after harvesting	tree spp., DBH, tree location	Percentage of dipterocarp trees map
Maximum volume extraction	no. of trees	no. of trees harvested
Harvestable trees	tree spp., DBH, tree location	Harvestable trees map

DBH should be remained in the residual stand; (iii) the percentage of dipterocarp for trees greater than 30 cm DBH should not be less than that in the original stand; and (iv) forest removal should be limited to less than 40 % of the standing volume or approximately $30\,m^3 \cdot ha^{-1}$. Before these rules can be carried out, however, the trees in the buffer areas must first be eliminated because they cannot be harvested and are categorised as conservation trees. The summary of the selection criteria for the harvestable trees is shown in Table 3.5.

3.4.3 Prediction of soil loss and its flow direction

Before a forest area is ready for logging, there are several steps that have to be taken into consideration. The most common environmental problems faced after logging include soil erosion and the consequent environmental degradation of the site. In this study, the

Table 3.6: Process of prediction of soil loss and its flow direction. (Source: Author, 2007)

Process	Symbol	Data needed	Spatial data sources
Rainfall factor	R	rainfall	
Soil erodibility factor	K	soil analysis	
Slope and steepness factor	LS	contour	TIN, DEM
Vegetation management factor	VM	vegetation and management	vegetation cover
Soil loss	A	R, K, LS, VM	R, K, LS, VM

MSLE technique is used to predict the likely levels of soil erosion experienced before and after the logging. Rainfall data and soil property parameters are used in this prediction. Once the damage has been assessed, treatment options can be suggested (although this is not implemented in this thesis). This will ensure the growth and sustainability of the forest not only for the next harvesting cycle but also for future conservation and management. The method of assessing the damage caused by soil erosion is summarized in Table 3.6.

3.4.4 Optimization of logging road and skid trail

Logging roads are built merely to transport timber that had just been harvested from the trees to the *batau* (timber loading area). Apart from felling activities, skidding activities also have some effects on the environment. Therefore, all skidding activities are usually confined to predetermined skid trails. In addition, engineering guidelines are used to protect against soil erosion and these pertain to main roads, secondary forest roads and skid trails.

From the topographic features, a base map can be produced. Basically the base map shows the forest boundary, existing roads (where these existed), rivers, slope gradients, *batau* and tree locations. When overlaying this map with the net production area map, the optimum road from the batau to the most harvestable trees area can be inferred. Again, the road should be aligned in accordance with guidelines similar to those used in delineating the net production area (ie in terms of road and river buffers, mother trees and conservation

Table 3.7: Optimization of logging roads and skid trails. (Source: Author, 2007)

Process	Spatial data sources	Data generated
Base map	forest boundary road map river map topo map tree map	
Delineation of harvestable trees area based on amount to be felled	tree map net production map	categories of harvesting trees
Integration of soil loss prediction and harvestable trees	soil loss map harvestable trees map	elimination of harvestable trees on high slopes
Align optimum road to the most harvestable trees area and skid trails	base map harvesting tree categories batau location	road alignment map

trees). A summary of the process and data used in the optimization of logging road and skid trail is shown in Table 3.7.

3.5 Summary

The relevant data collected in this chapter are classified into two classes based on the way they are stored. The numerical data such as rainfall, soil, slope and tree parameters are stored in Excel database whereas the spatial data such as tree locations, study area and river boundaries, contours, elevations and slopes are installed in the ArcGIS 9$^{\text{TM}}$ database. These data would be processed and analyzed differently in the next three chapters to obtain the results to be embedded in the timber harvesting plan.

Chapter 4

Determination of the Net Production Area and Identification of the Harvestable Trees

Overview This chapter presents an analysis of the rule-set, as specified in the SMS, which is used during forest harvesting in Malaysia. The rules are implemented in a GIS, using the ArcGIS 9^{TM} software, and these are applied to a small test area, part of the Bubu Forest Reserve in Malaysia. Although most of the rules specified in the SMS are based on fixed threshold values, this chapter also presents an analysis in which the threshold values are modified, such that the effect of variation in the thresholds is explored. Thus, the chapter evaluates the sensitivity of the forest management system to the specific threshold values employed in the SMS.

4.1 Introduction

The primary (or virgin) forest area of Malaysia has been decreasing in size over the past five decades. In the main, it is being replaced by plantations of rubber and oil palm. In the early 1980s, 4.4 million hectares of previously undisturbed closed tropical forest were logged and, on average, a further 1.1 million hectares were degraded each year (Johnson and Cabarle, 1993). The most important determinant of forest degradation is the worldwide demand for timber. Timber is one of the main sources of income for Malaysia, contributing to its economic growth. In the early years, and especially during the 1940s, Malaysia implemented a MUS in which all trees greater than 45 cm DBH, regardless of species, were harvested. This resulted in large areas of clear-felled forest where the bare land was exposed to a range of environmental problems, such as soil erosion, landslides, water pollution and loss of biodiversity. It also affected the sustainability and reproduction of commercially-important tree species for future harvesting. In the mid-1970s, widespread concern and an increasing awareness of the problems of environmental degradation led to the introduction of a new harvesting management system, known as the Selective Management System (SMS), in 1978. The aim of the SMS is to implement a more flexible and sustainable harvesting management system, which meets the needs of both environmental conservation and the timber market (Forestry Department, 1997). Presently, the SMS is the mandated forestry system used throughout Peninsular Malaysia.

In the SMS, a number of measures – including the retention of 'seed trees' (or 'mother trees'), buffer zones (for the protection of rivers, streams and roads) and a minimum level of dipterocarp species in the forest stands after harvesting – are taken to protect and preserve the forest resources during forest-harvesting operations, especially in the production forests of the PFE. In Peninsular Malaysia, for example, it has been prescribed that at least 4 seed trees must be retained per hectare in all logged-over forest, that buffer zones at least 20 m wide have to be marked and protected along rivers and streams, and that the percentage of dipterocarp species greater than 30 cm DBH in the residual stand should not be less than that in the stand prior to harvesting. As a result, the practice of selective harvesting in Malaysia ensures that the larger trees that remain should reach maturity over a period of between 25 years and 50 years. This practice should therefore allow subsequent cycles of harvesting. In combination, the measures embodied in the

SMS determine the NPA of the forest, which is the area that can be harvested.

To assist in the design of proper inventory, modeling and auditing systems that can be used to plan, control and report on operational performance, forest managers need to be able to apply their knowledge and experience responsibly and effectively. The requirement to plan and conduct harvesting operations, which accommodate and even enhance the multi-functional character of all types of forest, also demands that management practices need to be addressed and implemented successfully (Whyte, 1999). In Malaysia, management practices and forest silviculture have always been researched, updated and new practices implemented. These practices, in turn, need to consider a range of issues, including: (i) changes to the forests; (ii) the unpredictable nature of the finance and resource markets; (iii) issues of timber supply and demand; (iv) advances in the harvesting and processing techniques available to the forestry industry; and (v) various other matters of harvesting and forest production (Forestry Department, 1997). For example, a technique used in the SFM policy, known as RIL, involves the planned and carefully controlled harvesting of timber in a way that minimizes the impact on forest stands and soil. As tropical forests are both spatially extensive and dense, forest managers need to plan day-to-day activities, monitor any changes resulting from these activities and make decisions regarding the sustainability and conservation of the forest. For all these reasons, a comprehensive and accurate database is required to assist the forest managers in their daily tasks and to help them to achieve their immediate goals. To populate such a database, a detailed inventory of the forest resources is needed prior to harvesting.

One of the prerequisite requirements of the SMS, therefore, is to carry out a pre-F inventory. This typically involves the collection of a very large amount of data. At present, the collection, storage, analysis, retrieval and presentation of these data is done manually, but it lends itself well to the use of computerized databases and, in particular, GIS. By comparison, the manual approach is both costly and labour-intensive. It also leads to inefficiencies in management and decision-making by the forest managers. Inefficiencies in this case relate to the inability to respond on a day-to-day basis and hence to making rapid decisions in response to operational felling and harvesting. For example, without a detailed computerized database, and the ability to interrogate this rapidly, forest managers are unable to check the forest status after harvesting without carrying out a further, post-F, inventory. The foresters are also unable to determine the harvestable trees in relation to other environmental factors, which may influence soil erosion. If the database and GIS are already in place, the forest managers can use these to identify the location of the harvestable trees and, if necessary, make changes to the harvesting plan if the selected trees are located in areas that are highly susceptible to soil erosion.

Another factor that is likely to increase the efficiency with which forest harvesting is managed and planned is the ability to ask so-called 'what if?' questions. For instance, in determining the NPA, a mandatory set of rules has to be followed to ensure the conservation and sustainability of the forest. In principle, this set of rules could be modified if the forest managers had evidence to suggest that the present rule-set resulted in the degradation of the forest or generated insufficient (or surplus) income. An evaluation of this type demands a system that can analyze, for example, the effect of variation in the maximum terrain gradient on which forest harvesting is permitted, since this is likely to influence the amount of soil erosion and the number of landslides. Other potential advantages of using a GIS to aid forest harvesting include (i) the capability to determine the AAC when the DBH of the harvestable trees is changed, (ii) the ability to predict the sustainable timber production during the next harvesting cycle and (iii) the potential to conserve tree species of high importance. In short, using a GIS, forest managers would be able to manage effectively, make quick and reliable decisions, and hence increase the efficiency of forest management and planning.

Taking the preceding discussion as its basis, this chapter presents an analysis of the rule-set specified in the Malaysian SMS, which is used to control and direct harvesting. The SMS rules are implemented in a GIS, using the ArcGIS 9^{TM} software, and are applied to a small test area in the Bubu Forest Reserve, Malaysia. Although most of the rules specified in the SMS are based on fixed threshold values, this chapter also presents a further analysis in which the threshold values are modified, such that the effect of variation in the threshold values is explored. In this way, the chapter evaluates the sensitivity of the forest management system to the specific threshold values.

4.2 Bubu Forest Reserve pre-felling (pre-F) Inventory

Forest inventory has been practised for a long time and started with measurements of the available wood. Later the inventory was enhanced to detect changes in the forest and in the forested area, and subsequently to address a much wider variety of matters relating to forest and tree resources. New technologies and methodologies for obtaining forest information have also evolved and expected to continue to improve accuracy, efficiency and cost-effectiveness of global, regional and national inventories. One of the most important objectives of forest-resource assessment or forest inventory is to support decision-making for forestry policies and programmes at all levels. From the information provided by developing countries to Global Forest Resource Assessment 2000 (Food and Agriculture Organization, 2001), Saket (2002) concluded that there was generally insufficient information for many topics considered important in forest policy development. Key forestry statistics were found to be based upon expert opinion or coarse mapping in more than 60 % of developing countries. For many countries, apart from other sources of data such as detailed mapping, country-wide field sampling and general mapping, forest estimates seemed to be the only data available. Generally, the tree resources outside designated forest areas were not assessed.

In Malaysia, when the forests are ready for harvesting, the FD will issue logging licenses which are given annually. The most important activities during the licensing process are the demarcation of the logging boundary by the District Forestry Officer (DFO) and field inspection of the proposed logging area. The field inspection by the DFO includes field inventory, map creation and vegetation mapping. This forms part of the pre-F process. The fieldwork undertaking in this context includes analysis of the timber resource (timber resource accounting), transfer details regarding the delineation of the forest to be logged on to a map (with the geographical coordinates of the boundaries and the species used in boundary delineation), other land-use conflicts and commitments imposed by the Government, and information on the history of logging in the region. In Peninsular Malaysia, this work is carried out by the FD.

At the same time, the licensee prepares a forest harvesting plan, which includes the road and skid trail plan, the levels of manpower to be employed, the nature of the equipment to be used in the operation, and a list of all the trees that are to be logged. FD rangers subsequently mark all of the trees that are scheduled to be felled. This is checked by the DFO. Finally, the State Director of Forestry has to approve the harvesting plan before the licensee can log. The license also specifies the cutting limit for species.

All of the activities outlined above are required for logging in PRF, some are also required for logging in agricultural and State land-conversion forested areas. The primary reason for conducting detailed timber accounting at the outset is to ensure the full capture of rent from the logging operations for the State treasury. A further reason is to ensure that there is the necessary and adequate regeneration of the forest and that the productive capacity of the forest is not impaired. In doing so, it safeguards the forest ecosystem and environmental values. The preliminary data from the field also provide the basis for future monitoring and for legal enforcement once the license is approved (International Tropical Timber Organization, 2004b).

In Malaysia, pre-F inventory is carried out to obtain precise and up to date information which is very much needed in planning, managing and producing forest resources in a proper, complete and effective way as well as planning for long term development of the forest so that maximum benefits can be obtained sustainably. This has to be performed as prescribed by the Malaysian SMS on the study area one year before harvesting (Forestry Department, 1997). Although field sampling is more costly, certain information can only be obtained from the ground such as tree species, precise location and the tree diameter. Nevertheless, Thuresson (2002) demonstrated that field inventory with relatively low-intensity sampling can provide information useful for decision making, at acceptable cost.

Based on the results of the pre-F inventory and Equation 4.1, the estimation of net economic output from the forest can be derived. To maintain the pre-harvesting levels of tree species diversity, the net economic output has been determined to be in the range of $40\,\mathrm{m}^3$ to $50\,\mathrm{m}^3$ timber per hectare(Forestry Department, 1997). Besides that, the pre-F inventory could also evaluate the likely extent of the damage encountered after logging, such as soil erosion and site degradation based on the meteorological and topographic data collected. This helps in minimizing the environmental problem as stated in the **RIL** concept.

Reduced Impact Logging (RIL) aims to minimize any environmental problems caused by harvesting. There are still problems encountered after logging, however, such as soil erosion and site degradation. In measuring these impacts, meteorological and topographic data are important. These are required to evaluate the likely extent of the damage. Pre-F inventory not only serves this purpose, but also aims to produce net economic output in the range of $40\,\mathrm{m}^3$ to $50\,\mathrm{m}^3$ timber per hectare, while maintaining pre-harvesting levels of tree species diversity (Forestry Department, 1997).

In this chapter, spatial data on forests in the Bubu Forest Reserve are acquired, including information on forest boundaries and the boundaries of forest compartments and logging blocks. These data have been determined by the State Forest Department. The spatial data also contains information on geographical features, such as terrain slopes, contours and hydrological features (i.e. rivers and other water courses). Logging roads, skid trails and *batau* (timber loading areas) are not present, however, in this study area. Moreover, data on the previous history of the forest compartments, including pre-F, felling (F) and post-F inventories, do not exist. Consequently, an inventory was conducted for all trees $> 15\,\text{cm}$ DBH (or 1.43 m in height) within the pre-F plots. The DBH and taxonomic information (species, genus, or family) about each of these trees was recorded. A unique tree identification code, established by the Malaysian Forest Department, is also assigned to each tree (Unit Pengurusan Hutan, 1996). In combination, a comprehensive set of details (i.e. inventory plots, stand density or stocking, number of trees, volume and the basal area for all trees) are recorded for the forest. Information on stand volume and the spatial distribution of the trees to be harvested is essential to plan harvesting activities so as to minimize the impact of logging and to extract efficiently the timber from the forest (Malaysian Timber Council, 1997). A corresponding inventory, known as the post-F inventory, is typically conducted to collect data following harvesting. The intention of the post-F inventory is basically to gather information on residual stand volume. The post-F inventory also aims to identify any environmental damage caused by the logging and to determine the appropriate silvicultural treatments needed to ensure the long-term sustainability of the area.

4.3 Determination of the Net Production Area (NPA)

Before harvesting can be carried out in PFE, the suitable area has to be demarcated. This area can be determined using several rules prescribed in the "*Panduan Penentuan Catuan Tebangan Tahunan Hutan bagi Negeri-negeri di Semenanjung Malaysia*". The NPA is the total forest area less roads and road reserves, rivers and buffer zones, protection areas, research plots and conservation areas (Malaysian Timber Council, 2001). In this study, two of these exclusion criteria are used, namely (i) rivers and their buffer zones and (ii) steep slopes, both of which are used to define protection areas. GIS software (ArcGIS 9^{TM}) is used to determine the NPA and to select harvestable trees. The locations of trees that will be marked for felling are determined in the GIS from the pre-F records. These data are vital because logging must be carefully planned to determine the appropriate harvesting limits and techniques to be used within the compartment (or logging block) based on estimated volume, topography and site degradation risk (Malaysian Timber Council, 1997). These data are kept in the form of a tree-marking map.

4.3.1 River

The river network in the Bubu FR was extracted from the available topographic maps; the corresponding catchment boundary was derived from the forest map provided by Perak State FD. Due to very large and detailed nature of the data collection involved in a pre-F inventory and the limited amount of time available for this study, however, a restricted area (10 ha) of the Bubu FR was selected for detailed analysis in this thesis. The river network within this study area is obtained by intersecting the river network for the whole of the Bubu FR with the boundaries of the study area. Therefore, there are only two rivers on the map shown as crossing the study area, one in the north and the other in the south of the study area. The one in the north rises 0.2 km while the south rises 0.26 km to the east. In the SMS, logging activities are prohibited near river bank for conservation purposes and to minimize soil erosion, therefore a 20 m buffer zone has been established around the river network (Figure 4.1).

4.3.2 Slope

The purpose of production forests within the PRF is to supply forest products economically. These products are required for agricultural, domestic and industrial purposes, and for export. At the same time, protection forests ensure favourable climatic and physical conditions, by safeguarding water resources, soil fertility and environmental quality, by preserving biological diversity and by minimizing damage caused to rivers and agricultural lands by flooding and erosion (Naáman, 2002). In this context, it is worth noting

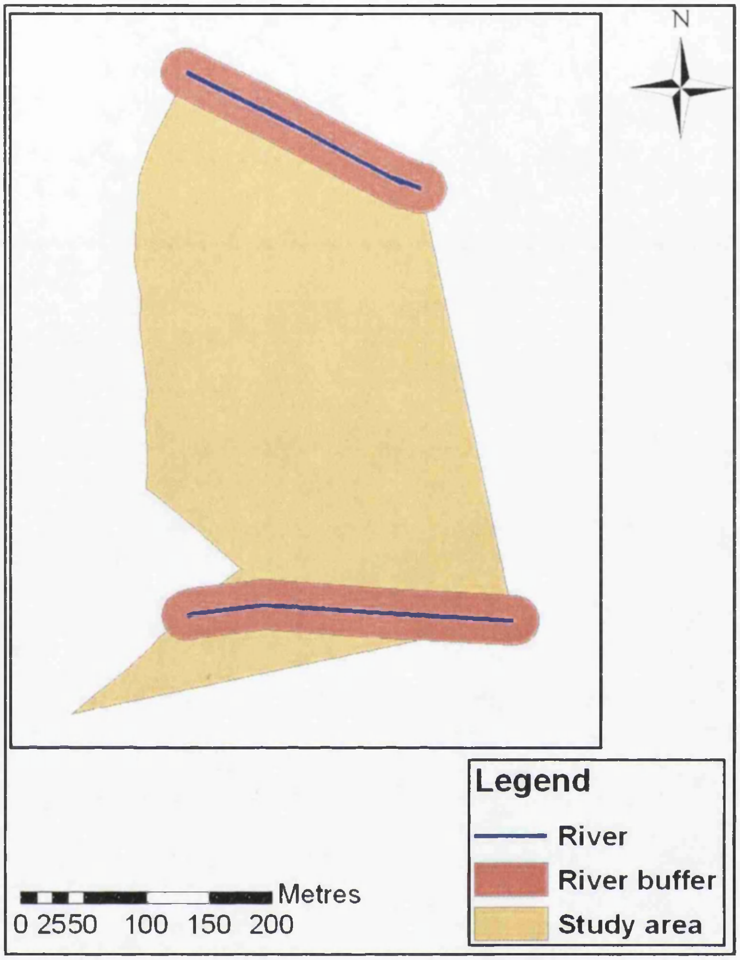


Figure 4.1: River buffer zones.

that forested areas greater than 1000 m ASL or which exceed 40° of slope are gazetted and cannot be harvested. Even so, there are some production forests that include small areas of terrain with gradients greater than 40° because of the practicalities of delineating these areas (International Tropical Timber Organization, 2004b). Machines are needed to haul logs from the point where they are felled to the roadside, where they are loaded into trucks for further transportation. The use of machinery depends on the slope of the ground. High slopes require the use of cable logging (towers), while less-steep grounds are handled using skidders (tractors). Access roads which are usually quite short are needed to connect the existing road network with the points where machinery is installed

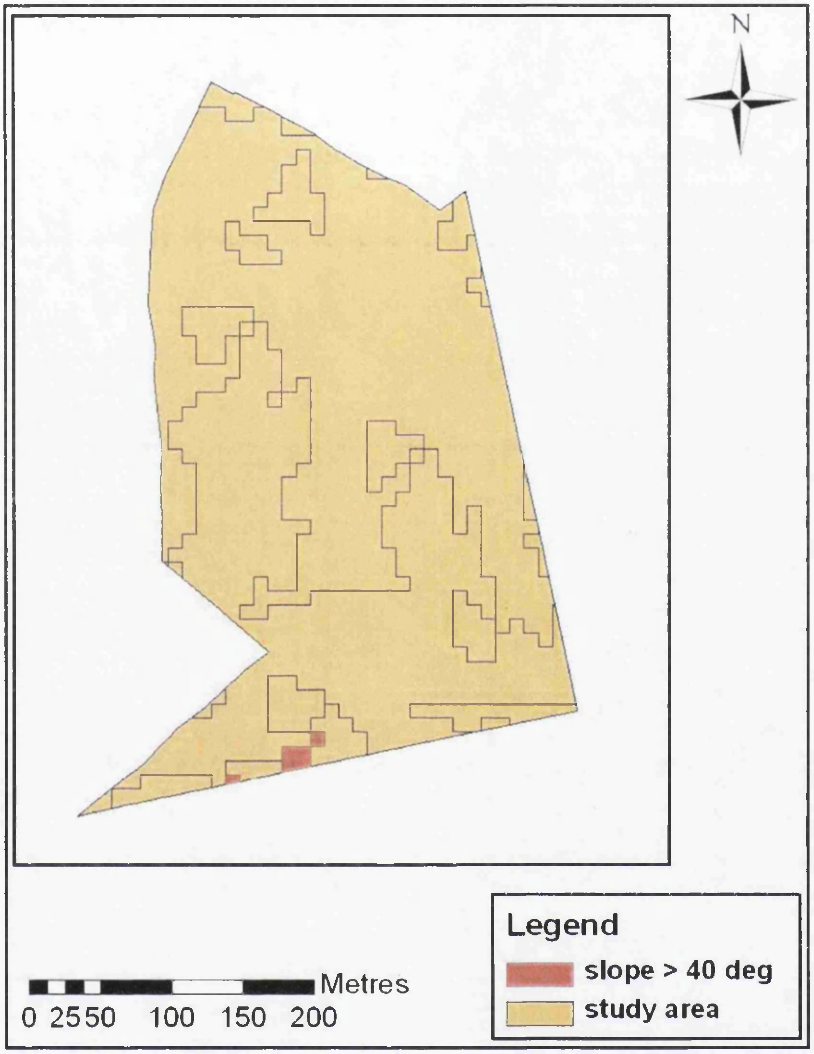


Figure 4.2: Terrain with a gradient exceeding 40°

(Legues et al., 2007). In this chapter, terrain gradient is obtained from the topographic map data (i.e. the contour data) and subsequently grouped into five classes: 0°-10°, 10°-20°, 20°-30°, 30°-40° and > 40°. According to the SMS, no harvesting should be carried out on slopes greater than 40°. In determining the NPA, therefore, these area are excluded from further analysis (Figure 4.2).

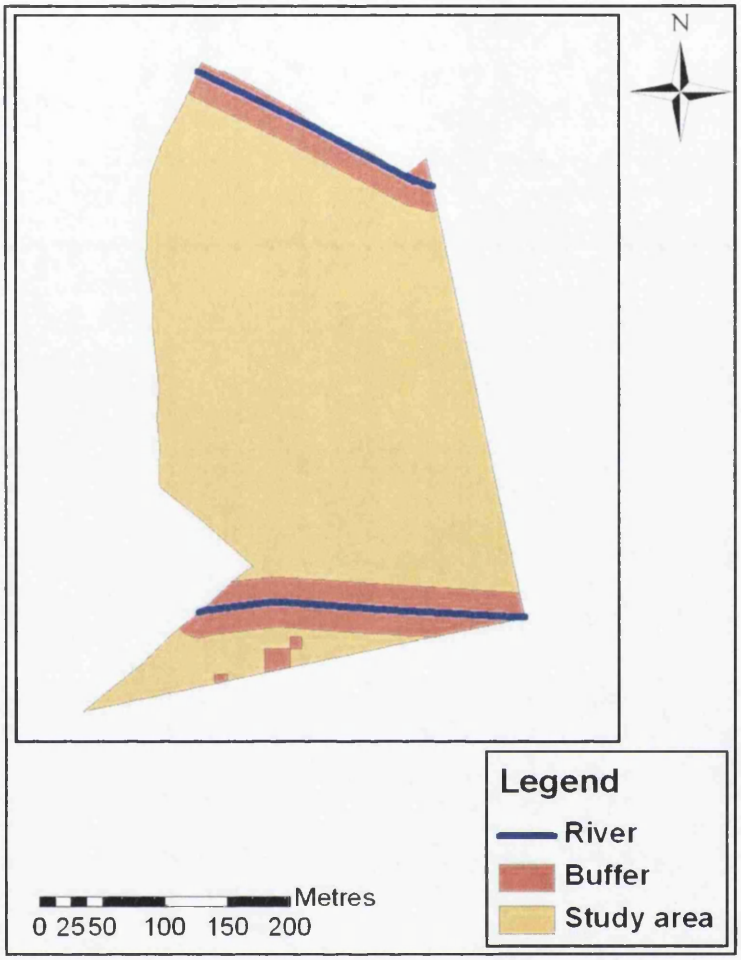


Figure 4.3: Derived Net Production Area (NPA) (areas other than those coloured pink).

4.3.3 The Net Production Area (NPA)

Forest areas suitable for logging are known as the NPA, which can be defined as the total forest area where trees can be harvested after eliminating protection and conservation zones. Protection areas include rivers, slopes steeper than 40° and riparian buffers. Conservation areas include areas where the trees have to be retained for special purposes (i.e. mother trees (trees that produce seeds), seed trees, tree species in danger of extinction and medicinal trees). In this study, two related parameter were used to determine the NPA which have been discussed in 4.3.1 and 4.3.2. These two parameters are merged and became area that have to be conserved which is red in Figure 4.3. Hence, trees found

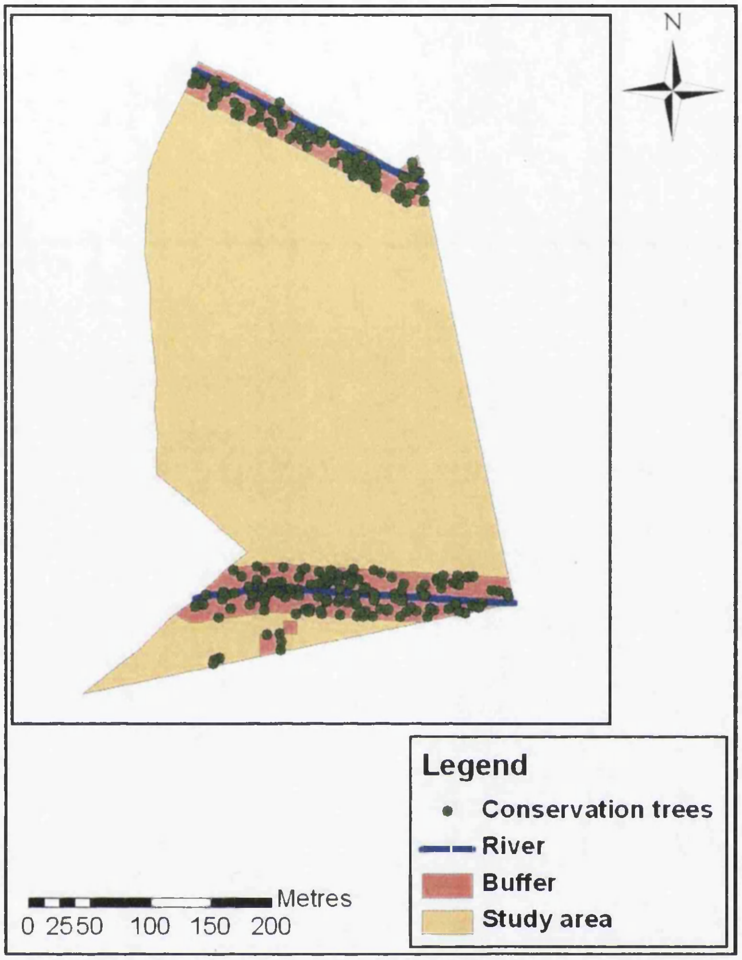


Figure 4.4: Locations of the conservation trees.

in this area are considered conservation trees which amounted to 221 and are prohibited from logging regardless of the spp. or diameter as shown in Figure 4.4. Areas outside the conservation area is regarded as NPA and generally the NPA trees (Figure 4.5) are allowed to be logged. The number of NPA trees in this study area is 1439.

4.4 Selection of trees to be harvested/trees removal

There are several rules that have to be implemented when selecting the trees that can be harvested within the NPA. These rules are as follows:

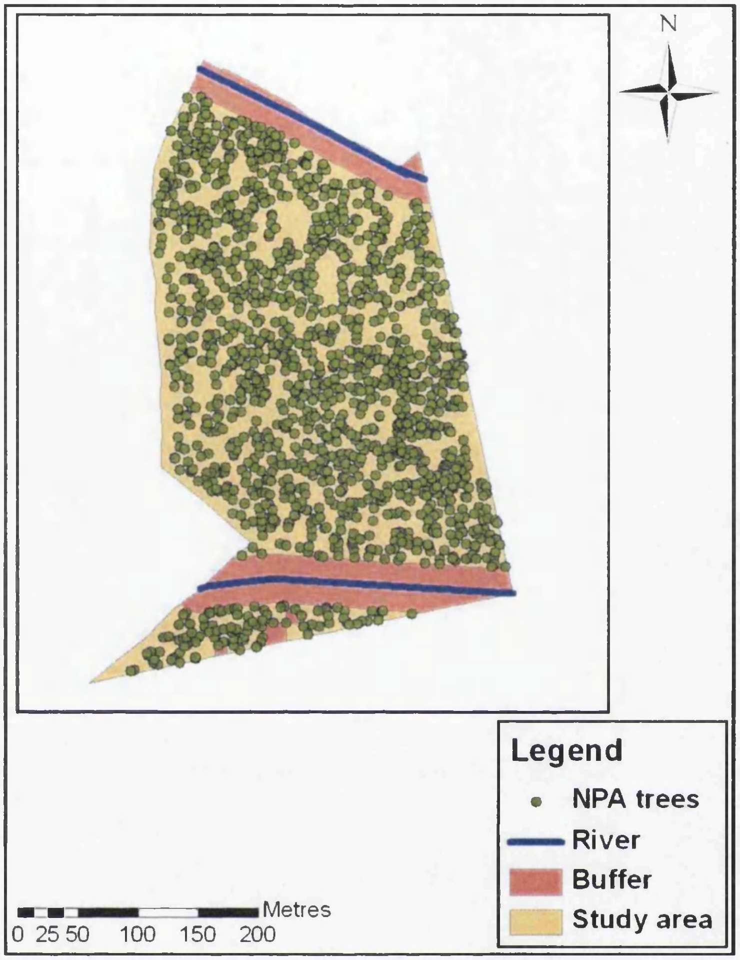


Figure 4.5: Net Production Area (NPA) showing locations of potentially harvestable trees.

1. The cutting limit for dipterocarp spp. is trees that are equal to or greater than 50 cm DBH, except for *Neobalanocarpus heimii,* for which the cutting limit is 60 cm DBH;
2. The cutting limit for non-dipterocarp spp. is equal to or greater than 45 cm DBH;
3. The residual stand must contain at least 32 sound commercial trees in the 30 cm to 45 cm diameter class per hectare;
4. The difference between the cutting limits prescribed for the dipterocarp and non-dipterocarp species must be at least 5 cm; and

5. The percentage of dipterocarp spp. in the residual stand for trees of 30 cm DBH and above must not be less than that in the original stand (Forestry Department, 1997).

Note, also, that under SMS, subsequent harvesting phases are predicted to occur 25 to 30 years after the preceding one with a net economic gain of $30\,\mathrm{m^3ha^{-1}}$ to $40\,\mathrm{m^3ha^{-1}}$, which consists of dipterocarp spp.

4.4.1 Standard tree-cutting regime

Normally, biologists and foresters do not identify all trees in a stand to the species level. In Malaysian forestry, however, every tree is usually identified using a species code, primarily because the pre-F inventory is concerned with setting cutting limits and assessing the timber volume of trees for economic purposes. The tree species codes therefore provide an accurate estimate of stocking densities and tree volumes for the trees of commercial interest. At the same time, these codes can be used to provide estimates of the residual forest cover after the commercial species have been harvested (Potts et al., 2005). During pre-F inventory, the diameter of every tree within the pre-F plots is measured. In addition, all trees are identified to the appropriate taxonomic level (species, genus or family) and a tree identification code established by the Malaysian Forest Department is recorded for every tree (Potts et al., 2005).

Altogether, there are 144 dipterocarp trees and 1516 non-dipterocarp trees in the study area. When overlaid with the NPA area, it is evident that a maximum of 130 dipterocarp trees and 1309 non-dipterocarp trees can be logged. Application of the minimum cutting limit determined by the SMS, however, reduces these figures to 344 and 49 trees, respectively. The selected trees are identified in Figure 4.6.

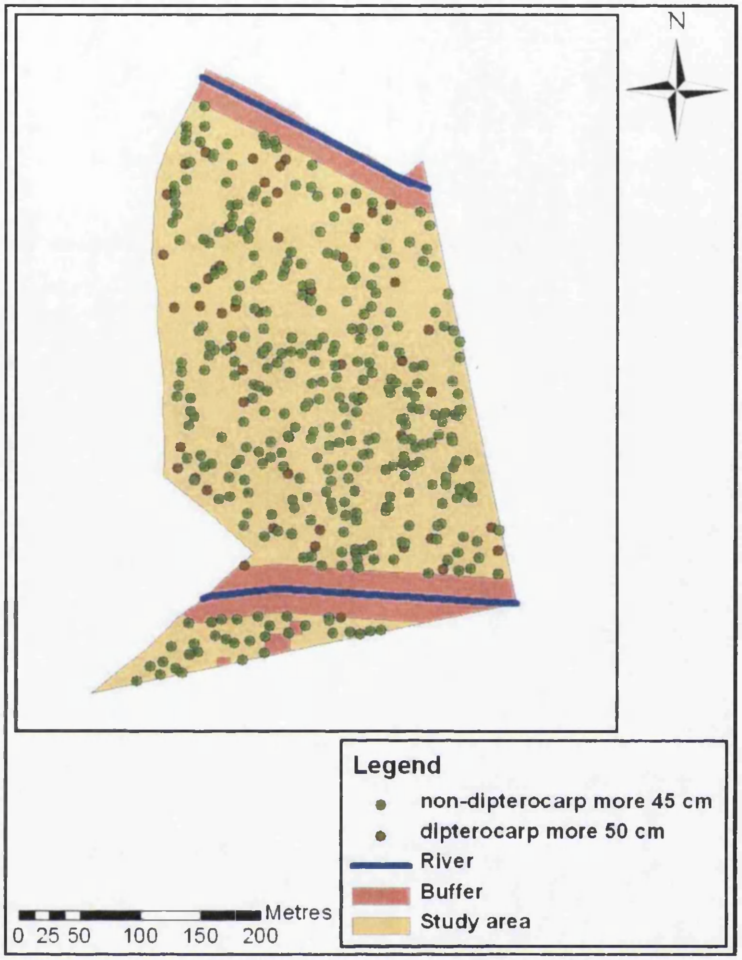


Figure 4.6: Standard cutting-limit trees

4.4.2 Proposed tree cutting regime

The minimum cutting limits prescribed by SMS can be modified somewhat by the foresters according to local conditions, depending on the richness or poorness of the forest. If the forest is considered to be relatively "rich" in species, usually determined by the net volume extraction per hectare and the net number of trees per hectare in the residual stand, the cutting limits can be raised (Forestry Department, 1997). The advantage in doing so is that in the future the forest will be more mature because the trees that are left behind are older than if the forest had been harvested according to the standard cutting limit. On the other hand, the cutting limits can be reduced if the forest is considered to be relatively "poor". This should only be carried out, however, if there is a really pressing need to do so, and even then the harvesters should only consider trees in the 15 cm to 30 cm diameter class range. More generally, it is preferable not to lower the cutting limits as the cutting cycle must then be lengthened to 44 years. The decision to raise or lower the cutting limit is usually determined by the District Forest Office based on information obtained from the pre-F inventory. For the forest compartment in the study area, the cutting limits have been raised to 65 cm DBH for non-dipterocarp species and 70 cm DBH for the dipterocarp species. The selected trees are then extracted in the same way as that used in the standard tree-cutting regime (section 4.4.1), and the results are shown in Figure 4.7. There are 174 non-dipterocarp and 27 dipterocarp trees, amounting to a total of 201 trees, that can thus be harvested in the study area.

4.4.3 Residual trees

After taking into consideration a range of factors that cause damage to the forest during harvesting, the SMS also prescribes that 32 sound commercial trees per hectare in the range 30 cm to 45 cm DBH must be be retained in the residual stand for the subsequent cutting cycle. These trees have to be mapped and their locations precisely determined in the forest harvesting plan, which can then be used to monitor the harvesting operation. The first step in this process is to select the dipterocarp and non-dipterocarp trees from the NPA trees. The second step is to extract from these groups trees in the range 30 cm to 45 cm DBH. As a consequence of applying these rules to the study area there are 436 residual trees (Figure 4.8), of which 411 are non-dipterocarp and 25 are dipterocarp.

4.4.4 Percentage of dipterocarp spp. in the residual stand

An important criterion in the operation of the SMS is that the percentage of dipterocarp spp. trees in the residual stand of 30 cm DBH or greater should not be less than that in

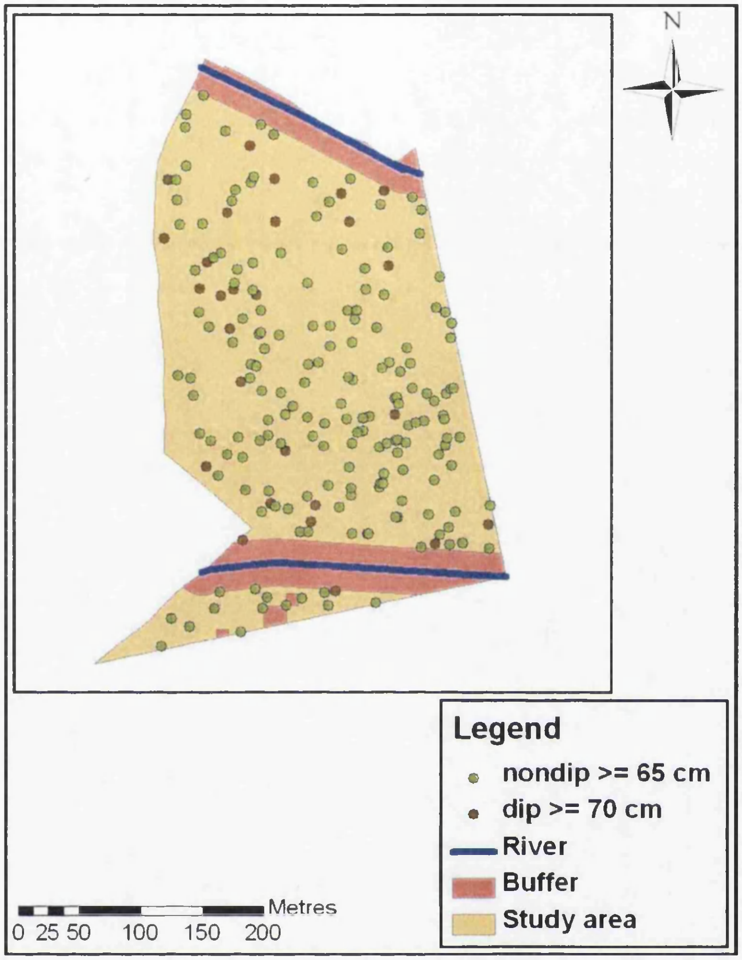


Figure 4.7: Raised cutting-limit trees

the original stand. In the study area, the percentage of dipterocarp spp. in the stand prior to harvest is 6.02 % (100 out of the total of 1660 trees are dipterocarp). After harvesting, during which 27 dipterocarp trees are logged, the number of dipterocarp trees in the residual stand is 73, while the total number of trees remaining is 1459. Hence, the percentage of dipterocarp in the residual stand is 5 %. This percentage is lower than that in the original stand.

The easiest way to solve the problem is to modify the number of dipterocarp that are harvested. Instead of cutting 27 dipterocarp trees, only 11 trees are logged, which means number of dipterocarp trees left after harvest is 89, in which case the number of

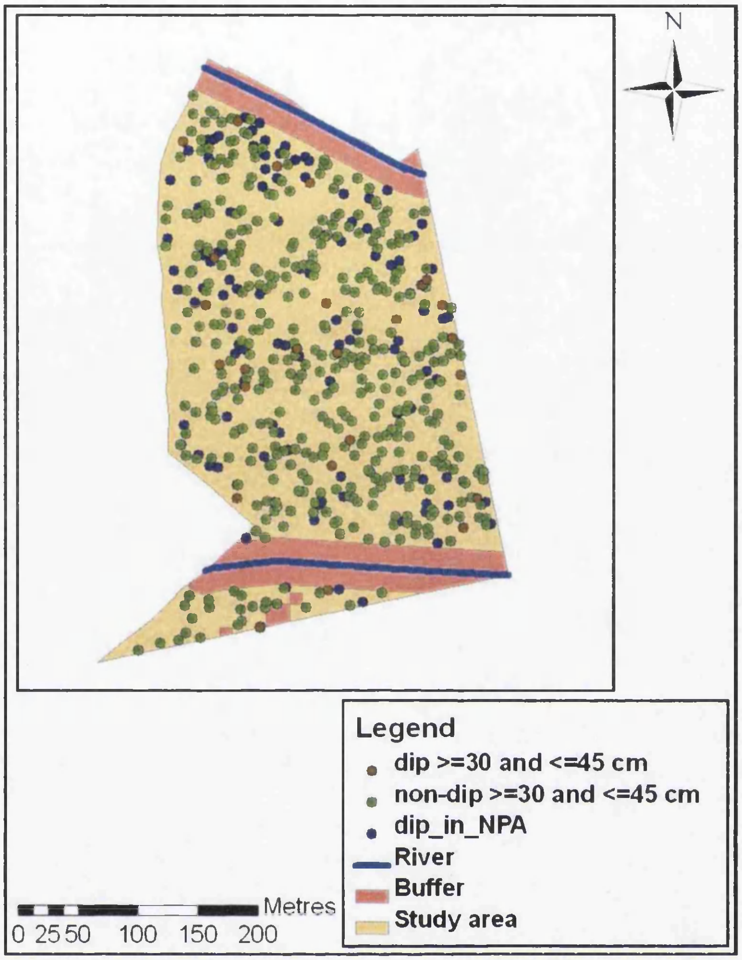


Figure 4.8: Residual trees

trees remaining becomes 1475. This increases the percentage of Dipterocarp spp. in the residual stand to 6.03 %, meeting the requirement of the SMS. All the results in this subsection are shown in Figures 4.9 to 4.11.

4.4.5 Maximum volume extraction

According to the SMS, tree removal should account for no more than 40 % of the standing volume, or approximately 30 $\mathrm{m^3 ha^{-1}}$. The gross maximum timber volume extraction can be calculated from Equation 4.1:

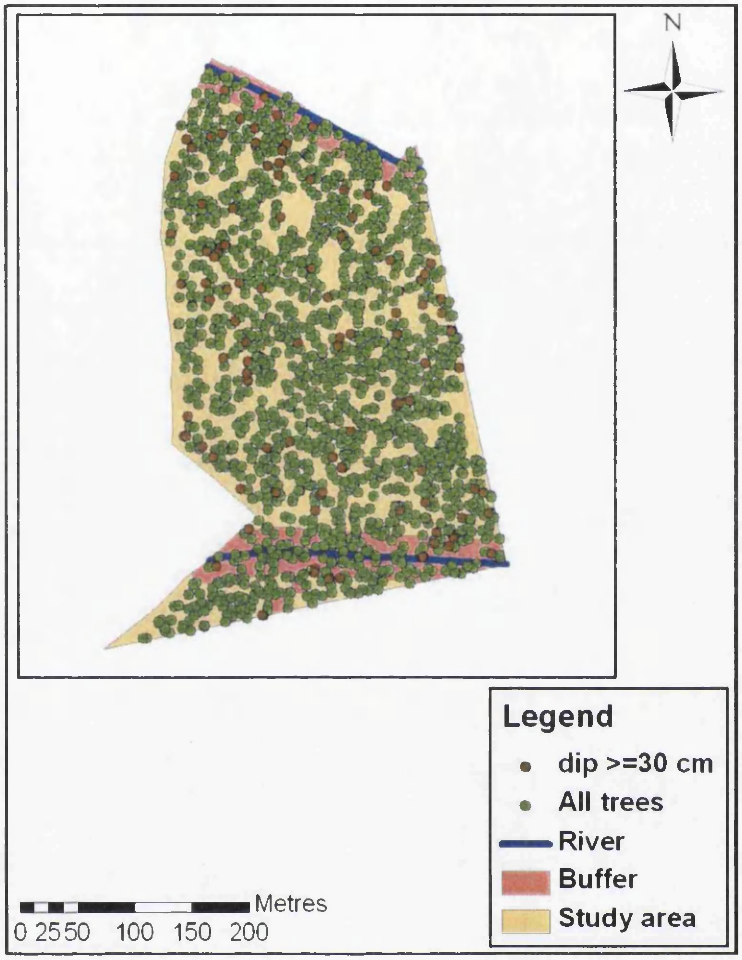


Figure 4.9: Percentage of dipterocarp trees in original stand

$$v = \frac{\pi \times (\mathrm{DBH})^2 \times L \times f}{4 \times 10000} \tag{4.1}$$

where v is gross volume in $\mathrm{m^3ha^{-1}}$, DBH is diameter at breast height in cm, f is a form factor ($f = 0.65$) and L is merchantable (marketable) height (see Table 4.1). Two calculations based on different cutting-limits are explored here: one is for non-dipterocarp greater than 65 cm DBH; the other is for dipterocarp greater than 70 cm DBH. The results of both timber-volume extraction calculations are $32.36\,\mathrm{m^3ha^{-1}}$ and $37.53\,\mathrm{m^3ha^{-1}}$, respectively.

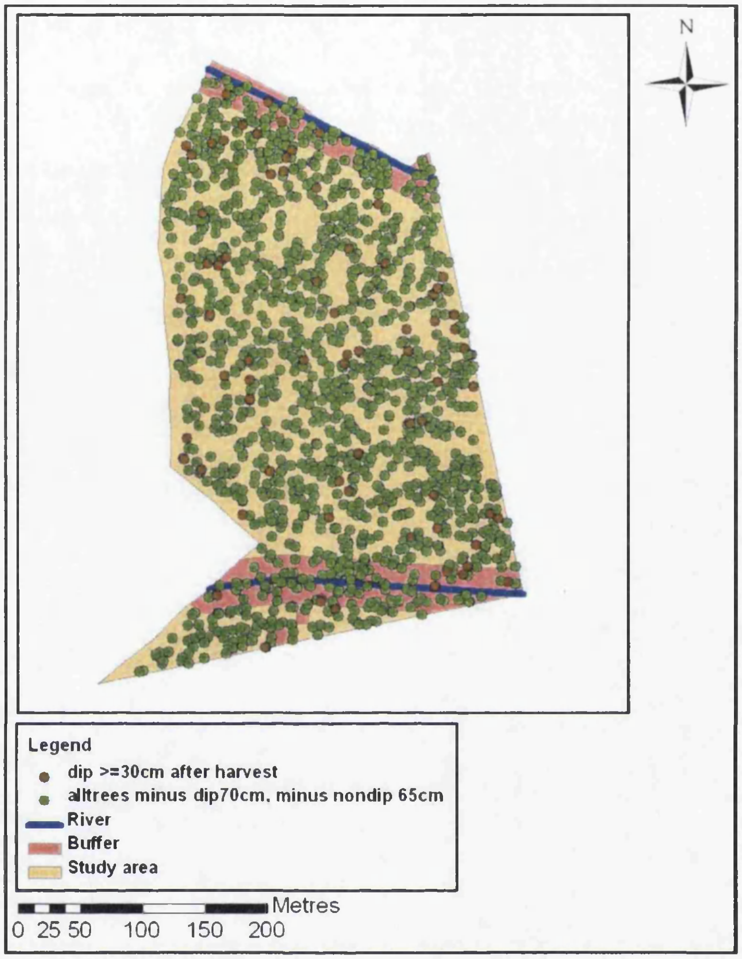


Figure 4.10: Percentage of dipterocarp trees after harvest

Table 4.1: Merchantable height. (Source: Forestry Department, 1997)

Diameter class	No. of timber 5 m long	Equivalent merchantable heights
30 cm– 60 cm	2	10 m
60 cm– 75 cm	3	15 m
>75 cm	4	20 m

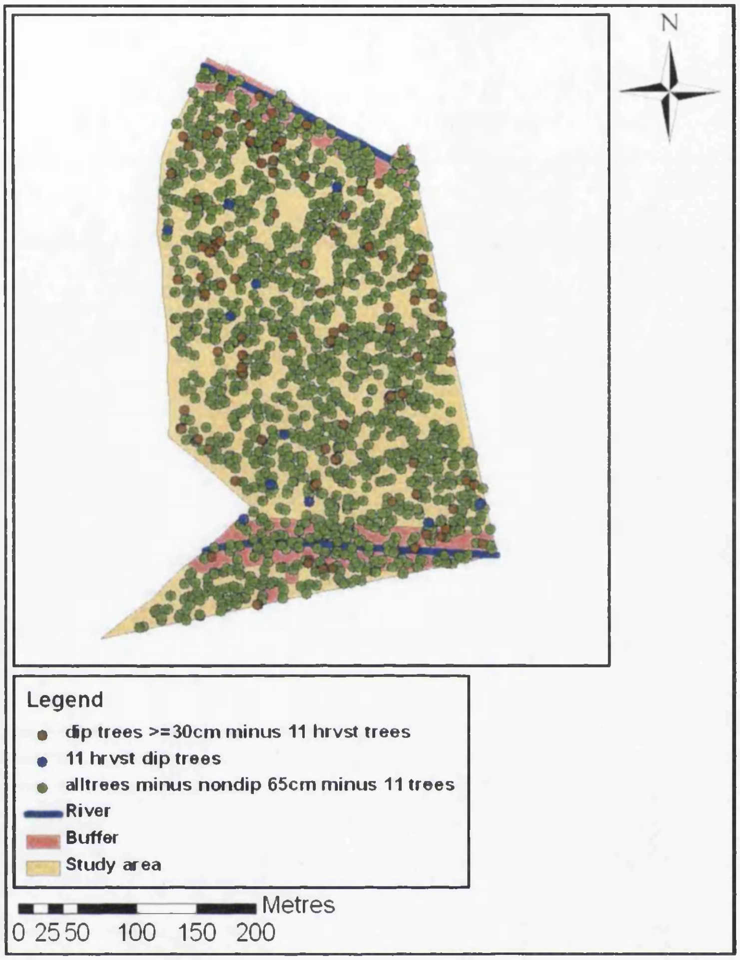


Figure 4.11: Percentage of dipterocarp trees after harvest with modification

4.4.6 Harvestable trees

All the operational criteria in the SMS have been applied using ArcGIS 9^{TM} and are presented in map form in various figures shown in this chapter. The results indicate that, for the 10 ha study area in the Bubu FR, only 185 out of 1660 (or 11 %) trees can be harvested within the SMS guidelines. These include 7.6 % dipterocarp trees and 11.5 % non-dipterocarp trees. The rest of the trees are kept for either environmental conservation or future regeneration.

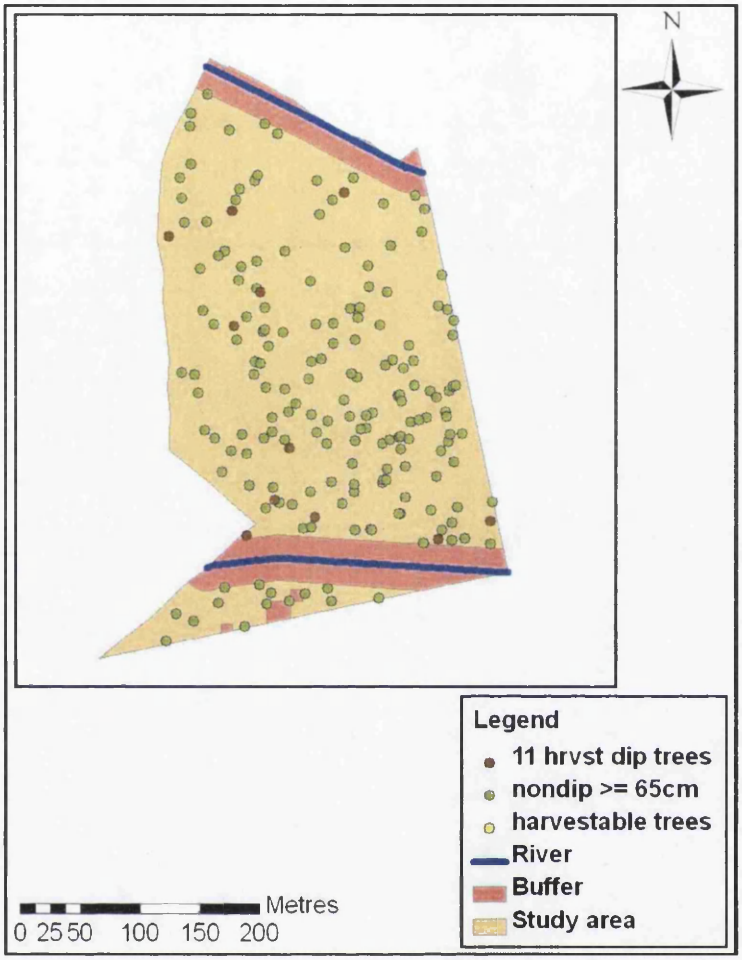


Figure 4.12: Harvestable trees

4.5 Analysis

The results of applying the SMS criteria using ArcGIS 9^{TM} have been discussed and presented in sections 4.3 and 4.4. Recall that the ultimate aim is to furnish the forest managers with a more precise, graphical and up-to-date decision-making process, which provides more accurate and consistent results than the conventional manual method. In other words, forest managers should, where permissible, be able to manipulate and change the criteria underlying the SMS and then run the process again to examine the new results. This would allow them to answer the "what if?" questions, which should increase the efficiencies of the management and planning of forest harvesting. In the next three subsections, an analysis is performed on variations in the allowable buffer zone distances, DBH cutting-limit values and maximum slope angles to demonstrate the potential of this approach.

4.5.1 Variation in the Buffer Zone Width

In this analysis, the river buffer distance is varied to examine the impact of this parameter on the NPA and, hence, the number of trees and volume of timber that can be extracted. In general, the relationship is expected to be broadly linear, because an increase in the width of the river buffer zone should reduce concomitantly the size of the NPA. The number of trees that can be harvested, however, might not necessarily change in a linear fashion, as this also depends on the spatial location of the trees within the stand which may also vary with respect to tree age and species (i.e. certain species may be preferentially clustered close to the rivers; also, older trees may perhaps be located closer to the rivers).

In this study, when the river buffer distance is reduced by 10 %, from 20 m to 18 m, the number of trees that can be harvested in the NPA is found to increase from 1439 to 1462 (i.e. by roughly 10 %) due to the increase in the NPA. Similarly the residual trees also increased to 436; however, the conservation trees are reduced from 221 to 198 (again, a reduction of approximately 10 %). These changes are shown in Figure 4.13.

There are two main benefits that arise from this brief analysis. First, rather than simply following standardized thresholds and criteria, the ability to examine "what if" scenarios of the type explored here would enable forest managers to determine acceptable thresholds, in this case for the river buffer, that could be adapted, perhaps within pre-defined limits, to local conditions, according to environmental circumstances or conservation purposes. Second, since harvesters cannot log to the precise limits specified in the SMS, but instead operate within reasonable tolerances (i.e. a 20 m river buffer plus or minus 2 m), the ability to examine the potential impacts of this uncertainty is extremely valuable.

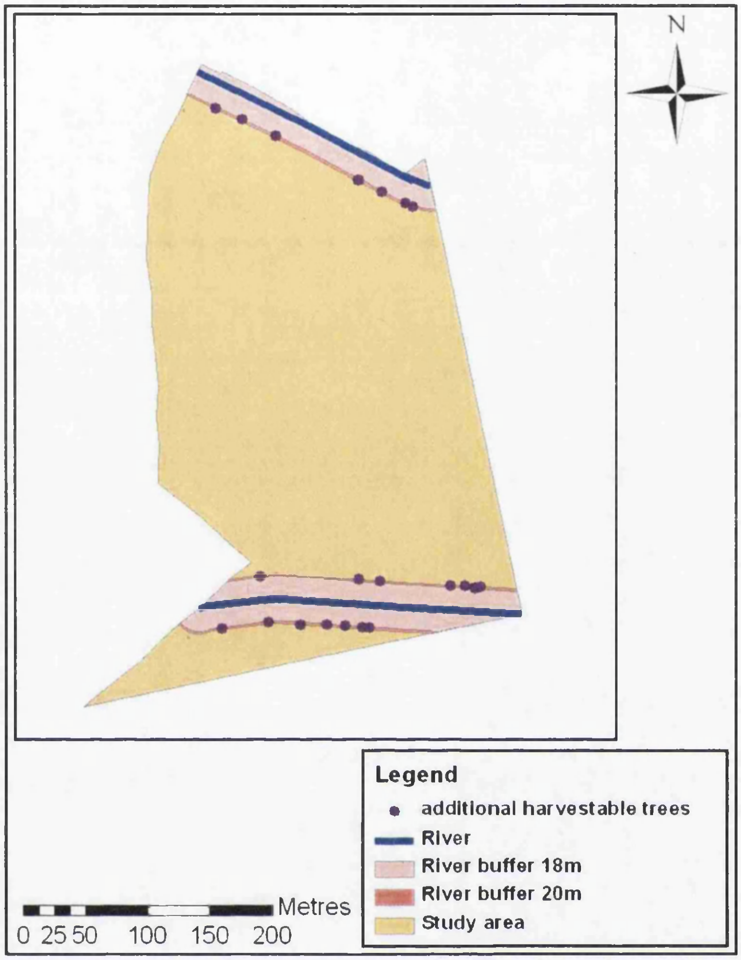


Figure 4.13: Results from buffer river change

4.5.2 Cutting limit

It is possible to perform an analysis similar to that described in the preceding section for the cutting-limits (defined in terms of DBH). Here, again, the purpose is to examine the impact of either latitude and/or uncertainty in the threshold criteria employed in the SMS guidelines; i.e., what would happen if the cutting limits were raised or reduced in response to local conditions, or due to imprecision/uncertainty in their application in the field by the forest loggers. Rather than simply modifying the thresholds, however, it is instructive to examine the absolute and cumulative frequency distributions of different tree sizes (DBH) within the study area, partly to establish whether there are any obvious break-points in the

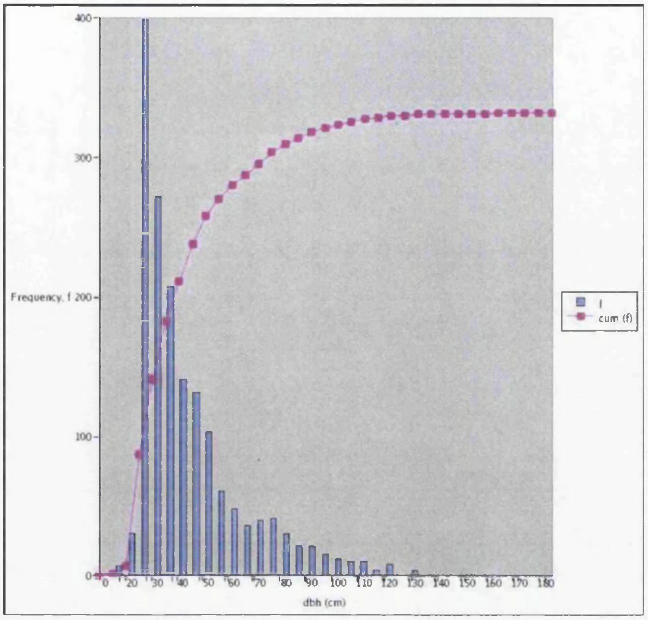


Figure 4.14: Absolute and cumulative frequency distribution of DBH for all trees in the study area. (Source: Author, 2007)

distributions, and partly to get an overall indication of the likely impact of changing the SMS thresholds.

Three DBH distributions are examined here, namely: (i) all trees; (ii) non-dipterocarp species; and (iii) dipterocarp species only. The data are derived from the detailed pre-F inventory of the study area. The results are presented in Figures 4.14 to 4.16. All three figures exhibit a negatively-skewed tree-size distribution, as might be expected, with larger numbers of small diameter trees and relatively fewer larger ones. This could probably be related to the study area having been previously logged as compared to the distribution of an undisturbed forest in as shown in Figure The small number of very small diameter trees in each instance is likely to be due to the fact that many seedlings are generally not surveyed or recorded in the pre-F inventory. Because of the relatively small total number of dipterocarp trees in the study area, the absolute frequency distribution for this plot is somewhat more 'spikey', but the overall distribution is similar.

Examining these plots in greater detail, one notes that the bulk of all trees and non-dipterocarp trees lies in the range from 20 cm to 50 cm DBH. This shows that there are

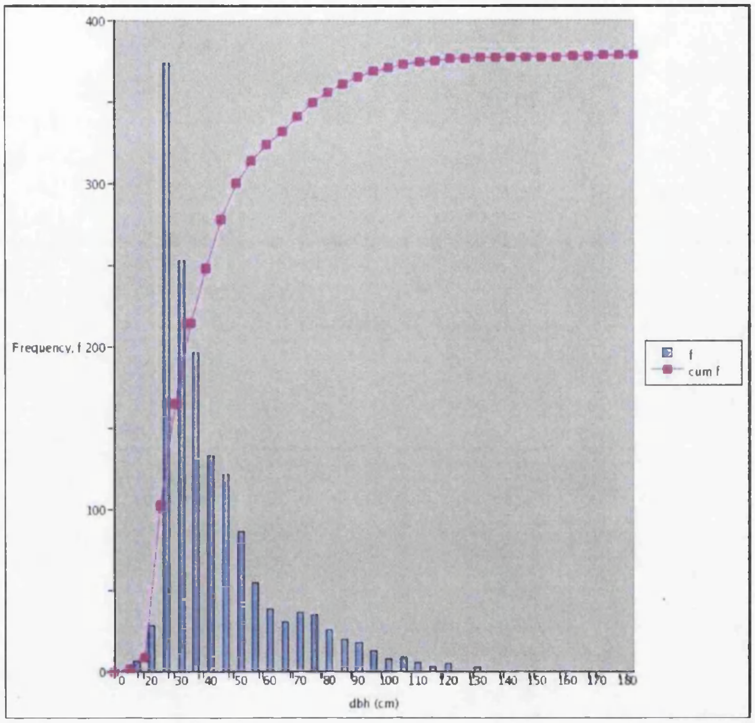


Figure 4.15: Absolute and cumulative frequency distribution of DBH for non-dipterocarp trees in the study area. (Source: Author, 2007)

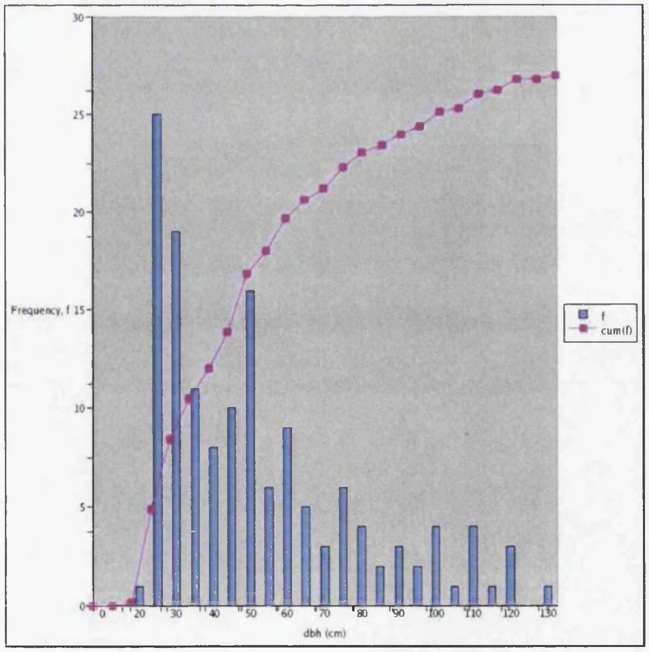


Figure 4.16: Absolute and cumulative frequency distribution of DBH for dipterocarp trees in the study area. (Source: Author, 2007)

lots of small and young trees in the study area. In fact, it can be shown that these small trees make up more than 75 % of the total number of trees in the study area. The existence of these trees and the relatively few dipterocarps could probably be related to the study area having been previously logged because all big dipterocarps trees would have been removed during the logging. Comparing this to the distribution for an undisturbed forest like in Semangkok Forest Reserve, Selangor, Peninsular Malaysia, as shown in Figure 4.17, huge amount of small trees are in the range from 10 cm to 30 cm DBH.

What this implies is that a relative small change in the cutting-limit threshold in or around this range is likely to have a significant effect on the number of trees that can be felled. This, in turn, means that the forest harvesting system is likely to be especially sensitive to the particular threshold values that are selected, and that variation in, or uncertainty/imprecision with respect to, this threshold is likely to induce major changes in the amount of timber harvested and the number of trees remaining. This parameter is therefore likely to be one that an automated or computer-augmented management system might be able to give greatest guidance on to the forest managers and loggers. By contracts, the number of trees above 50 cm DBH declines rapidly with increasing DBH. This, naturally, reflects the fact that there are not many older and bigger trees, especially one exceeds 115 cm DBH.

4.5.3 Slope

In the final analysis of this section, the sensitivity to the maximum slope angle for which logging is allowed is examined by exploring the terrain slope-angle distribution within the study area. Since harvesting is prohibited on slopes greater than 40°, only slope classes from 0° to 40° are considered, with a class interval of 10°. Slopes greater than 40° are grouped together into a single slope class. Despite the relatively coarse nature of the resulting plot (Figure 4.18), the frequency distribution appears to be broadly normally distributed, with a slight negative skew. The modal class is 20°-30°. Note that 70 % of

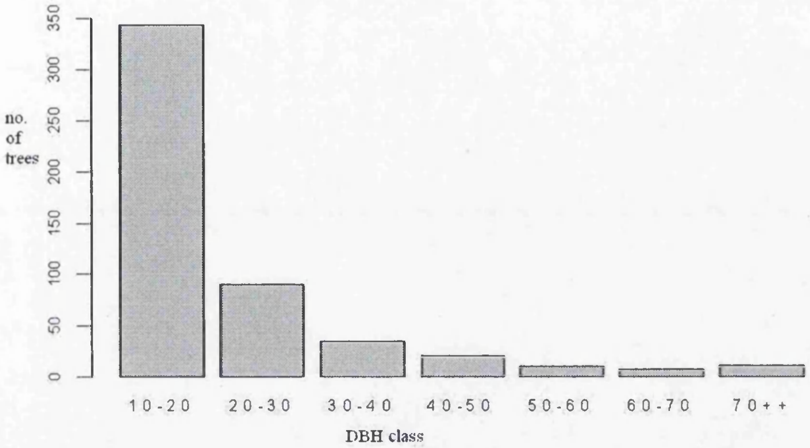


Figure 4.17: Distribution in 1 ha forest in Semangkok Forest Reserve, Selangor, Peninsular Malaysia. (Source: Niiyama et al., 1999)

the slopes in the study are fall between 10° and 30°.

From the distribution in Figure 4.18, it can be observed that if harvesting is prohibited from slopes greater than 40°, roughly 10 % of the study area will be unavailable for logging. If the forest managers decided to reduce the maximum slope angle from 40° to 30° then the conservation area will be increased to about 23 %, with a further reduction in economic gain of the same percentage.

4.6 Summary

This chapter discusses forest harvesting planning in Malaysia under the SMS guidelines. It also presents an application of these guidelines, performed within ArcGIS 9^{TM}, for a 10 ha study area in the Bubu FR. The chapter shows how the standard planning rules can be integrated to a GIS, which can be used by forest managers to plan, manage, monitor and assist their decision-making process and to estimate future forest resources. Adopted more widely across Malaysia, this approach could be used to assist the Country's timber production, both in economic and sustainable environmental terms, using cutting limits, buffer zone distances and other properties that are tailored to local conditions, leaving

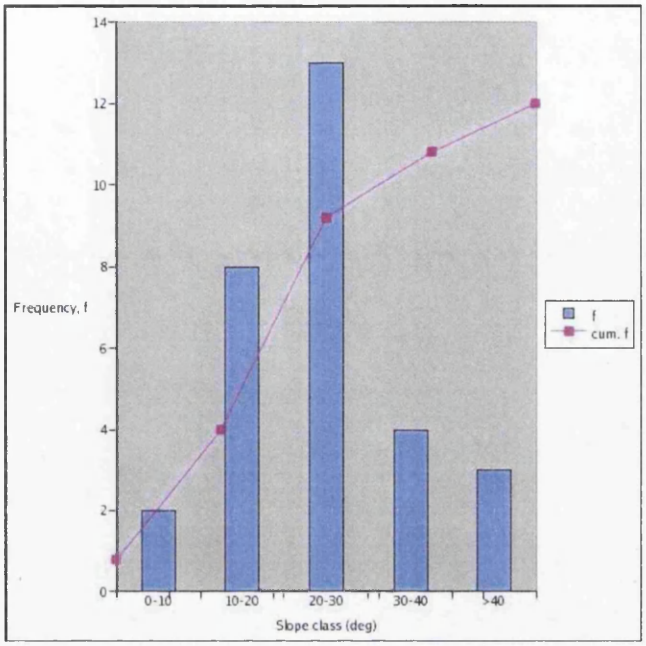


Figure 4.18: Frequency of slope distribution. (Source: Author, 2007)

an adequate number of medium-sized trees of marketable species future growth to commercial sizes. Moreover, enhancing the practice of selective harvesting in Peninsular Malaysia would ensure that the larger trees that remain would reach maturity in 20 to 30 years to allow for a sustainable second harvesting cycle.

Chapter 5

Predicting soil loss

Overview This chapter presents detailed technique of predicting soil loss using MSLE as well as derivation of the MSLE factors i.e. R, K, LS and VM factor. Once these parameters are obtained, the prediction of soil loss could be calculated. The calculation of soil loss is integrated with GIS software, ArcGIS^{TM}, hence the results are produced in map form. The selection of harvestable tree obtained from the previous chapter are then overlaid on the soil loss prediction map to ensure that no harvestable trees on high soil loss risk are selected. The soil flow direction are also determined to identify areas from which the soil erodes and where it deposits. Trees located on the area where the soil erodes should not be harvest as this will accelerate erosion. Knowledge on the soil flow direction also helps in optimization of forest road network which will be discussed in the next chapter.

5.1 Introduction

Problems of soil erosion have become a major concern in Malaysia and these are often associated with the process of deforestation. Studies on erosion in Malaysia have a long history, dating back to the 1960s when the development phase started, and still continue today as the country grows in terms of social and economic development. This development has resulted in many forest areas being cleared and converted to other land uses, such as agriculture, settlements/urban, and industry. While Malaysia is rich in terms of tropical rainforests, the nature and scale of changes to the forest soils brought about by forestry operations is very significant. Hence, to ensure the sustainability of forest soils, forest management operations should not, in the long term, exceed the capacity of the soil to recover by natural processes (i.e. erosion losses should not exceed soil formation rates and nutrient removals should not exceed nutrient inputs). Soil erosion and compaction, nutrient removal, and changes in organic matter content and soil water status are identified as the most important effects involved in the impacts of soil management (Worrell and Hampson, 1997).

In forested areas, the rates of soil erosion are generally expected to be higher in areas of steep terrain, although in certain circumstances there may be sufficient litter and exposed roots to impede overland flow. The impact of soil erosion is typically enhanced after a forest is logged, particularly when it is left exposed to heavy rains, which may wash away the litter, roots and top soil, and deposit them in nearby rivers and streams. The collorary of this is that forests tend to protect water resources by reducing surface erosion and sedimentation, filtering water pollutants, regulating water yield and flow, moderating floods, enhancing precipitation and mitigating salinity. Forests also prevent surface soils which are uncompacted from the impact of falling precipitation, which can sometimes result in accelerated erosion. One of the most effective protective functions of forests is to reduce soil erosion by water, which degrades water quality. Malaysia duly recognised this fact, which is reflected in the NFC, 1978 (Revised 1992) where the PFE is categorised into four major functional types, namely: protection forest, production forest, amenity forest and research and education forest. Protection forests ensure that the favourable climatic and physical conditions of the country are maintained, in addition to safeguarding water resources, soil fertility and environmental quality, conserving biological diversity and minimizing damage by floods and erosion to rivers and agricultural lands. These functions are further elaborated where all State Directors of Forestry in Peninsular Malaysia are required by law to classify further the PFE, particularly the protection forest, into one or more of the following functional uses:

1. timber production forest under sustained yield
2. soil protection forest
3. soil reclamation forest
4. flood control forest
5. water catchment forest
6. forest sanctuary for wildlife
7. virgin jungle reserved forest
8. amenity forest
9. education forest
10. research forest
11. forest for federal purposes (Food and Agriculture Organization, 1997).

The response of different terrain elements to soil erosion and mass wasting after selective logging can vary widely. Therefore the complexity of short-term and long-term impacts of logging operations needs to be identified and understood (Clarke and Walsh, 2006). Activities such as timber harvesting, litter collection, grazing in forest lands, and fires will also bare and compact the soil and hence reduce the protective role of forests. Again, this highlights the important role that forests play in Malaysia, not only in economic terms, but also in connection with environmental conservation. Although tropical forest resources are vast in Malaysia, they need to be managed effectively to ensure their future sustainability. Any effort to change the forest must consider the fact that forest resources are not only for timber production, but for other equally important protection functions, such as biological diversity conservation, water protection, environmental protection and other social needs. Thus timber extraction methods have a direct effect on the quality and sustainability of the environment, as well as the economic value of future forest stands. It is important, therefore, that proper planning and management be taken into consideration before any harvesting is carried out. Forest resources should be managed so as to maintain their multiple functions, including the protection of the national land, headwater conservation, conservation of the natural environment, recreation, minimisation of global warming, and provision of forest products (Fujisawa, 2004).

Many models and techniques have been developed to measure or assess the risk of soil erosion. In Malaysia, one of the most widely used is the USLE, which is applied mainly in the context of studies of agricultural land, hydrology, recreational facilities, and highway and urban construction. This technique is considered by many researchers to be one of the most useful tools for guiding soil conservation planning practices, and many efforts been carried out to adapt the underlying factor relationships to local conditions. The USLE has also had a major impact on soil conservation research. Apart from erosion processes research, modeling processes has became a major activity. Soil erosion research modeling has been perfected through the use of the USLE in farm planning and soil erosion control.

In this study, the MSLE is used to assess the potential risk of soil erosion in the study area. The MSLE is selected because it has been modified for use under similar environmental conditions to those exhibited by the study area, i.e. Malaysia's tropical rainforests. To quantify and map the soil erosion risk, GIS software is used to identify areas that are at potential risk of extensive soil erosion, and to provide information on the estimated value of soil loss at various locations. This analytical framework can also potentially provide answers to spatial queries such as whether the erosion is associated with specific factors (e.g. the loss of continuous vegetation cover). The soil flow direction of the soil loss is also investigate so that information on the likely accumulated soil losses and soil gains can be obtained.

5.2 The USLE and MSLE

With reference to Subsection 2.2.2.1, this section demonstrates the calculation of the MSLE factors for the study area as presented in subsections 5.2.1, 5.2.2, 5.2.3, 5.2.4 and the estimation of soil loss is presented in sub-section 5.2.5. The soil loss values are then loaded into ArcGIS™ so that the location of potential low and high soil erosion areas can be identified within the study area.

5.2.1 Rainfall Factor, R

The factor R is a quantitative expression of the erosivity of local average precipitation and runoff. It reflects the fact that soil erosion is greatly influenced by the intensity and duration of precipitation events and the resulting runoff. Equation 5.1 calculates R as a product of rainfall energy (total storm energy) and maximum 30 minute intensity, known as the Erosion Index 30 (EI_{30}), divided by 100:

$$R = \frac{E \times I_{30}}{100} \tag{5.1}$$

where E is the total kinetic energy for each storm ($\mathrm{J{\cdot}m^{-2}}$) and I_{30} is the maximum 30-minute rainfall intensity ($\mathrm{mm{\cdot}hr^{-1}}$).

On an annual basis, the EI_{30} value is the sum of values over the storms in an individual year. Values of EI_{30} used in Malaysia vary. For instance, Baharuddin et al. (1999) use $EI_{30} = 85$, the value estimated for Kuala Lumpur, because the study area is near to Kuala Lumpur. Nevertheless, in this study $EI_{30} = 75$ is used, as recommended by Wischmeier and Smith (1978) for tropical regions, on the grounds that the median raindrop size does not increase when I exceeds $75\,\mathrm{mm{\cdot}hr^{-1}}$.

Morgan (1974) suggests that the annual erosivity value, E, can be computed as follows

$$E = 9.28P - 8838.15$$

where E is measured in $\mathrm{J{\cdot}m^{-2}}$ and P is the annual rainfall. In the study area, the annual rainfall is approximately 4198.8 mm. This value has been derived by the author from rainfall records for the nearest rainfall station at Taiping Hospital, Taiping, Perak.

Consequently, the formula used to compute the rainfall factor, R, is as follows:

$$R = \frac{(9.28 * 4198.8) - 8838.15 * 75}{100 * 17.02}$$

$$R = 1327.56$$

5.2.2 Soil Erodibility Factor, K

The soil erodibility factor, K, quantifies the erodibility of local soils and depends mainly on the soil texture, structure, permeability and organic carbon content. This factor defines is the soil loss rate (per erosion index unit) for a specified soil as measured on a unit plot. Because the K factor reflects the susceptibility of a soil to erosion, soils that erode easily will have large K values, but never greater than 1. The K value can be estimated either using a soil erodibility nomograph (Wischmeier and Smith, 1978) or the formula given in Equation 5.2, below:

$$K = (2.1 \times 10^{-6})(12 - OM)M^{1.14} + 0.0325(S - 2) + 0.025(P - 3) \qquad (5.2)$$

where, OM is the organic matter (%), M is $\%\text{silt} + \%\text{very fine sand} \times (100 - \%\text{clay})$, S is a structural code and P is the permeability code: there are four soil structure codes and six soil permeability codes used in the MSLE, as shown in Table 5.1 and Table 5.2 respectively. In this study, to obtain an accurate result, the K factor was determined from

Table 5.1: Soil structure codes, S (Source: (Wischmeier and Smith, 1978))

Structure class	MSLE code
very fine granular	1
fine granular	2
medium or coarse granular	3
blocky, platy or massive	4

Table 5.2: Soil permeability codes, P (Source: (Wischmeier and Smith, 1978)

Permeability class	Permeability rate (cm·h^{-1})	MSLE code
very slow	< 0.2	6
slow	0.2 – 0.5	5
slow to moderate	0.5 – 1.5	4
moderate	1.5 – 5.0	3
moderate to rapid	5.0 – 15	2
rapid	15 – 50	1

field measurements input to Equation 5.2. Soil samples were collected from the study area and analyzed in the laboratory to obtain the organic matter content to be used in Equation 5.2. The analysis showed that the soil is derived from granite parent material. It has a coarse sandy clay texture. Soil of this nature can be classify as erodable due to its coarse nature (depending on the slope and forest coarse). Least erosion is expected under undisturbed forest and serious to very serious erosion or landslides may occur if the area is clear-felled. Bringing all of this information, the soil erodibility factor, K, is estimated to be as follows for the study area:

$$K = (2.1 \times 10^{-6})(12 - 0.53)1568^{1.14} + 0.0325(3 - 2) + 0.025(3 - 3)$$

$$K = 0.138$$

5.2.3 Length and Steepness of Slope Factor, *LS*

The *LS* factor combines the slope gradient and the length of eroding surface into a single factor, which can be calculated from Equation 5.3.

$$LS = (\lambda/22.13)^m(0.065+0.046S+0.0065S^2) \tag{5.3}$$

where, λ is the slope length (m), S is the slope gradient (%), m has value of 0.2 for $S < 1$, 0.3 for $1 < S < 3$, 0.4 for $3 < S < 5$, 0.5 for $5 < S < 12$ and 0.6 for $S > 12\%$. To obtain λ and S, the following formula are used:

$$\Delta z = z_{\mathrm{max}} - z_{\mathrm{min}} \tag{5.4}$$

(where, Δz is the elevation difference, z_{max} is maximum elevation and z_{min} is minimum elevation. Consequently,

$$\lambda = \sqrt{(\Delta x^2 + \Delta z^2)} \tag{5.5}$$

and where Δx is the distance on the ground between the minimum and maximum elevation points. Similarly,

$$S = \left(\frac{\Delta z}{\Delta x}\right) \times 100(\%) \tag{5.6}$$

During inventory, the study area is divided into uniform grid cells of 5 m × 5 m which are similar to raster-based GIS, therefore, the implication is that the study area contains a number of slopes that are likely to give different responses to soil erosion, which depend on the local *LS* factor. Generally, soil erosion increases with increases in slope gradient (*S*) and slope length (*L*), owing to an increase in the velocity and volume of surface runoff. A single value of the *LS* factor for the study area as a whole cannot simply be calculated from the Equation 5.3 because, unlike the R, K and VM factors, it varies spatially according to the local topography. This means that the 5 m × 5 m plots or 25 m^2 grid cells each has an individual local values of *LS* factors. However, if this gridcells size is to be used to calculate the *LS* factor, there are insufficient representative elevation points and therefore the calculation of *LS* factor using Equation 5.5 could not be calculated. To solve this problem, these grid cells have to be further divided into smaller grid cells. Various DEM raster resolutions for these cells have been considered, including 20 m, 10 m, 5 m, 2.5 m and 1.38 m. In the end, the most appropriate resolution was deemed to be 2.5 m for two reasons: (a) it represents an acceptable compromise between data volume and the accuracy of the DEM and (b) it nests within the smallest inventory plot size, 5 m × 5 m, used in this study. Therefore, the grid cells of 5 m × 5 m are divided into smaller 2.5 m × 2.5 m grid cells.

As a result of the spatially-explicit nature of the *LS* factor, soil loss calculations have to be carried out within ArcMap$^{\mathrm{TM}}$. First of all, as mentioned before, the DEM has to be acquired before the *LS* factor can be calculated. However, the DEM cannot be generated directly from contour in ArcMap$^{\mathrm{TM}}$. There are few stages of procedure that have to be carried out first, before the DEM can be generated and from which the *LS* factors can be derived. The stages of procedures are shown in the flow chart in Figure 5.1.

In ArcMap$^{\mathrm{TM}}$, a contour map of the study area (Figure 3.1) is used to create TIN as shown in Figure 5.2. Since the TIN is in vector format, it has to be converted into raster format, the result of which is shown in Figure 5.3. Nevertheless, it is not easy to extract individual elevation points from raster in ArcMap$^{\mathrm{TM}}$. Therefore, a program to extract and process the elevation points from the raster was created using Gawk programming in the GNU/Linux$^{\mathrm{TM}}$operating system. Since Gawk only handles American Standard Code for Information Interchange (ASCII) text files, not binary data files, the raster file had to be exported to ASCII file first. The Gawk program used to manipulate the resulting ASCII text file is presented in Listing 5.1. The algorithm used in this study is based on 2.5 m ×

Listing 5.1: Gawk program script to extract elevation points from the raster

```
BEGIN{
   col=0;
   row=0;
}

{
   if(NR==1){
      ncols=$2;
   } else if(NR==2){
      nrows=$2;
   } else if(NR==3){
      xllcorner=$2;
   } else if(NR==4){
      yllcorner=$2;
   } else if(NR==5){
      cellsize=$2;
   } else if(NR==6){
      nodata=$2;

      ytlcorner=yllcorner+(cellsize*nrows);
   }

   if(NR>6){
      for(i=1;i<NF;++i){
         printf("%f %f %f\n", xllcorner+(col*cellsize), \
               ytlcorner-(row*cellsize), $i);
         ++col;
      }
      ++row;
      col=0;
   }
}
```

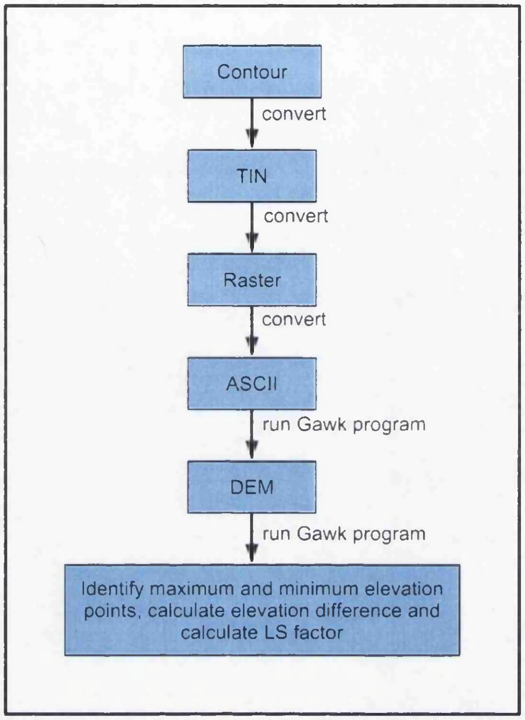


Figure 5.1: Flow chart of conversion from contour to DEM.

2.5 m resolution in a 5 m × 5 m window (mask) as well as lowest and highest elevation points in that resolution. The output of this program which contained the elevation points were loaded back into ArcMap$^{\text{TM}}$ to display the DEM. However, only soil loss within the study area as well as in the inventory plots needs to be calculated; hence, the boundary of the study area and the 5 m × 5 m plots are intersected with the DEM, so that only elevation points in these areas are shown in Figure 5.4.

As the DEM resolution is 2.5 m, there are nominally four elevation values in a single inventory plot (5 m × 5 m). Thus, to calculate elevation difference (Δz), the maximum and minimum elevation points among these four points need to be identified as illustrated in Figure 5.5. Again this cannot be done simply in ArcMap$^{\text{TM}}$ and therefore, another Gawk program script was written for this purpose. This program also calculates the length, L, gradient, S, and slope length, LS factor of the terrain within each inventory plot using

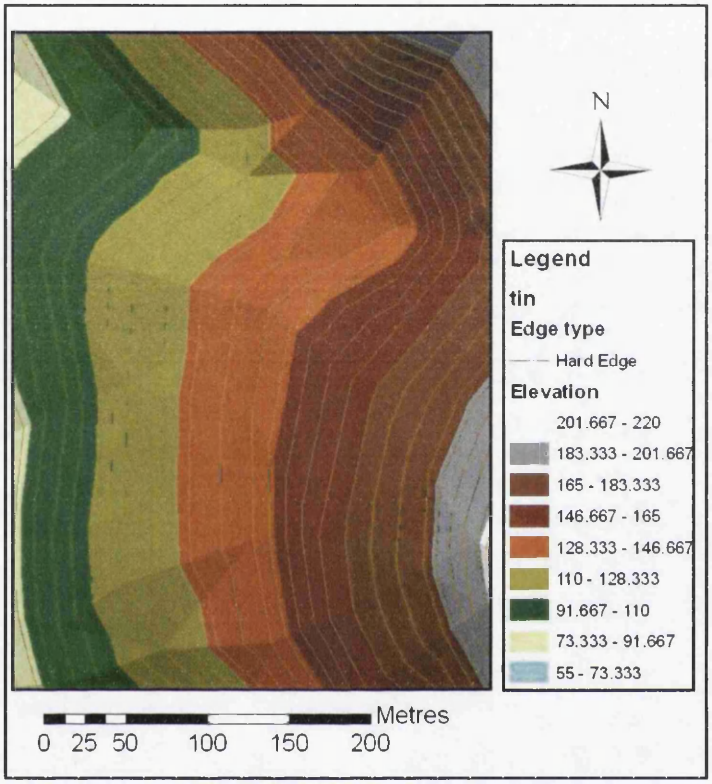


Figure 5.2: Result of TIN creation from the contour map.

Equations 5.4, 5.5, 5.6 and 5.3. The results are converted to ASCII file once again to enable the data to be run under the Gawk program shown in Listing 5.2. The computed *LS* factor is shown in Figure 5.6, where a zoom-in graphic shows that there is one *LS* point per inventory plot. The *LS* points are then resampled to show *LS* values in the 5 m × 5 m plot as in Figure 5.7. The result of *LS* factor are categorised into five classes i.e. very low (0 to 0.728), low (0.729 to 1.180), medium (1.181 to 1.817), high (1.818 to 3.388) and very high (3.389 to 5.828). These values are then used to calculate soil loss, A, according to Equation 2.2.

Listing 5.2: Gawk program script to calculate LS factor

```
#*******************************************************#
#                                                       #
# Name: ls3.awk                                         #
#                                                       #
# Purpose: Calculates the LS factor on a plot by plot   #
# basis from an ASCII file containing x,y,z values and  #
# plot numbers                                          #
#                                                       #
# Usage: gawk -f ls3.awk -v plots=<value>               #
# spacing=<value -v cell_size input_file > output_file  #
#                                                       #
# Where m is a factor depending on slope                #
#                                                       #
#*******************************************************#

BEGIN{
   # Reset variables
   x_min_elev= 9999;
   x_max_elev=-9999;
   y_min_elev= 9999;
   y_max_elev=-9999;
   min_elev=   9999;
   max_elev=  -9999;

}

(NR>1){
   # Consider each plot in turn
   for(plot_number=1;plot_number<=plots;++plot_number){
      # While we're still considering the same plot
      this_plot=$4;
      while(this_plot==plot_number){
         # Note the x,y and z coordinates of the current point
         # and its plot Id
         x_coord=$1;
```

Listing 5.2 continued.. Gawk program script to calculate LS factor

```
      y_coord=$2;
      elev=$3;
      this_plot=$4;
      plot_id=$5;

      # See if this point is the lowest or highest in the
      # current plot
      if(elev>-9999){
         if(elev<min_elev){
            min_elev=elev;
            x_min_elev=x_coord;
            y_min_elev=y_coord;
         }
         if(elev>max_elev){
            max_elev=elev;
            x_max_elev=x_coord;
            y_max_elev=y_coord;
         }
         ++points;
      }
      if(getline){
         # Still data to be read
         this_plot=$4;
      } else {
         # No further data to be read so end program
         exit;
      }
   }

   if(points>=2){

      # Now calculate the terrain gradient and LS factor

      x_diff=(spacing*(x_min_elev-x_max_elev))^2;
      y_diff=(spacing*(y_min_elev-y_max_elev))^2;
```

Listing 5.2 continued.. Gawk program script to calculate LS factor

```
xy_diff=sqrt(x_diff+y_diff);

# Find mid-point between highest and lowest points
x_mid_point=x_min_elev-((x_min_elev-x_max_elev)/2);
y_mid_point=y_min_elev-((y_min_elev-y_max_elev)/2);

# Referred to as Y in FRIM Technical Information
# Handbook No. 25
z_diff=max_elev-min_elev;

lambda=sqrt((z_diff*z_diff)+(xy_diff*xy_diff));

# Referred to as S in FRIM Technical Information
# Handbook No. 25
if(xy_diff!=0){
   gradient=(z_diff/xy_diff)*100;
   if(gradient<1.0){
      m=0.2;
   } else if(gradient>=1.0 && gradient<3.0){
      m=0.3;
   } else if(gradient>=3.0 && gradient<5.0){
      m=0.4;
   } else if(gradient>=5.0 && gradient<12.0){
      m=0.5;
   } else {m=0.6}


   # Referred to as LS in FRIM Technical Information
   # Handbook No. 25
   slope_length=((lambda/22.13)^m)*(0.065+
   (0.046*gradient)+(0.0065*(gradient*gradient)));

   # Print out results for this plot
   printf("%5d %10.3f %10.3f %10s %10.3f %10.3f
   %10.3f %6.4f %10.3f\n", plot_number, x_mid_point,
```

Listing 5.2 continued.. Gawk program script to calculate LS factor

```
            %10.3f %6.4f %10.3f\n", plot_number, x_mid_point,
            y_mid_point, plot_id, z_diff, xy_diff, gradient,
            m, slope_length);
         } else {
            # We have a cell in which all the points are of
            # the same elevation, so...
            # Set the x,y coords to be the midpoint of
            # this cell
            x_mid_point=x_min_elev+(cell_size/2);
            y_mid_point=y_min_elev+(cell_size/2);
            # Set the gradient to be zero
            gradient=0;
            # Set parameter m to be 0.2
            m=0.2;
            # Calculate slope length
            slope_length=((lambda/22.13)^m)*(0.065+(0.046*
            gradient)+(0.0065*(gradient*gradient)));
            # Print out results
            printf("%5d %10.3f %10.3f %10s %10.3f %10.3f
            %10.3f %6.4f %10.3f\n", plot_number,
            x_mid_point, y_mid_point, plot_id, z_diff,
            xy_diff, gradient, m, slope_length);
         }

      }

      # Reset variables
      # Reset variables
      x_min_elev= 9999;
      x_max_elev=-9999;
      y_min_elev= 9999;
      y_max_elev=-9999;
      min_elev   = 9999;
      max_elev   =-9999;
      points     =    0;

      # Now move on to next plot
   }
}
```

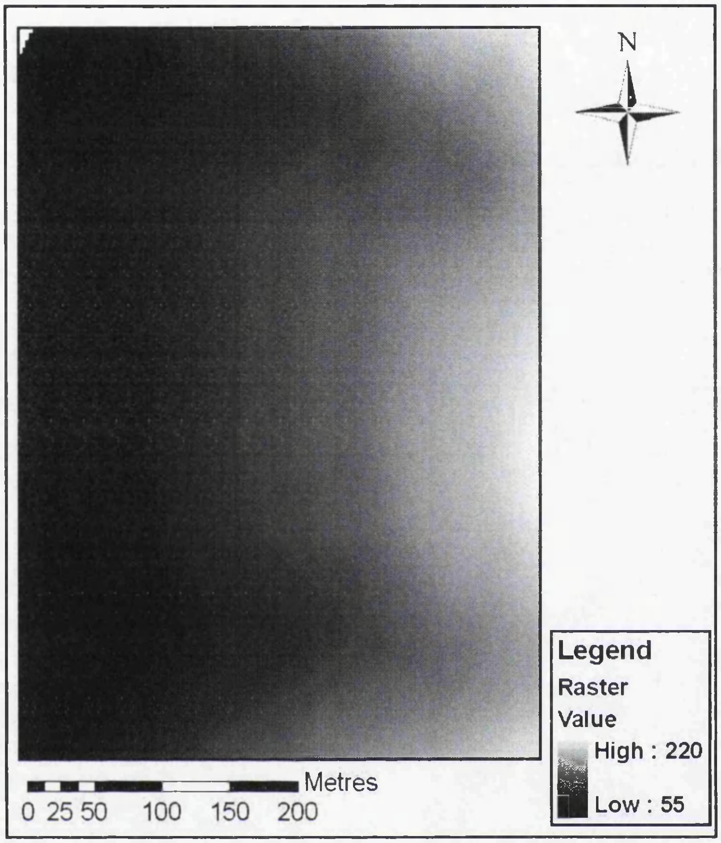


Figure 5.3: Raster DEM generated from TIN.

5.2.4 Vegetation Management Factor, *VM*

The vegetation management factor, *VM*, is used to evaluate the effects of vegetation cover and land management practices on soil erosion over the entire slope length for which the *LS* factor was calculated. The *VM* factor is defined as the ratio of soil loss from a field subject to a system of control measures to that of the same site without any control provision. It combines two factors, *C* and *P*, which are used in the USLE. The expression for *VM* is intended mainly for forest cover. It is a combination of vegetation cover and soil surface conditions into single factor; it incorporates three sub-factors for forest canopy cover, mulch and ground vegetation cover, and bare ground with fine roots. Details on

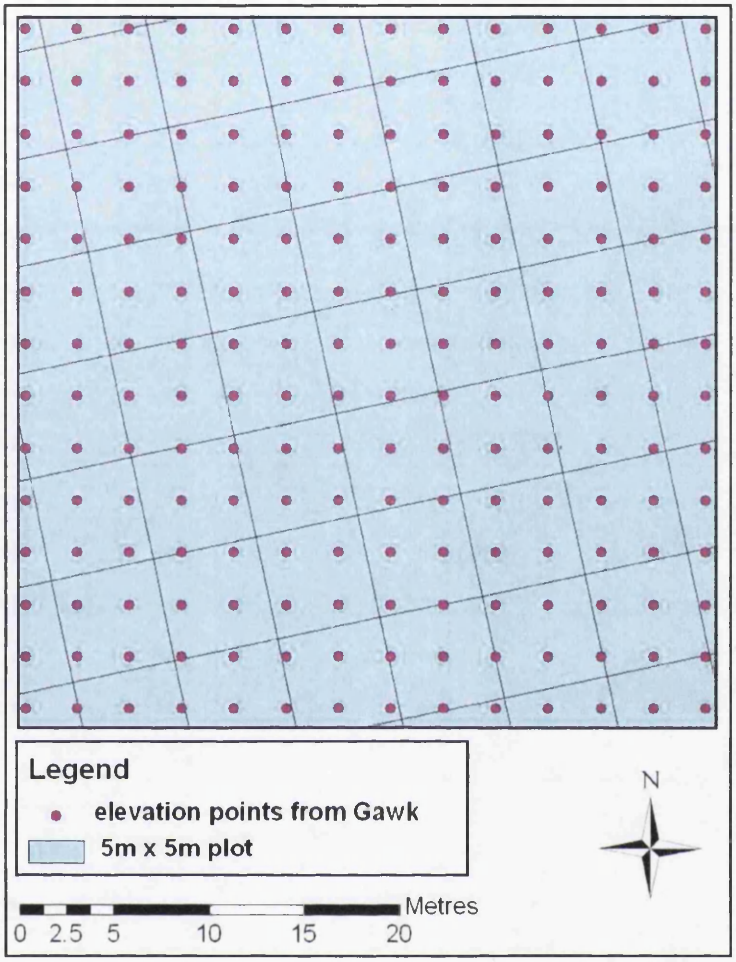


Figure 5.4: A zoom-in graphic showing DEM points in 5x5m plots in the study area.

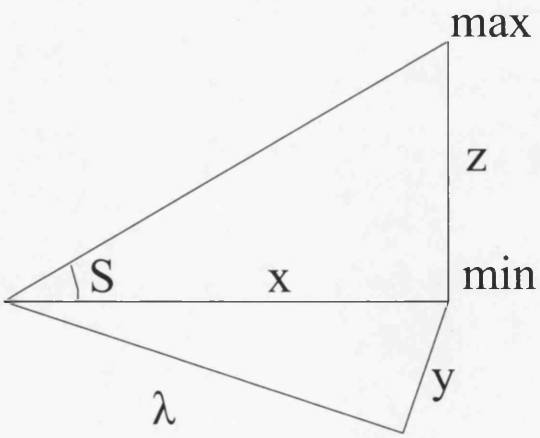


Figure 5.5: Illustration on the maximum and minimum elevation points.

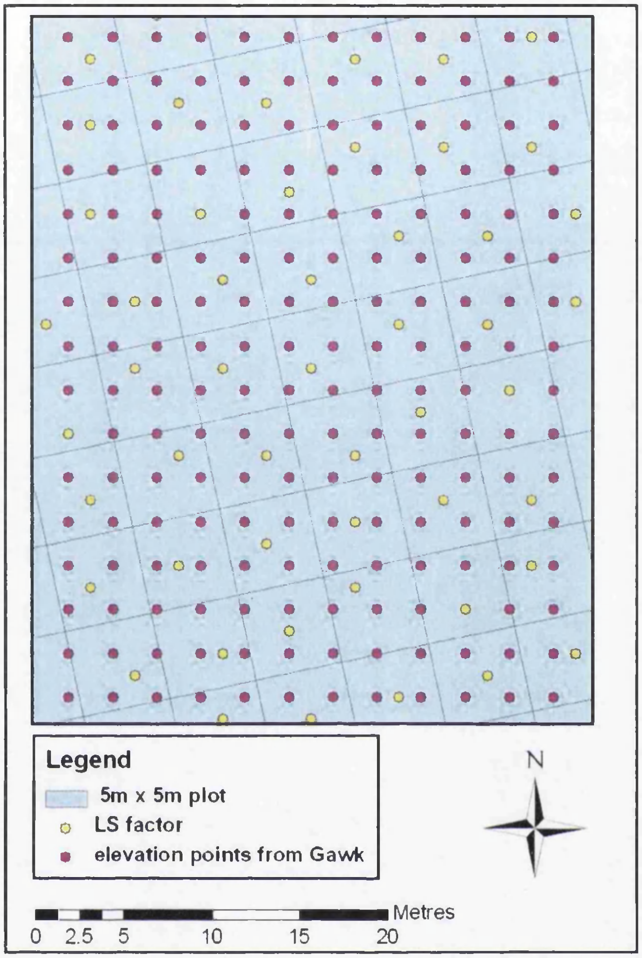


Figure 5.6: A zoom-in graphic of length steepness, *LS* factor in 5 m × 5 m plot.

how the *VM* factor is derived can be obtained in Subsection 2.2.2.1. As the study area is 100 % under forest, the *VM* factor used here is the same as that adopted in the study by Baharuddin et al. (1999), shown in Table 5.3.

5.2.5 Soil Erosion, *A*

Finally, to determine the critical soil loss or soil erosion, *A*, in the study area, the spatial distribution of plot-based MSLE parameters is calculated by multiplying the *LS* value in each 5 m × 5 m inventory plot with the *R*, *K* and *VM* factors derived in subsections 5.2.1, 5.2.2 and 5.2.4. The *A* values were computed in ArcMap^{TM} to produce a soil erosion

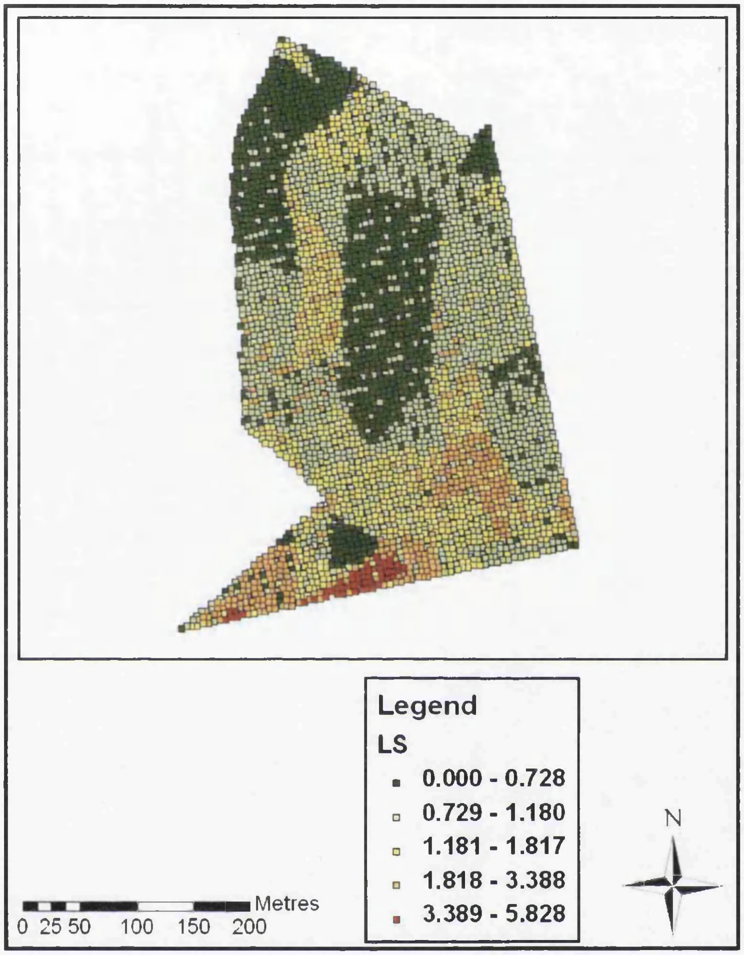


Figure 5.7: *LS* values in the 5 m × 5 m plots.

Table 5.3: Estimation of the VM factor. (Source: Baharuddin et al., 1999)

Area with canopy		Area with mulch		Area with fine root		VM
%	factor	%	factor	%	factor	
100	0.62	99	0.02	98	0.1	0.001

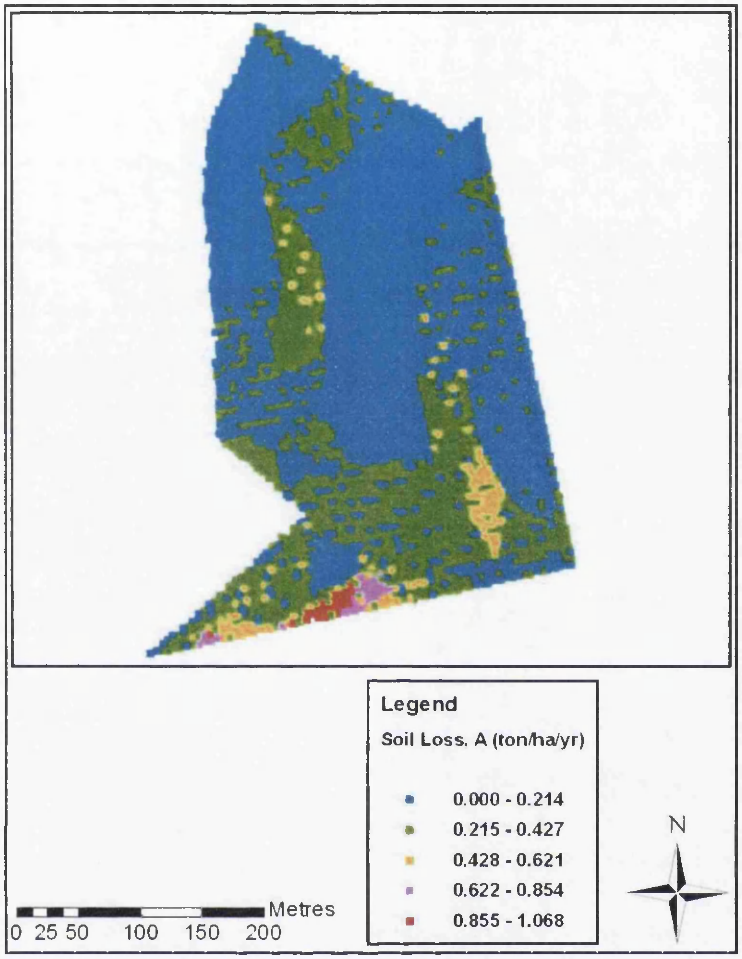


Figure 5.8: Soil erosion, *A*, risk map for the study area.

risk map for the study area, and the resulting image is shown in Figure 5.8. It is found that the soil erosion risk map produced some speckles effects and broad swathes that have identical soil erosion values. This is due to the fact that this map is derived especially based on the *LS* factor points, therefore, the soil loss calculation resulted in point form in the 5 m × 5 m plot. Plots that have same values of soil loss would group together and formed broad swathes or polygons and there are some plots within the polygons that have different values of soil loss, thus, resulted in the speckles effect. The amount of soil loss in the study area ranges between 0 and 1.068 $\text{metric ton} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$, and is classified into five classes: i.e. very low (0 to 0.214), low (0.215 to 0.427), medium (0.428 to 0.621),

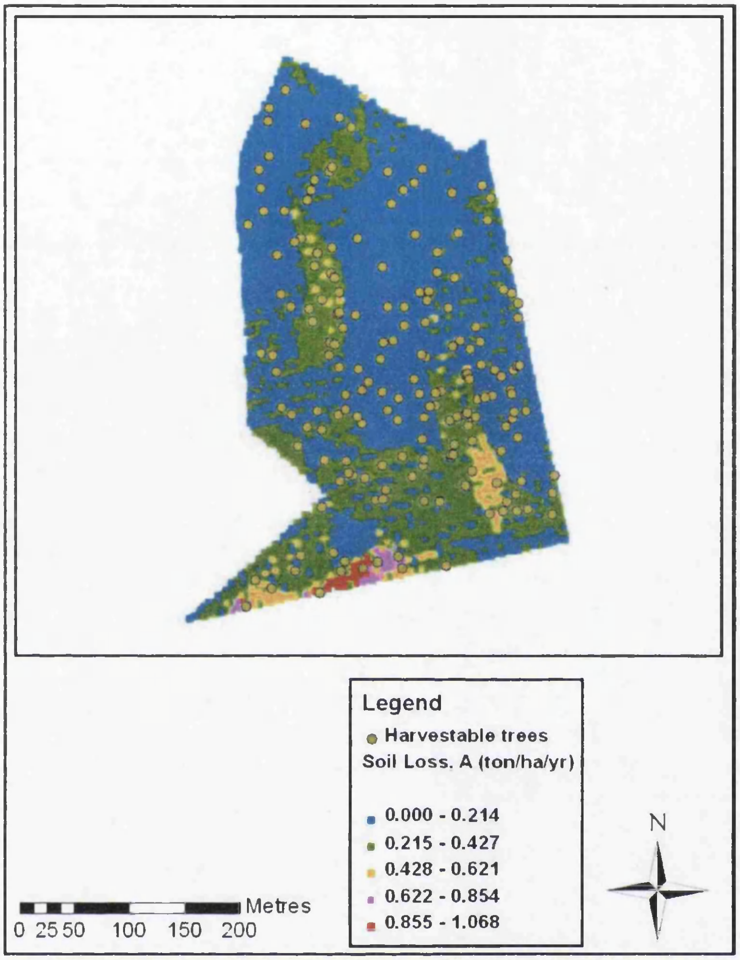


Figure 5.9: Proposed harvestable trees overlaid on the soil erosion risk map.

high (0.622 to 0.854) and very high (0.855 and 1.068).

5.3 Harvestable trees and soil erosion

The proposed harvestable trees layer obtained from Subsection 4.4.6 in Chapter **4** can be combined with the soil loss data to show the location of trees in areas with different levels of soil erosion risk, as shown in Figure 5.9.

Although the selection of trees that can be harvested has been carefully made based on the SMS requirements where steep slopes are excluded, there are still few selected trees

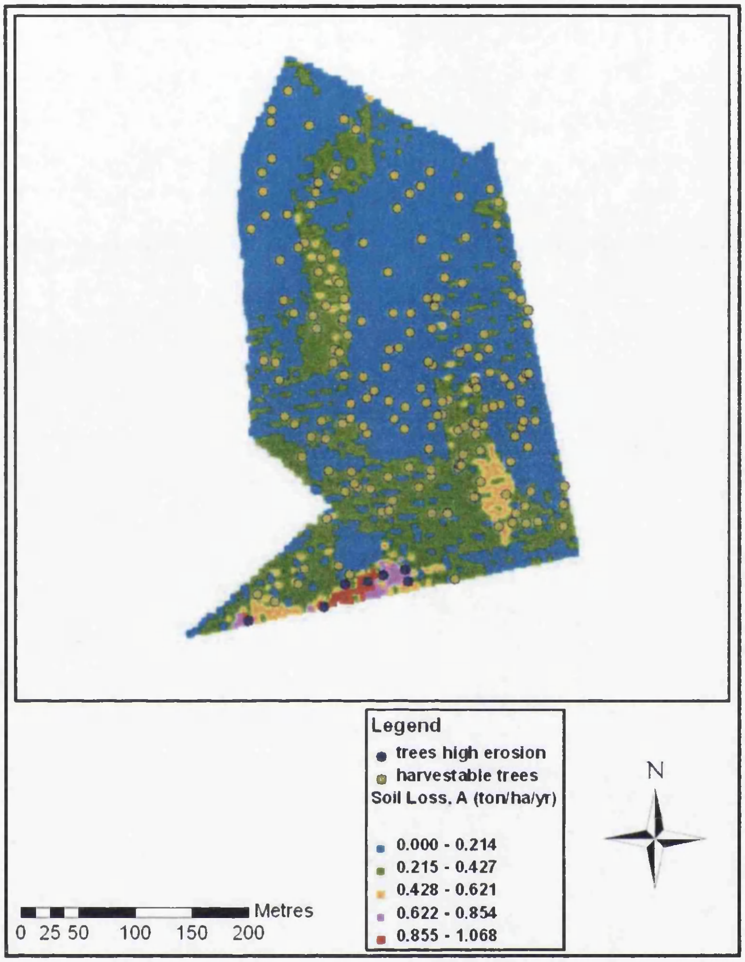


Figure 5.10: Trees in high soil erosion risk areas.

fall on areas of high soil erosion risk, as highlighted in Figure 5.10.

In the area studied here, there is a modest number (7) of harvestable trees situated in areas of high soil-erosion risk. In the circumstances, the forest managers have two alternatives: the first is to remove those trees from the harvest plan, and harvest the remainder, as shown in Figure 5.11; the second is to discard the trees in the high risk areas and substitute them with others in lower risk areas, selected using the standard SMS criteria, as shown in Figure 5.12. In this study, the second approach is adopted; consequently, the final harvestable trees selected after consideration of the SMS requirements and the potential soil loss map are presented in Figure 5.13.

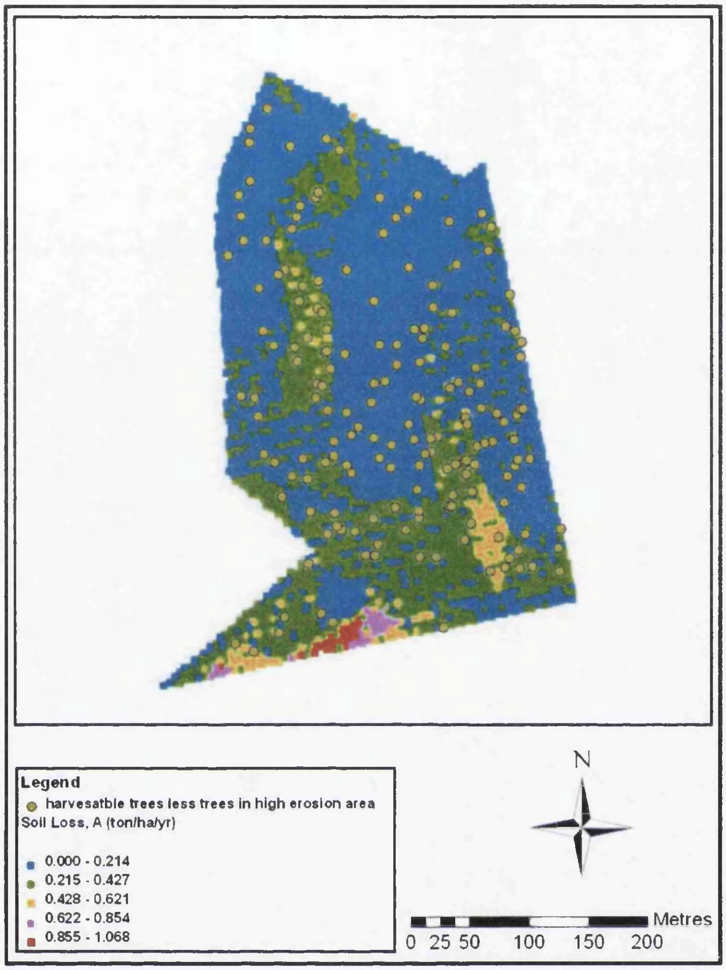


Figure 5.11: Elimination of trees on areas of high soil erosion risk.

5.4 Flow direction of soil erosion

Knowledge of the potential soil-erosion risk alone is insufficient to protect and conserve forest soils. Information is also required on soil movement and deposition, which, in the case of non-aeolian erosion, is largely dependent on the direction of water flow across the terrain surface. Normally, soil loss from one area is transferred to and deposited in another by flow processes. The direction of flow, specifically overland flow or runoff, can be determined by finding the direction of steepest descent from each point on the terrain surface or, in the case of a raster DEM, from each cell in the DEM (Desmet and Govers, 1996). This section therefore investigates the principal directions of flow across the

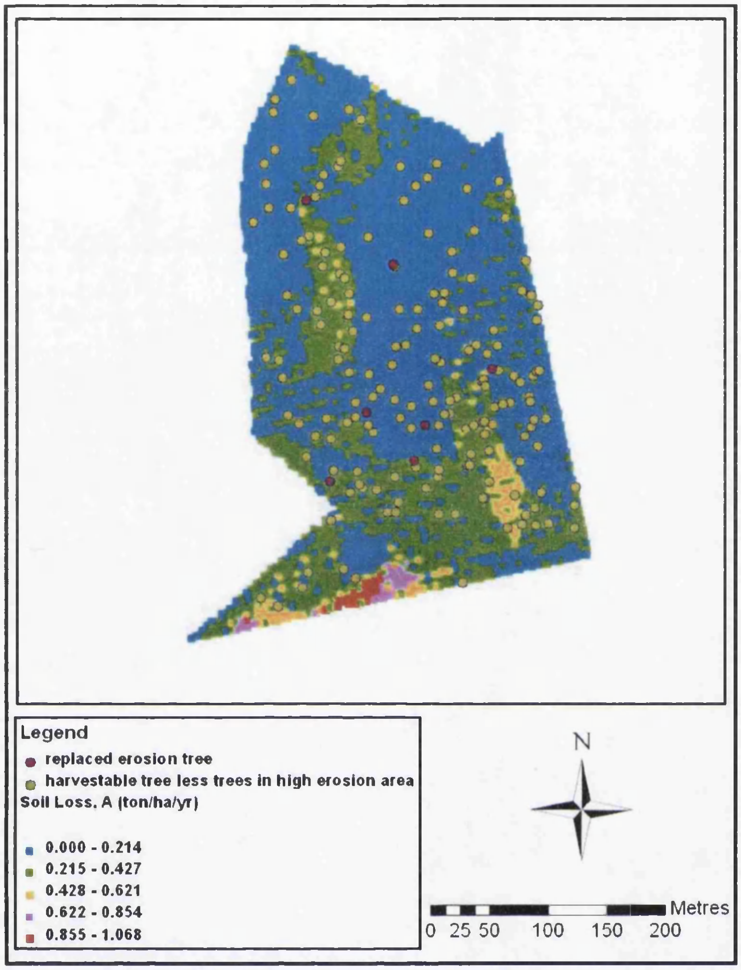


Figure 5.12: Selection of ‘replacement’ trees.

DEM of the study area and combines this with the soil-erosion risk map to identify areas of net erosion and accumulation. It also describes how the raster DEM is manipulated to fill ‘sinks’, to define the Local Drainage Direction (LDD) vectors, and to delineate the watershed boundary for the study area. Consequently, this chapter provides information on areas that are exposed to net soil erosion and its magnitude, areas where there is likely to be a net accretion of sediment through deposition, and the effect of the overland movement of soil in relation to tree and road locations.

The procedures carried out to determine the LDD and perform hydrological modeling were primarily conducted using Spatial Analyst in ArcMap$^{\text{TM}}$. These procedures require

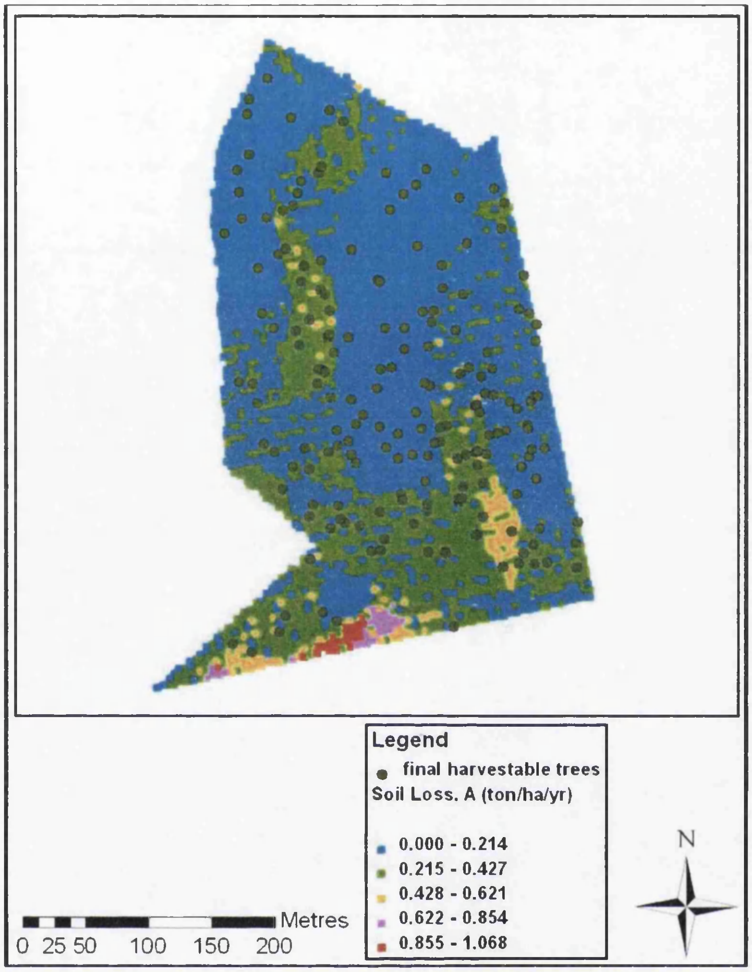


Figure 5.13: Final map of harvestable trees.

the development of three general utility data sets, namely: (i) a DEM in which the ‘sinks’ (i.e. points for which there is no direction of outward flow) are filled, so that the LDD vectors can be properly determined; (ii) a set of vectors indicating the soil flow direction from each cell in the DEM; and (iii) a flow accumulation data set in which each cell receives a value equal to the total number of cells that drain into it. Sinks in a DEM prohibit proper determination of flow routing across the terrain and need to be resolved prior to developing the soil flow direction and flow accumulation grids. Most sinks need to be eliminated because they are artefacts of the DEM creation process, but some may be faithful reflections of the actual terrain. In this study area, however, no natural sinks are

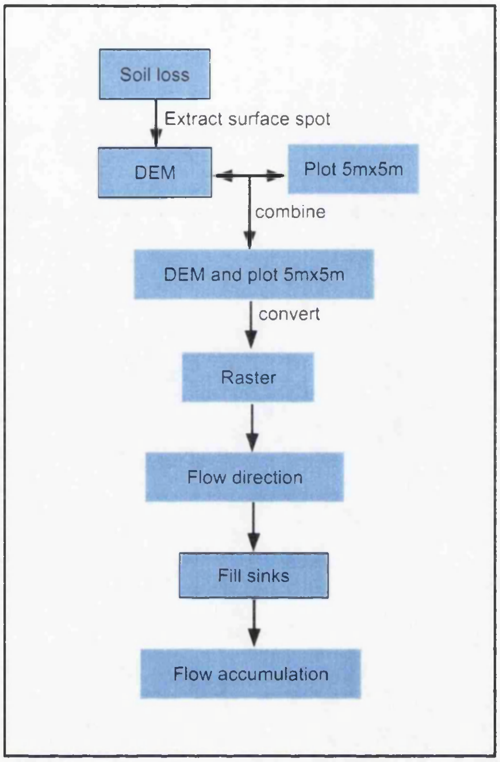


Figure 5.14: Flow chart showing the process of obtaining soil flow direction and accumulation in the study area.

expected, and so a process of sink removal is conducted. The algorithm on how to obtain the soil flow direction is given in a flow chart in Figure 5.14.

Before the soil loss flow direction could be determined, DEM from the soil loss layer has to be generated first. This was carried out in ArcMap^{TM} by extracting surface spots from the soil loss layer. However, the surface spots could not be displayed in the layer itself but added in a new field in the soil loss attribute table. The data of the soil loss with the surface spots are then combined with the 5 m × 5 m plot data, which acted as cell size in this case, before they are converted to raster which produced the map in Figure 5.15. These features are converted to raster in order to obtain a continuous surface and to remove any blank cells which might result in no data values and hinder further processing. This was followed by computing the soil flow direction for the study area.

Using Spatial analyst tool in ArcMap^{TM}, raster of soil flow direction are created from

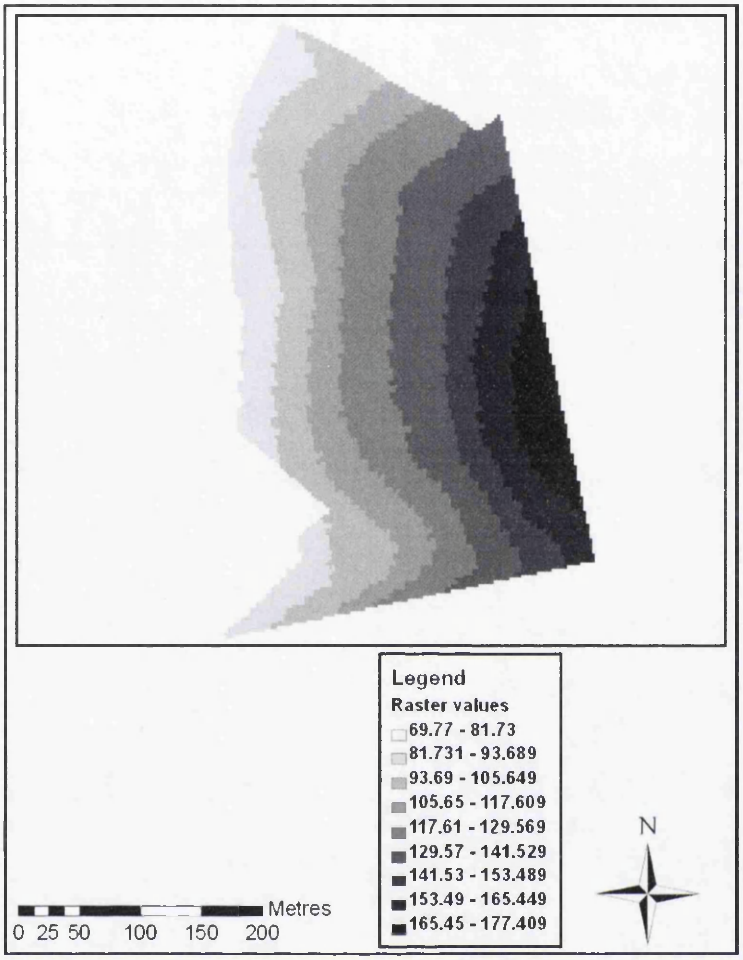
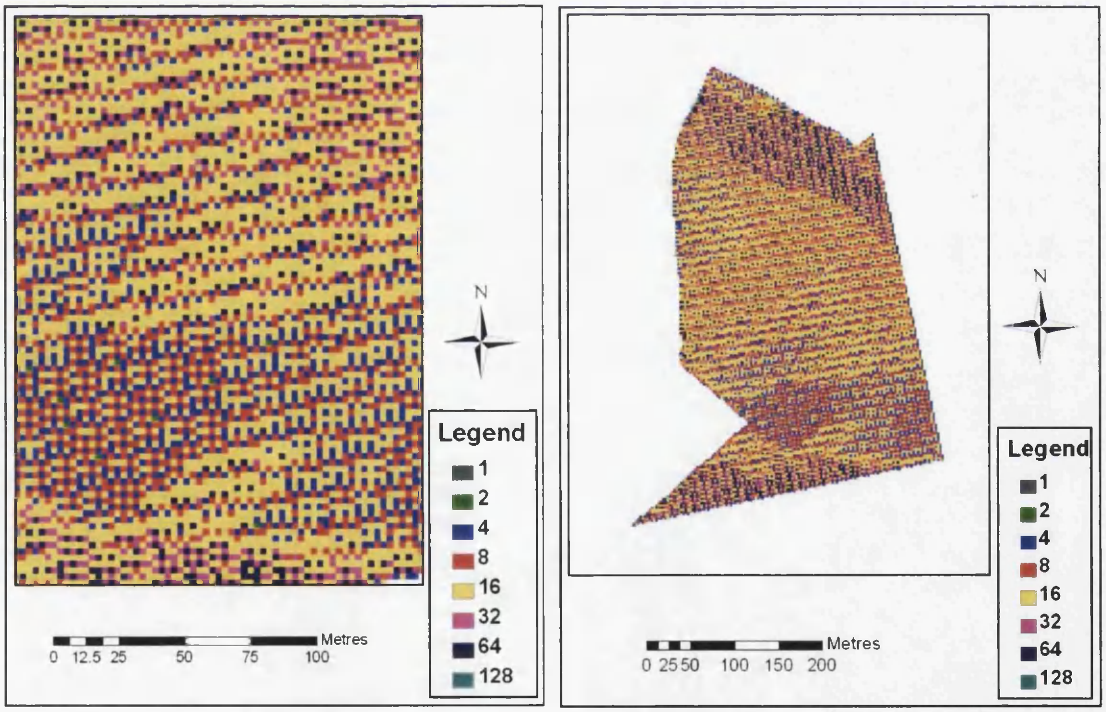


Figure 5.15: Raster of joint soil loss and plot 5 m × 5 m with surface spots.

each cell to its steepest downslope neighbour. The output of the soil flow direction tool is an integer raster whose values range from 1 to 255. The values for each direction from the center are shown in Figure 5.16. For example, if the direction of steepest drop is to the left of the current processing cell, its soil flow direction would be coded as 16. The result of soil flow direction for the whole study area and a zoom graphic of the sample extract is presented in Figure 5.17. The purpose of zooming the output map is to visualize more clearly the flow direction of the soil loss from one cell to the nearest cell and sink areas. It is clearly shown from sample extract in Figure 5.17(a) that most of the soil loss flow towards the cells which have values of 4, 8 and 16. Besides, from Figure 5.17(b), the

32	64	128
16		1
8	4	2

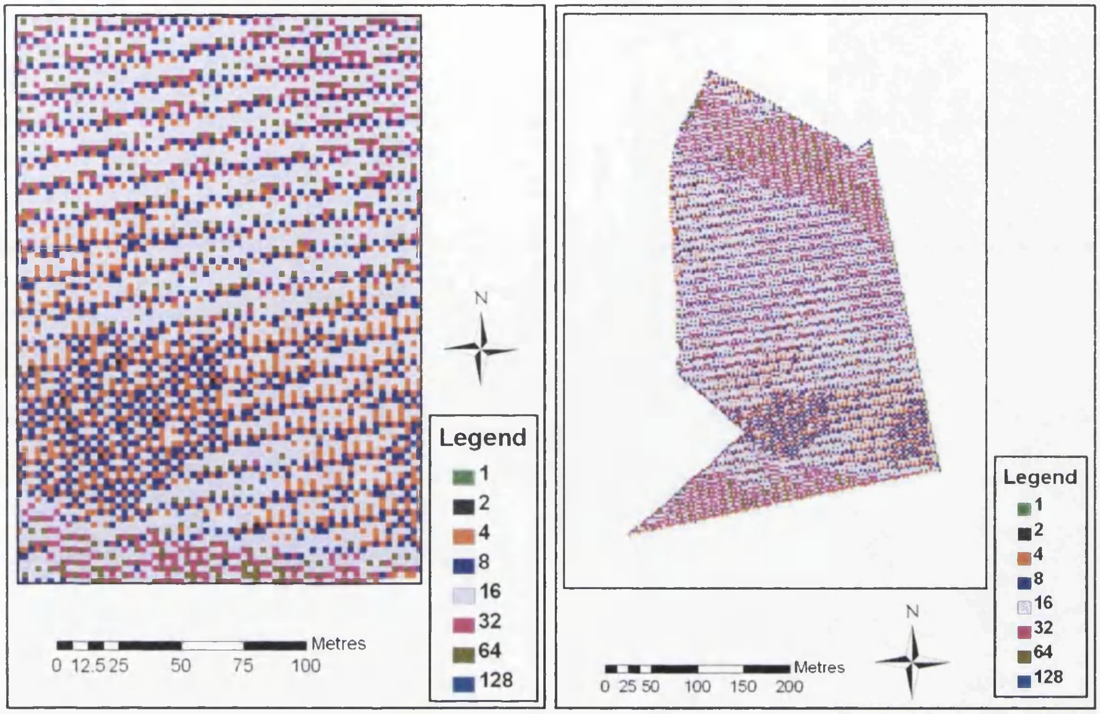
Figure 5.16: Integer raster values for each soil flow direction from the center.



(a) Sample extract

(b) Whole study area

Figure 5.17: Soil flow direction of the study area.



(a) Sample extract

(b) Whole study area

Figure 5.18: Fill of sinks in the soil flow direction

whole study area shows that the soil flow direction is towards the southwest.

If a cell or set of spatially connected cells whose soil flow direction cannot be assigned one of the eight valid values in a flow direction raster, it is called sink and the value is 255. This can occur when all neighbouring cells are higher than the processing cell or when two cells flow into each other, creating a two-cell loop. Sinks are considered to have undefined flow directions and are assigned a value that is the sum of their possible directions. For instance, if the steepest drop and, therefore, soil flow direction, are the same to both the right (1) and left (16), the value 17 would be assigned as the soil flow direction for that cell (Mark, 1988). In this study, where perturbed soil flow direction exists and to remove small imperfections in the data, the sinks are filled and the result is shown in Figure 5.18.

Soil loss that flow from its origin would ultimately be deposited somewhere along its flow direction and finally accumulated at the lowest point of the surface. Therefore, once

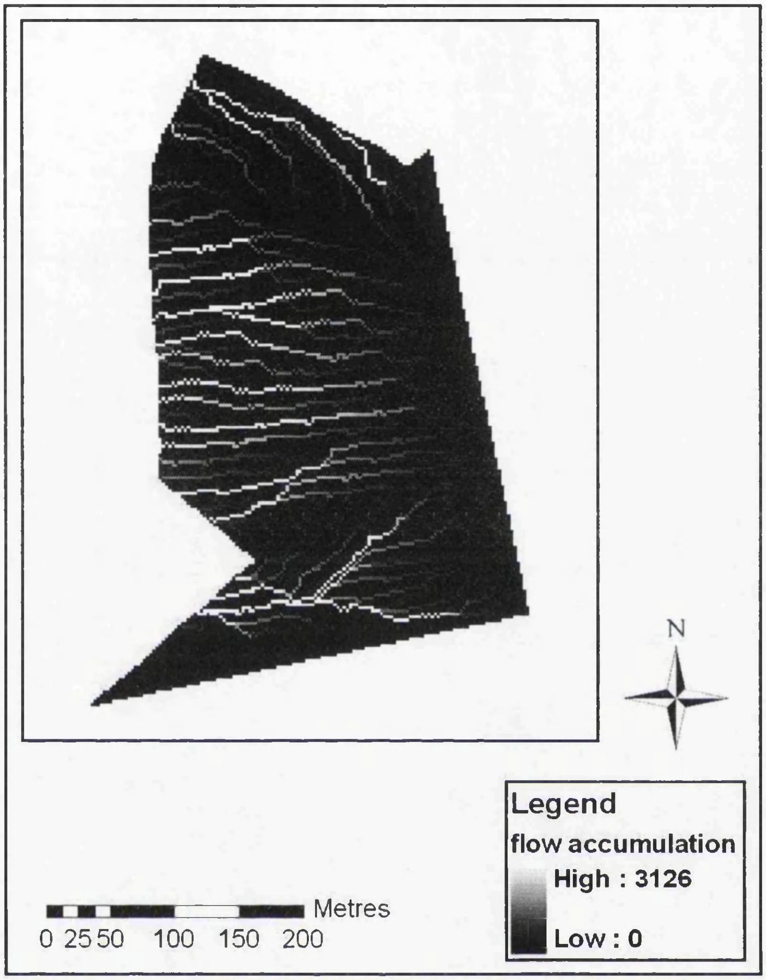


Figure 5.19: Study area showing the soil loss accumulation.

the soil flow direction is known, where the soil loss accumulate could be investigate. Flow accumulation is a raster of accumulated flow to each cell, as determined by accumulating the weight for all cells that flow into each down slope cell. When computed in ArcMap$^{\text{TM}}$, the result of flow accumulation of the study area is derived and shown in Figure 5.19. The result demonstrates that most of the soil loss are generated from east part of the study area and flow towards the west while gradually increase its volume during the accumulation process. This is in line with the contour of the study area which range from 180 m in the east to 70 m in the west. Output cells with high flow accumulation values are areas of concentrated flow and may be used to identify stream channels whereas output cells with flow accumulation values of zero are local topographic highs and may be used to identify ridges (Jenson and Domingue, 1988; Tarboton et al., 1991).

Apart from flow accumulation analysis, another analysis that was carried out is the potential for soil movement from cell to cell (sediment transport accounting). During the process of sediment flow, there are cells that receive soil from one or more neighbouring cells, which will be referred to as soil gain. This is also the basic concept of soil accumulation where, if the cell continuously receives soil from other cells, the soil would be collected and deposited in that cell. Hence, when the volume increase, soil is accumulated. However, there are cells which do not receive soil from other cells; instead, they loose soil when the soil moves to other neighbouring cells. This process is known as soil loss. In this analysis, the study investigates soil loss and soil gain in the study area. However, this procedure is not straight forward and ArcGIS$^{\text{TM}}$ alone cannot be used. The analysis has been supported by a program written by the author in the Gawk programming language and the algorithm for calculating soil gain and soil loss is shown in Figure 5.20. The hsoil loss data is first joined with the 5 m × 5 m plot data as in Figure 5.21 before converting the feature layer to raster. This has to be done to obtain a continuous surface and to remove any blank pixels which would result in no data values when the program to calculate soil gain and soil loss are run. The result of the raster conversion is presented in Figure 5.22. This layer was further converted from a binary raster to ASCII text format, so that it could be read by the Gawk program: in an operational application of these techniques, the Gawk program used here would need to be replaced by a more efficient program developed in a compiled language, such as C, but the Gawk script suffices here. Similarly, the filled flow direction layer obtained earlier in Figure 5.18 was also converted to ASCII format. These two ASCII data files are needed to run the processing of the Gawk program, presented in Listing 5.3, which then produced soil gain and soil loss files also in ASCII format.

The soil gain and soil loss files are subsequently loaded back into ArcMap$^{\text{TM}}$, the

Listing 5.3: Gawk program script to calculate soil movement

```
BEGIN{
   # Set the first row to be row number 1
   row=1;
}

{
   if(NR==1){
      # Read first record of flow direction data file
      # to establish number of columns
      ncols=$2;
   } else if(NR==2){
      # Read second record of flow direction data file
      # to establish number of rows
      nrows=$2;
   } else if(NR==3){
      # Read second record of flow direction data file
      # to establish number of rows
      xllcorner=$2;
   } else if(NR==4){
      # Read second record of flow direction data file
      # to establish number of rows
      yllcorner=$2;
   } else if(NR==5){
      # Read second record of flow direction data file
      # to establish number of rows
      cellsize=$2;
   } else if(NR>6){
      # Read the other records into an array called
      #'direction', which holds information
      # on the flow direction from each cell
      #
      # First, consider each column in a given row
      for(col=1;col<=ncols;++col){
         direction[col,row]=$col;
      }
      # Now, move to the next row
      ++row;
   }
}
```

Listing 5.3 continued.. Gawk program script to calculate soil movement

```
END{
   # Read first few reconds from MSLE data file
   fn_read_msle_header(file);

   #print "ncols         ", ncols > "soil_loss.txt";
   #print "nrows         ", nrows > "soil_loss.txt";
   #print "xllcorner     ", xllcorner > "soil_loss.txt";
   #print "yllcorner     ", yllcorner > "soil_loss.txt";
   #print "cellsize      ", cellsize > "soil_loss.txt";
   #print "NODATA_value  -9999" > "soil_loss.txt";

   #print "ncols         ", ncols > "soil_gain.txt";
   #print "nrows         ", nrows > "soil_gain.txt";
   #print "xllcorner     ", xllcorner > "soil_gain.txt";
   #print "yllcorner     ", yllcorner > "soil_gain.txt";
   #print "cellsize      ", cellsize > "soil_gain.txt";
   #print "NODATA_value  -9999" > "soil_gain.txt";

   # Read in flow direction and MSLE data sets and output
   # to a unified data file
   for(row=1;row<=nrows;++row){
      getline < file;
      for(col=1;col<=ncols;++col){
         fn_flow_direction(direction[col,row]);
         if($col!=-9999){
            printf("%13.6f %13.6f %9.6f\n",
               xllcorner+(cellsize*(col-1)), \
               yllcorner+(nrows*cellsize) \
               -(cellsize*(row-1)),
               -1*$col) > "soil_loss.txt";
            soil_gain[col+i,row+j]+=$col;
         } else {
            printf("%13.6f %13.6f %9.6f\n",
               xllcorner+(cellsize*(col-1)), \
               yllcorner+(nrows*cellsize) \
               -(cellsize*(row-1)),
               0.0) > "soil_loss.txt";
            }
      }
   }
```

Listing 5.3 continued.. Gawk program script to calculate soil movement

```
   for(row=1;row<=nrows;++row){
      for(col=1;col<=ncols;++col){
         printf("%13.6f %13.6f %9.6f\n",
            xllcorner+(cellsize*(col-1)), \
            yllcorner+(nrows*cellsize) \
            -(cellsize*(row-1)),
            soil_gain[col,row]) > "soil_gain.txt";
      }
   }

}

function fn_flow_direction(x){
   # Convert flow direction into relative column (i)
   # and row (j) values and return these values as
   # global variables to the function call.
   if(x==1){
      i=1.0;
      j=0.0;
   } else if(x==2){
      i=1.0;
      j=1.0;
   } else if(x==4){
      i=0.0;
      j=1.0;
   } else if(x==8){
      i= -1.0;
      j=1.0;
   } else if(x==16){
      i= -1.0;
      j=0.0;
   } else if(x==32){
      i= -1.0;
      j= -1.0;
   } else if(x==64){
      i=0.0;
      j= -1.0;
   } else if(x==128){
      i=1.0;
      j= -1.0;
```

Listing 5.3 continued.. Gawk program script to calculate soil movement factor

```
    }
    return;
}

function fn_read_msle_header(file){
    # Read first record of MSLE data file to establish
    # number of columns
    getline < file;
    ncols_data=$2;
    # Read second record of MSLE data file to establish
    # number of rows
    getline < file ;
    nrows_data=$2;
    # Read third record of MSLE data file to establish
    # lower left corner (x)
    getline < file ;
    xllcorner2=$2;
    # Read fourth record of MSLE data file to establish
    # lower left corner (y)
    getline < file ;
    yllcorner2=$2;
    # Read fifth record of MSLE data file to establish
    # cellsize
    getline < file ;
    cellsize2=$2;
    # Read sixth record of MSLE data file to establish
    # missing data value
    getline < file ;
    missing=$2;
    # Check to see whether MSLE data file is the same
    # size (rows and columns) as flow direction data set
    if(nrows!=nrows_data || ncols!=ncols_data){
        print "Data sets are different sizes!";
        print ncols_data, nrows_data, ncols, nrows;
        exit;
    }
}
```

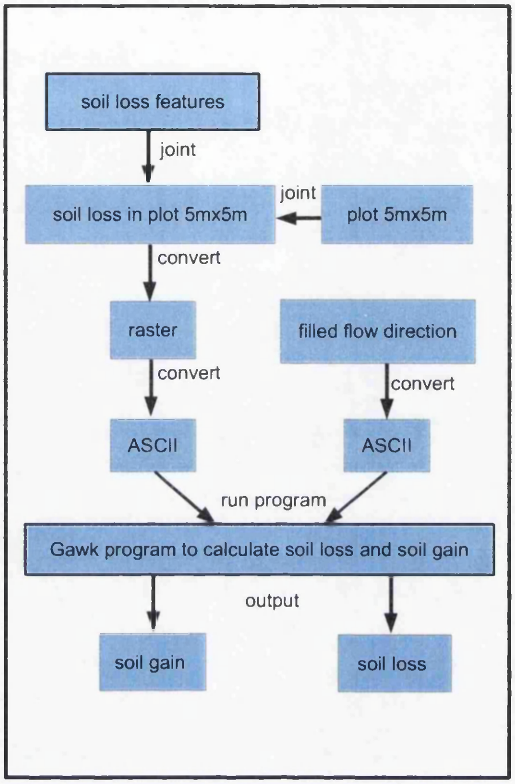


Figure 5.20: Algorithm for soil gain and soil loss calculation.

results of which are shown in Figure 5.23 and Figure 5.24, respectively. Both files are converted to raster format and the output are presented in Figure 5.25. From the result, it is observed that soil gain raster (Figure 5.25(a)) is more speckly than the soil loss. There are few reasons why this happened: firstly, the analysis carried out is grid-based modeling and not sectoral-based, which allows for the specification of a subset of cells for processing and the resolution at which to process them. So if the area of interest is a portion of a larger grid, the analysis window can be set to encompass only the desired cells. In this study, the analysis window is a $5\,\mathrm{m} \times 5\,\mathrm{m}$ square and is specified by identifying the coordinates of the window in map space. Grid performs all operations and functions (except zonal and global functions) on a cell by cell basis. Also the output cell resolution for any

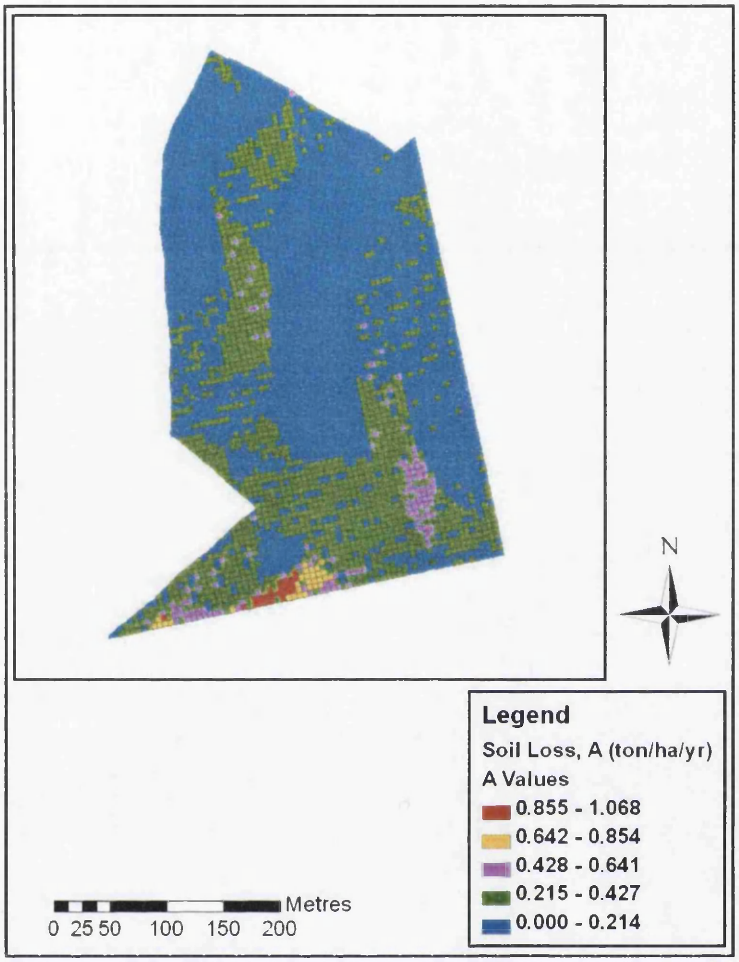


Figure 5.21: Joint data of soil loss and 5 m × 5 m inventory plots.

operation or function can be set to any size desired by the user (Environmental Systems Research Institute, 1991). Secondly, the speckly effect might be caused by the highly contrast values of neigbouring cells. If two adjacent cells produce two extreme contrast values i.e. one is very low (dark) and the other very high (bright), as in the soil gain result, speckles are likely to develop. On the contrary, soil loss in Figure 5.25(b) resulted in a more smoother and less speckly image due to smaller range of low and high values. Therefore, extra and careful considerations have to be taken to avoid more disturbances on areas where soil loss is high, which are marked with dark colour in Figure 5.25(b). The amount of highest soil gain is 3.032 metric ton while soil loss is 1.068 metric ton.

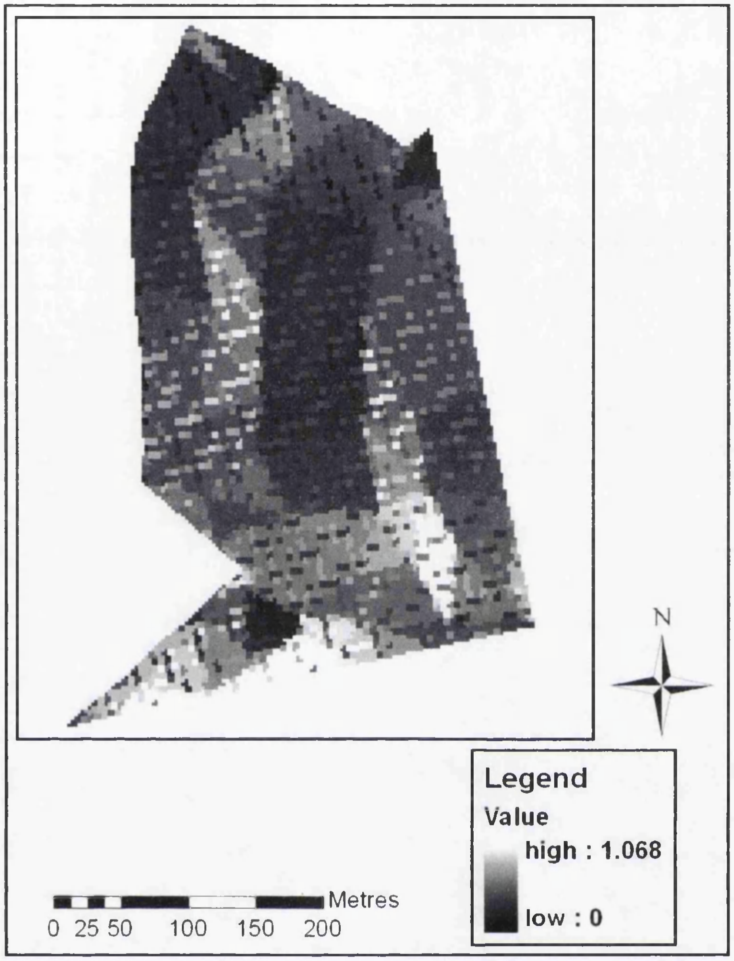


Figure 5.22: Conversion of joint soil loss and 5 m × 5 m plot to raster.

Once the amount of soil gain and soil loss in a cell is known, the net soil gain or net soil loss can be computed using the raster plus whereby values of two rasters are added on a cell by cell basis. The result will produce net soil gain or net soil loss for each and every cell. Specifically, the soil loss and soil gain maps were added together to produce an estimate of net soil loss or soil gain per cell (Figure 5.26). The highest amount of net soil gain obtained is 2.135 42 metric ton and the lowest which is soil loss is 1.068 metric ton. At a glance, this map also shows that the amount of soil gain and soil loss is fair because most of the areas are grey and not much of contrast values i.e. very bright or very dark colours.

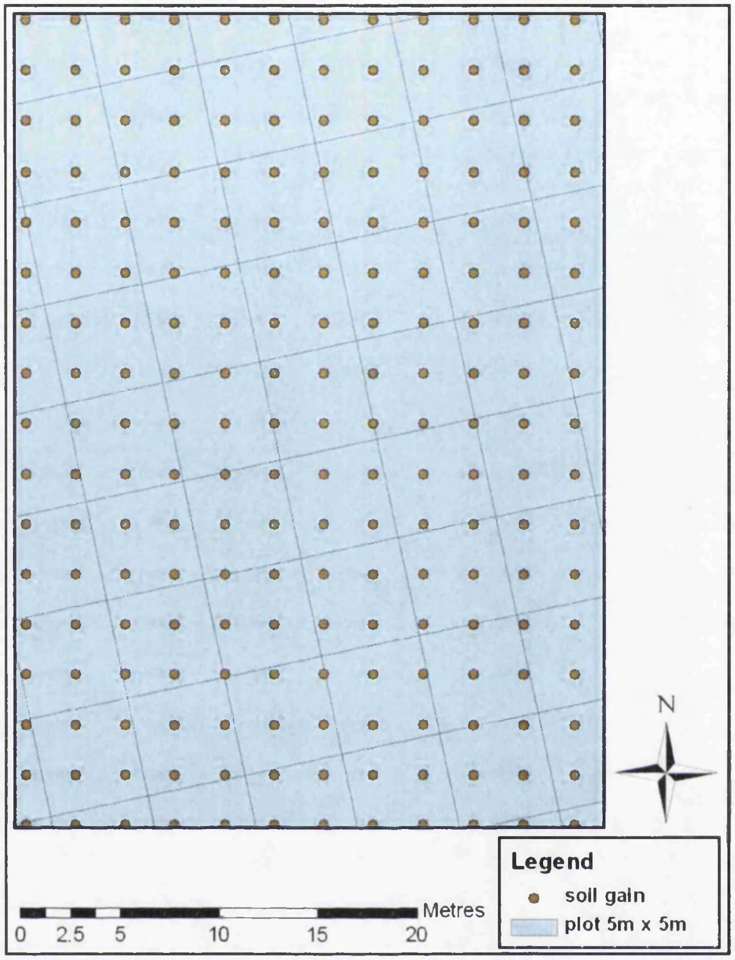


Figure 5.23: Soil gain obtained from Gawk programming.

5.5 Discussion

Discussion of the analysis and observation derived from the research carried out in Section 5.2, 5.3 and 5.4 is given in the following subsections.

5.5.1 Soil erosion prediction

When mapped in the ArcMap^{TM}, the derived values of *LS* factor are found to be proportional to slope of the study area where steep slopes resulted in high *LS* factor. Similarly, as predicted, the map indicates relatively high erosion in areas where steep slopes exist,

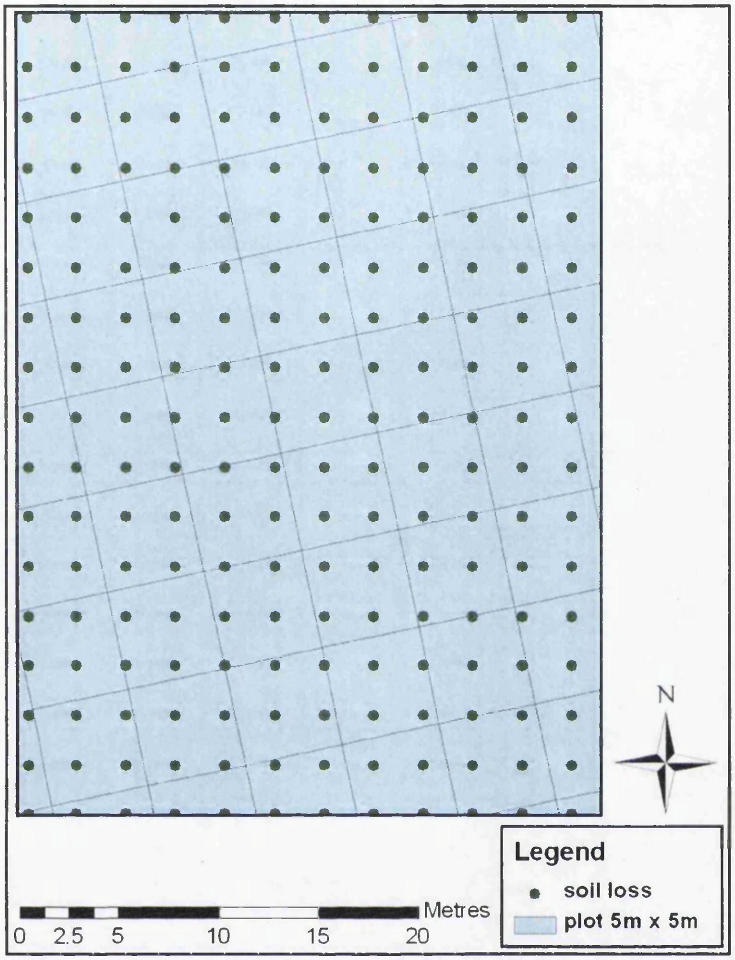
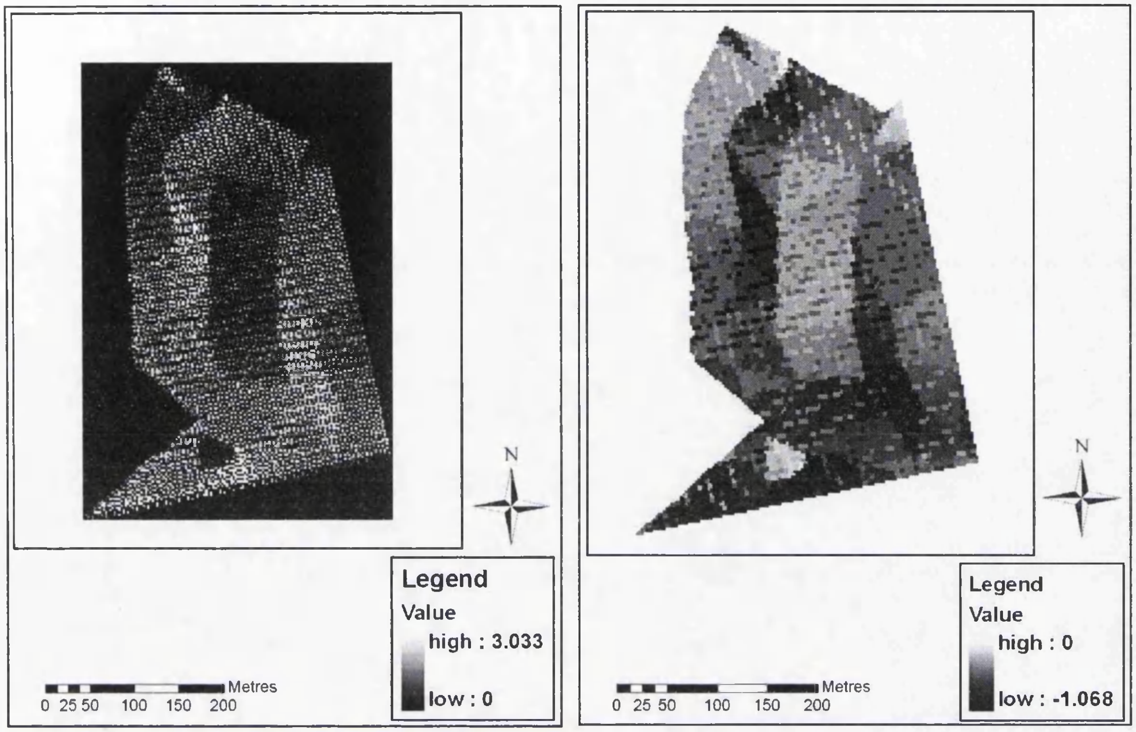


Figure 5.24: Soil loss obtained from Gawk programming.

especially at the southern part of the study area. Besides that, it shows spatial information about the plot sensitivity with respect to the parameters that affect erosion and, hence, shows the zones likely to experience critical soil loss. A total of 0.1325 ha of the study area is identified as being of high erosion risk. This implies that about 1.5 % of the study area has to be excluded from timber harvesting for soil conservation purposes because of soil erosion risk alone. If other features like trees and water bodies that have to be conserved are taken into account, then the area that has to be excluded or protected would become larger.



(a) Soil gain

(b) Soil loss

Figure 5.25: Conversion of soil gain and soil loss from feature to raster.

5.5.2 Harvestable trees

Results of this research show that although the set of rules to select harvestable trees has been followed strictly and carefully, when soil loss and harvestable trees layers are overlaid, there are still trees selected on the high erosion risk area. As a result, there are two implications: firstly, this suggests that if the standard timber harvesting plan is combined with an estimate of potential soil loss using GIS, a more detailed and objective guide to timber harvesting can be produced, which can assist the forest managers in making better informed decision. Secondly, if this tool is employed at a sufficiently early stage, the forest managers will still be able to make changes to their plans, if it is shown that there are crucial needs to do so. Therefore, this acts as a double-check procedure which would also help in monitoring harvesting carried out by loggers and speed up the process of enforcement.

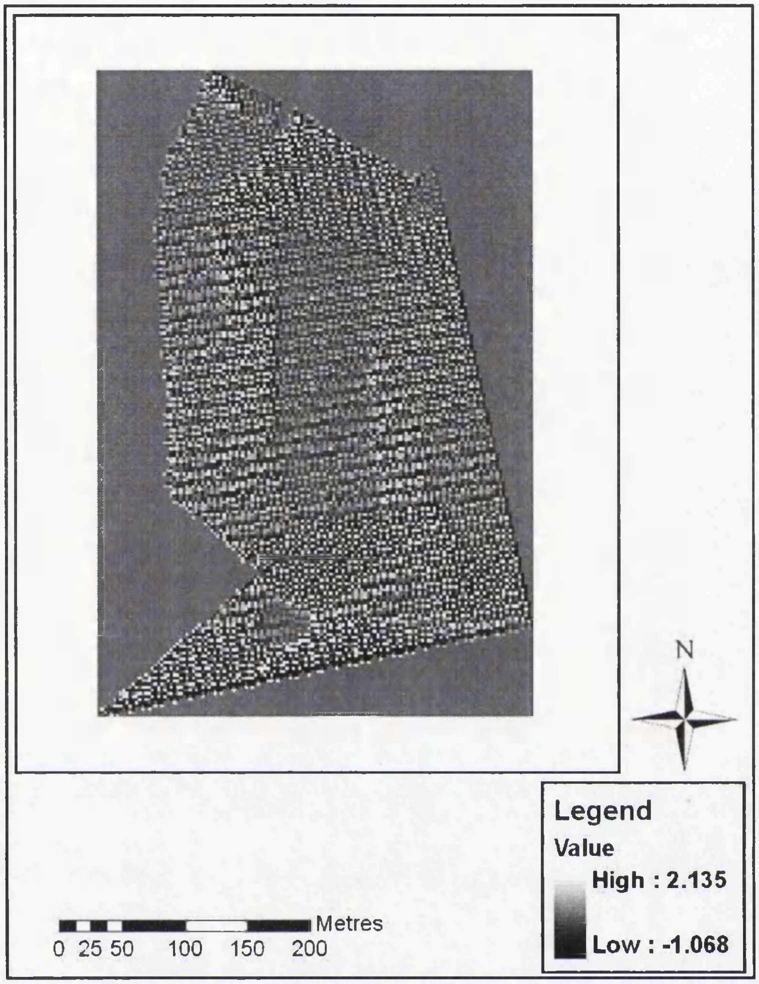


Figure 5.26: Net soil gain/soil loss raster resulted from plus raster.

5.5.3 Soil flow direction

Information of the flow direction of soil loss are vital in this study as it helps in avoiding the soil loss flow area when aligning and building of forest roads are carried out. If this information is not known prior to the forest road construction and the road are built in the soil loss flow pathways, volume of soil loss would be increased and the process would be accelerated. In addition, there are possibilities that the constructed road might be washed away especially during rainy season due to sudden increase in soil and water flow.

Soil gain and soil loss computed in the analysis support result of flow accumulation obtained earlier as they showed that in the process of soil erosion, there are soil moved and deposited along the soil flow direction. The deposition increase with time and hence soil accumulation took place. This analysis also enable the amount of soil gain and soil loss to be measured. In this study, contrary to the standard USLE slope steepness of 9 % and slope length of 22.13 m, the soil loss is calculated from slopes which are divided into smaller sectors along the slope because the cell size has been determined to be the same as the plot size of 5 m × 5 m. Thus, grid-based does not support MSLE and the soil loss and soil gain results might be affected. Probably a grid-based soil erosion model could be applied to obtain more accurate result.

5.6 Summary

This chapter discusses how the soil loss in the study area is predicted using an empirical model of soil erosion, namely the MSLE, which is modified version of the widely used USLE. Apart from a novel method to derive the *LS* factor used in the in MSLE, another innovative aspect of this study is the integration of the soil loss results with ArcGIS$^{\text{TM}}$. The soil loss is not only measured in terms of amount, but also the direction of its flow and the net gains and losses of soil at different locations within the study area. The study discusses how the results of these analysis can help to assist the planning of forest harvesting and road building, because these two activities have significant impacts on forest soils by accelerating the process of soil erosion. Compaction caused by heavy harvesting and extraction machinery, nutrient depletion resulting from whole tree harvesting on infertile sites where rotations are short, and erosion following road building and harvesting on erodible soils are the greatest causes of concern. Therefore, the methods developed in this study, and the results arising from them, could help to identify areas of severe soil-erosion risk, where harvesting and road building might best be avoided. It is also hoped that the results of this work would lead to innovations in the way that forest managers go about the process of estimating potential or actual soil loss in the forest, as there is a continuing need to improve the capability to predict soil erosion in Malaysian forests.

Chapter 6

Optimization of the Route of the Forest Logging Road

Overview This chapter begins with an introduction to forest road construction and its relation to forest harvesting. In this third research component of the GIS-based timber harvesting plan, the aim is to optimize the forest road network so that it is aligned based on results of the determination of the NPA and the identification of harvestable trees in Chapter 4, while being constrained by information on soil loss prediction and hydrological flow direction in Chapter 5. In optimizing the road routing, there are several matters that have to be considered, namely that the road should be: (1) as near as possible to clusters of harvestable trees, (2) away from the rivers and their buffers, (3) avoid high erosion risk areas, and (4) avoid relatively steep land. A number of software problems are experienced in implementing this procedure, but the results obtained in this chapter show how the final timber harvesting plan might be constructed for the study area, which is ready to be implemented in the forest.

6.1 Introduction

Effective forest management very much depends on the construction and maintenance of an appropriate forest road network. Road building is essential to the extraction of multiple-use forest resources; hence, roads must be designed to satisfy a whole range of needs. However, careless logging and road building have been the main causes for environmental degradation in many forest regions. In particular, road building can produce severe negative effects on soil stability, on the local water regime and on landscape quality. Implementing a number of measures during all three stages of the road construction process (planning, construction and maintenance) can reduce these environmental impacts. Generally speaking, careful route selection, the avoidance of unnecessary earth-moving and the construction of an effective drainage system yield the best results (Spinelli and Marchi, 1998).

The main sediment sources created by the selective harvesting of tropical rainforests come from building access roads, as well as log haulage tracks, which often extend the drainage network. When not monitored, these tracks develop into gullies that continue to erode long after the logging has ceased (Douglas, 2003). In forest lands, the stream channels receive the highest amount of sediment during road construction activities owing to removal of vegetation cover from road surface, cut-slopes, fill-slopes, and ditch areas. Sediment delivered from a road section to streams causes serious damages to local water resources and aquatic life (Akay et al., in press). The extent of soil disturbance associated with bulldozer yarding and the re-growth of woody vegetation on skid trails in selectively logged dipterocarp forest have been examined by Pinard et al. (2000) who found that in areas logged using conventional (i.e. uncontrolled) harvesting methods, about 17 % of the area was covered by roads and skid trails. On the other hand, in an experimental area where RIL guidelines were implemented, only 6 % of the area was similarly disturbed. Skid trails with subsoil disturbance in the RIL areas were less than half as common than that in conventional logging areas. Likewise, four years after logging, woody plant recovery on skid trails was greater in areas logged by RIL than by conventional methods. Both species richness and vegetation density increased with time since logging, but even 18 years after logging, abandoned skid trails were poor in small woody stems compared with the adjacent forest. Therefore, minimizing soil disturbance during logging and road construction allows more rapid recovery of vegetation on bulldozed soils.

One of the main timber extraction methods involves the use of tractors and chains. The employment of this technique has enormous hydrological impacts, as it involves varying degrees of disturbance to the subsoil. This disturbance results in differential compaction and the development of a high level of spatial variability depending on the precise location from which individual trees are extracted. The main processes involved with this method include construction of log landing sites, where trees are collected together prior to transportation from the area, and the use of skid roads radiating from these landings to the main clusters of harvestable trees. Once the trees are felled they are then dragged by tractors, via the skid trails, to the log landings. Thus, the level of disturbance is conditioned by the number of tractor passes, involving areas of heavy soil compaction and other areas where soil is disturbed only to a minimal extent (Brooks and Spencer, 1997). Apart from that, the use of machinery depends on the slope (gradient) of the ground. Steep slope gradients require the use of cable logging (towers), while less steep ground can be handled using skidders (tractors). Access roads, which are usually quite short, are needed to connect the existing road network with the points where machinery is installed (Legues et al., 2007).

From a study carried out in the Chilean forestry industry, Epstein et al. (2006) note that harvesting and road network construction account for around 55 % of total production costs. Production costs include machinery installation and operating costs, the cost of road construction, and the cost of moving timber beyond the harvesting area. Parts of the harvesting area may be left unharvested if the production costs per cubic meter exceed the established ceiling. Therefore, if timber harvesting activities and forest road network construction are cautiously and properly designed, both the production costs and the environmental degradation can be reduced.

This chapter intends to optimize and align the forest road network in the study area based on the selection of the harvestable trees and the potential for soil loss predicted in the NPA. There are several requirements that have to be considered, i.e. the road should:

1. Be as near as possible to clusters of harvestable trees
2. Be away rivers and buffers
3. Avoid high erosion risk areas
4. Be on relatively less-steep land.

The result would induce a very important problem-solving in designing forest road in the production forest.

6.2 Forest Road Network in Malaysia

Forest roads in Malaysia include main roads, secondary roads, feeder roads and skid trails (Forestry Department Peninsular Malaysia, 1999). Main roads are dual-lane roads in or out of a forest area that are designed to accommodate a high number of vehicles (notably timber haulage lorries) to transport logs to the sawmill. Secondary roads are single lane roads connecting a feeder road to a main road for the purpose of log transportation, rehabilitation and monitoring works. The main and secondary forest roads are permanent roads that normally have an all-weather running surface with the formation width of between 9 m and 12 m, or 8 m and 10 m, respectively. Feeder roads are temporary roads which are used to transport timber by lorry out from a harvest site. These roads are generally unsurfaced and are used only during timber extraction. Skid trails are routes from the main, secondary or feeder roads made by wheeled skidders, crawler skidders or crawler tractors (Sist et al., 1998) to transport timber from the stump to the log landing areas. In Malaysia, ground skidding is the principal method for moving logs from where a tree is felled to the landing area where the timber is loaded onto haulage lorries (Jusoff and Mustafa, 1996). Logs are dragged behind the skidder or tractor using a cable and winch.

All roads should be carefully designed according to the proposals of the Forestry Department in *Forest Road Specification 1988* with cross drains at certain intervals. Within the Peninsula Malaysia, the Standard of Performance (SOPs) guidelines for forest road lay-out, including drainage requirements and conservation of buffer strips along streams and rivers, are as follows:

1. The density of feeder roads must be less than or equal to 40 $\mathrm{m{\cdot}ha^{-1}}$
2. The density of skid trails must be less than or equal to 300 $\mathrm{m{\cdot}ha^{-1}}$
3. The corridor width for feeder roads must be less than or equal to 15 m
4. The gradient of feeder roads must be less than or equal to 20 %, but will follow natural benches and topographic features when using existing roads or when newly specified by the FD's Forest Engineer
5. The road camber (ie surface curvature) of feeder roads must be at least 5 %
6. The cross-fall (ie average transverse slope) for feeder roads must be at least 3 %
7. The carriageway of feeder roads (single lane) must be at least 4 m wide, except at corners and lay-bys
8. V-shaped, earth side-drains must be constructed along feeder roads
9. Adequate culverts (made from hollow logs, concrete, metal or High Density Polyethylene) must be located at stream or river crossings, where required, or as specified by the FD's Forest Engineer
10. Bridges (made from timber, concrete box culvert, or steel) must be at least 3.5 m in width at stream or river crossings, where required
11. Silt traps must be constructed in erosion prone areas along feeder roads, as specified by the FD's Forest Engineer
12. Buffer strips for permanent streams and rivers in Inland Dipterocarp Forest and Peat Swamp Forest must be at least 5 m wide on either side of the stream or river
13. Buffer strips for all perennial streams must be demarcated and felling of trees within these zones is prohibited (Malaysian Timber Certification Council, 2001).The RIL

> procedures which aim to improve the sustainability of timber production and reduce wider environmental damage include: (i) optimizing the skid-trail networks, given a knowledge of the exact location of each tree to be felled; (ii) minimizing stream crossings; (iii) minimizing skid trail earthworks; (iv) maintaining canopy cover over skid trails; (v) construction of water bars on unused haulage roads, and critically (vi) careful supervision of all forestry operations (Chappell et al., 2004a).

Forest road or skid trail construction is an integral part of the logging of tropical rainforests. Where primary transportation is by ground skidding, rather than cable yarding, skid trails then extend out from the lorry haulage roads. The haulage roads and most used skid trails become compacted by vehicle use, giving reduced near-surface permeability. Skid trails commonly cover 20 % to 40 % of the operational area of commercial forests after selective logging or clear-cutting (Malmer and Grip, 1990). Skid trails are systematically aligned parallel to one another, as far as natural features allow. Both uphill and downhill skidding are permissible, but sharp curves are avoided. Skid-trail alignment is based on the assumptions that an average log, say 20 m in length, will be extracted with a winching distance of no more than 15 m, and a tractor backing-up distance of 7 m to winch out logs (Cedergren et al., 1996). A cable wire is used for winching. Skid-trails are opened up before felling and intermediate-size trees along the skid-trails are marked with paint in an attempt to avoid damaging them. During the logging operation, tractors are not allowed to open up new tracks or to deviate from the aligned trails while skidding out logs.

Trees are usually felled towards skid-trails. An angle of about 45° between felled trees and skid trails is attempted, except for trees close to skid trails, which are supposed to be felled into the skid trail. Tree crowns are directed to fall into skid trails to minimize gap creation. Trees that cannot be felled towards skid-trails are felled in a direction that will cause the least problems when winching out the logs to the tractor. As can be seen from this discussion, logging involves close teamwork, with frequent communication between skilled fellers, tractor operators and hook men (Forshed et al., 2006).

6.3 Optimization of logging road using GIS

Apart from roads, other Linear Engineering Structures (LES) such as natural gas and oil pipelines, irrigation-drying channels, power lines and railways cover larger areas than other technical infrastructure facilities. Because of the need of route selection, LES require strategic planning, evaluation and management. The operations to choose the optimum route for such features depends on the effective collection, processing, storing and analysis of spatial data, such as that pertaining to topography, vegetation, geology, soil type and land use. This demands the use of GIS technology, which provides an effective spatial data management system. In this context, where much of the base data used in this study is held in raster format, using raster network analysis has some advantages for route selection operation. Generally, route selection operations are determined optimally so as to minimize some cost function. But, in some developing countries, route selections operations are determined by medium-scale topographic maps and only slope (gradient) data are taken into consideration (Yildirim et al., 2006).

In the process of optimizing the logging road network in the study area, several prerequisites have to be considered, based on the research results obtained in the preceding two chapters; specifically, the logging road must:

1. Be as close as possible to clusters of harvestable trees
2. Be away from rivers and their buffers
3. Be away high erosion risk areas
4. Be located along relatively less steep land.

An attempt was made to meet these prerequisites in ArcGIS 9^{TM} using the Spatial Analyst tool set. In this study, the suitable area to build logging roads must be determined first,

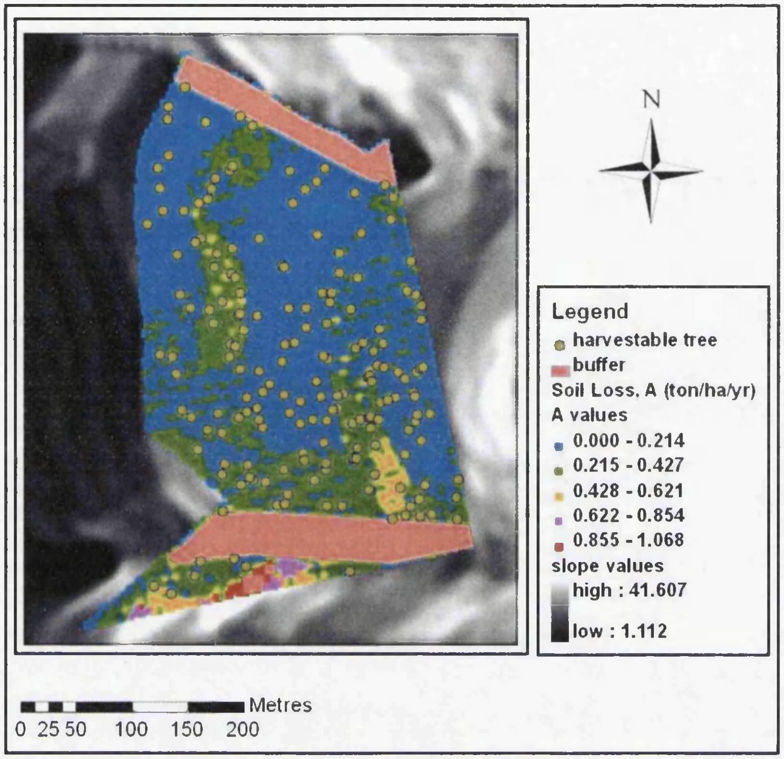


Figure 6.1: Base map for forest road in the study area.

before the roads can be aligned. Therefore, identifying the relevant input data sets relevant to the suitability of the area is very important. Based on the requirements outlined above, there are four layers of data that are needed. These are information on the potential soil loss, on the river buffer zones, on the terrain slopes (gradients) and on the locations of the harvestable trees. These are overlaid in Figure 6.1 to produce the basic map for this study.

Since the study area is mountainous and the roads ideally need to be built on the least steep areas, the terrain slope (gradient) of the study area has to be considered. The terrain gradient is derived from the elevation data, the result of which is presented in Figure 6.2. In this figure, the red areas are ones that have steep slopes, whereas the green areas indicate relatively gentle slopes.

In addition to terrain slope, another factor that has to be considered is the distance

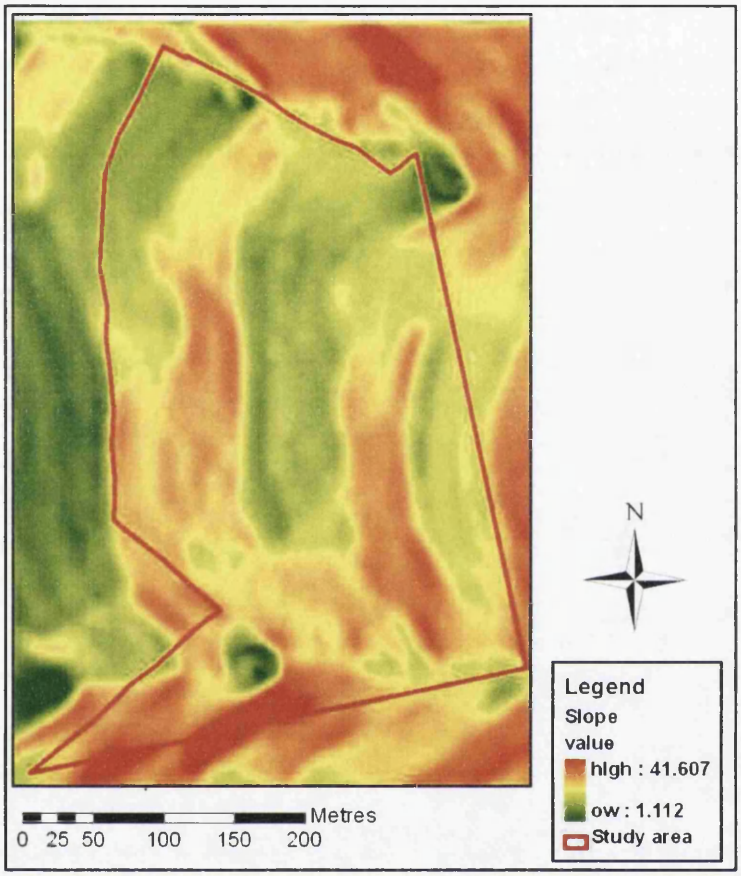


Figure 6.2: Derived terrain slope (gradient; degrees) of the study area.

from the road or skid trail to groups of harvestable trees. Evaluating this distance implies that the harvestable trees are grouped into clusters first. This can be achieved by applying buffer of 10 m around each tree. A buffer of 10 m is chosen in this study for two reasons: 1) based on the assumption that it is the acceptable distance to drag logs behind the skidder or tractor using a cable and winch from the tree; and 2) it is the most appropriate distance to group trees which are close to each other. The net effect of this procedure is that trees which are 10 m or less apart are grouped together as shown in Figure 6.3.

For future work, another way of grouping the harvestable trees is to apply a morphological filter which is sometimes known as dilation. By following the dilation procedure

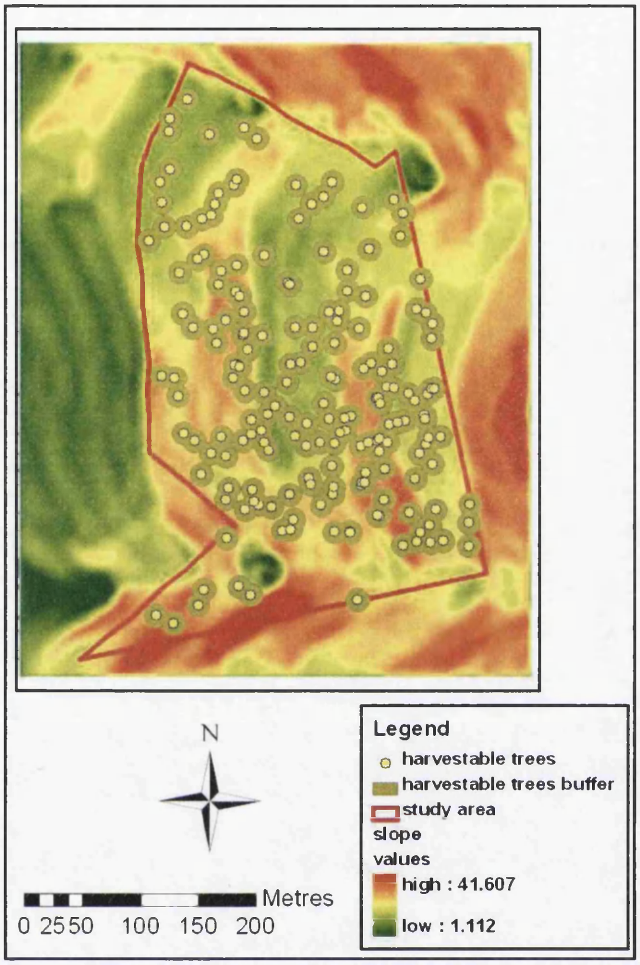


Figure 6.3: Buffer of 10 m around the harvestable trees.

with a second morphological filter, known as erosion, a cluster point can be established. Dilation, in general, causes objects to dilate or grow in size; erosion causes objects to shrink. The amount and the way that they grow or shrink depend upon the choice of the structuring element. Dilating or eroding without specifying the structural element makes no more sense than trying to lowpass filter an image without specifying the filter (Young et al., 2003).

It is preferable that the road passes as near as possible to the clusters of trees. For this reason the straight line distance from the harvestable trees is calculated, the output of which is shown in Figure 6.4. The values in this figures indicate increasing distance from

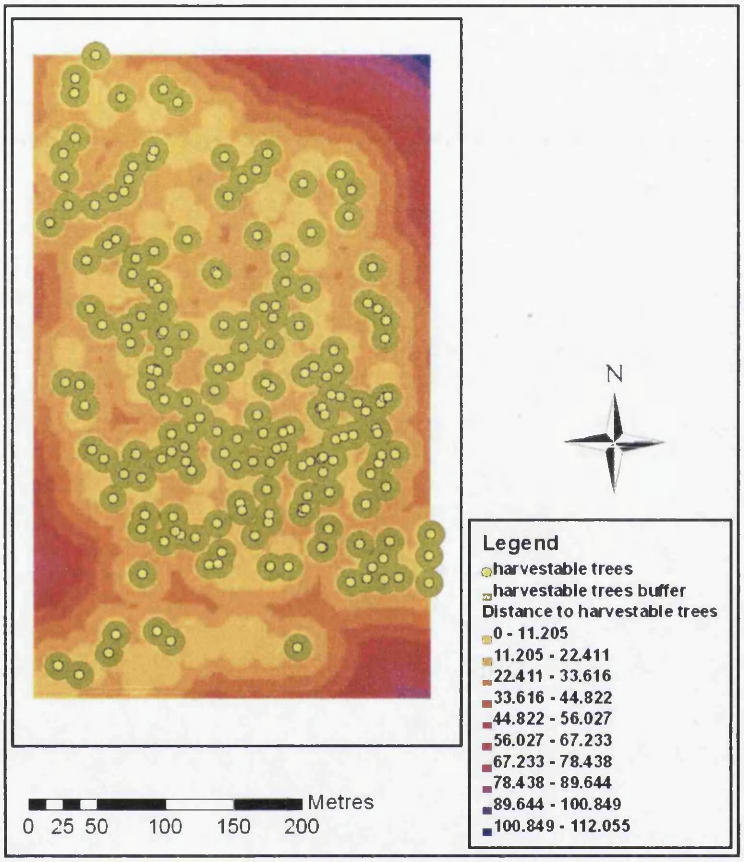


Figure 6.4: Distance to harvestable tree buffer.

the previously determined buffer zones around the harvestable trees.

In this study area, rivers and terrain slopes with a gradient of more than 40° are also buffered, so that they can be conserved (i.e. no logging or road construction is performed in these areas). Roads should preferably be built away from these regions. Therefore, the straight-line distance is computed from these zones, and the result is shown in Figure 6.5. After each of the foregoing data sets has been prepared, the next step is to combine them to establish the potential locations for road construction. To combine the data sets in a meaningful way, they must first be set to a common scale. In this study, the data sets have been re-classified onto a scale with the range 1 to 10, where higher values indicate

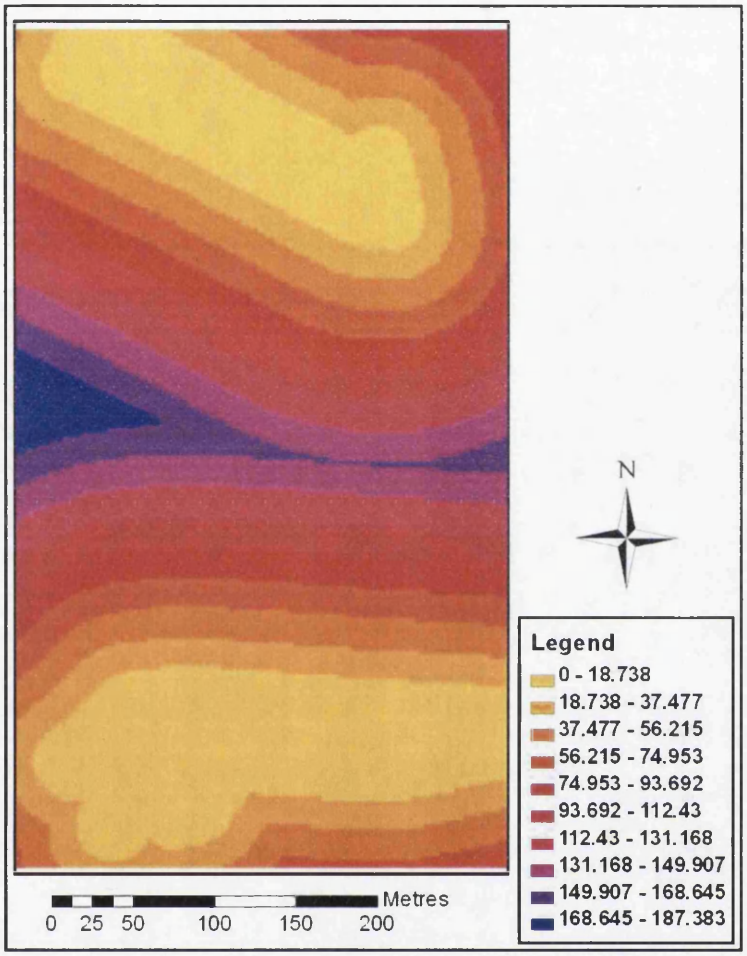


Figure 6.5: Distance to river and steep-slope buffer zones.

land that is more suitable for locating the logging road. For example, since it is preferable to build roads on less steep slopes, the slope layer is re-classified such that the value 10 is assigned to the slopes with smallest gradient and 1 to those with steepest gradient, as demonstrated in Figure 6.6. It is assumed that there is a linear relationship between slope gradient and the suitability for road construction.

As for the groups of harvestable trees, the roads should be located as close as possible to them, therefore the relevant data set is re-classified by assigning a value of 10 to areas closest to the harvestable trees (the most suitable locations) and a value of 1 to areas that lie at some distance from them. Once again, a linear relationship is assumed between

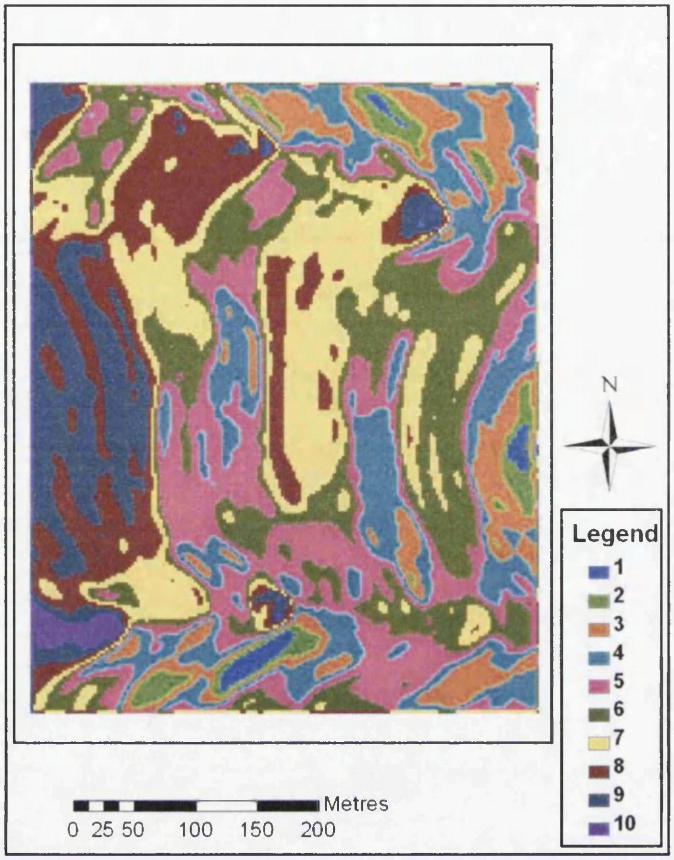


Figure 6.6: Reclassification of terrain slope (gradient) within the study area on the basis of the suitability for road construction.

distance and suitability. The result is presented in Figure 6.7.

It is also necessary to locate the road away from the river and steep slope buffer zones, therefore the distance to these buffer zones is re-classified into a set of ten discrete classes. Here, though, a value of 10 is given to areas that lie farthest away from the river and steep-slope buffer zones and a value of 1 is given to those areas nearest to these buffer zones. The results are presented in Figure 6.8. Once again, a simple linear relationship is assumed between distance from the buffer zones and relative suitability for road construction.

The final requirement is to build the logging roads on land that has the least potential for soil loss. Therefore the soil loss data set is re-classified into ten discrete classes, such

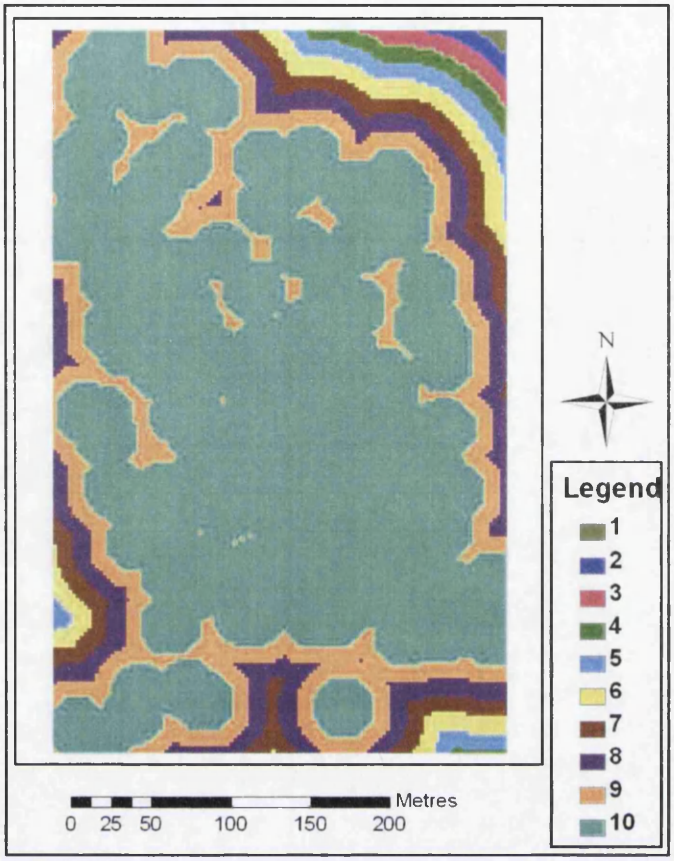


Figure 6.7: Re-classification of the distance to the harvestable tree buffer, which is used to assess the relative suitability of land for road construction.

that a value of 10 is assigned to areas with low potential for soil loss and a value of 1 is assigned to areas with high potential for soil loss. The result is presented in Figure 6.9. Once again, a simple linear mapping has been made between the potential for soil loss as predicted by the MSLE and the ten classes shown in Figure 6.9; in effect, the original continuous data have been discretized.

After the reclassification process outlined above, the data sets can be combined to find the most suitable locations for road construction. If all data sets were equally important in determining the location of the roads, this would be a relatively simple task of combining the data sets additively. However, if one data set (e.g. potential soil loss) has greater impact on the decision than the others, some kind of weights need to be given to each of the

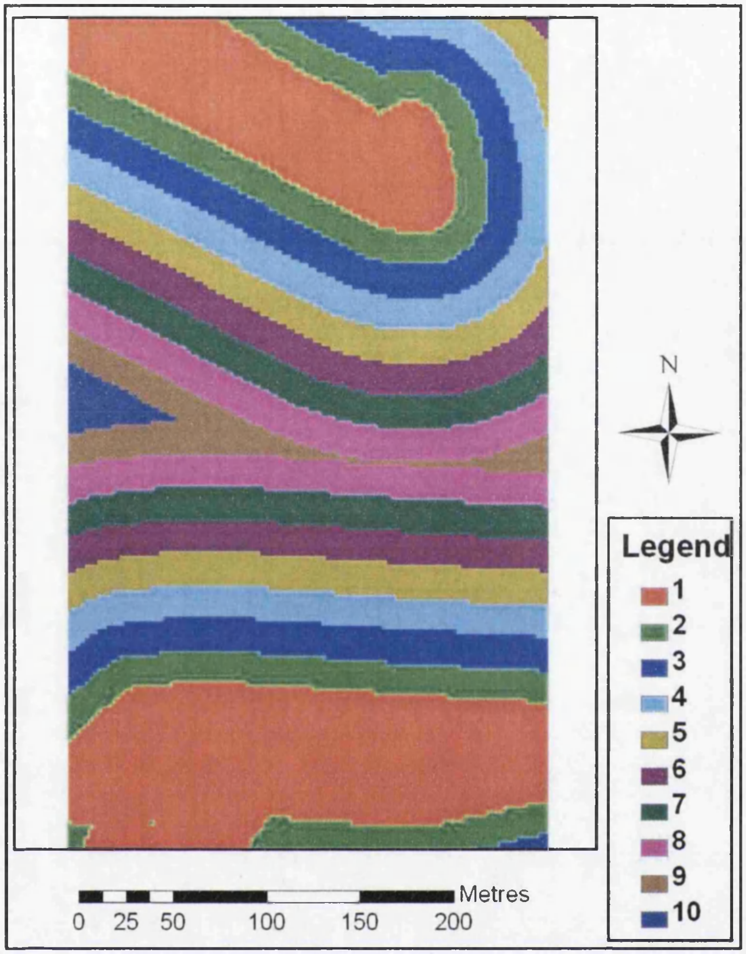


Figure 6.8: Re-classification of the distance to buffer for road suitability.

data sets, giving each a proportional influence, and a decision must be made as to whether the data sets combine in a simple linear (i.e. additive) or non-linear (i.e. multiplicative or more complex) manner. The higher the weighting factor, the more influence a particular data set will have in determining the outcome of the land suitability model. In this study, the proportional influence values (i.e. the weights) for the different layers are as follows and each percentage is divided by 100 to normalize the values:

slope (gradient) 0.3 or 30 %

distance to harvestable tree buffer zones 0.3 or 30 %

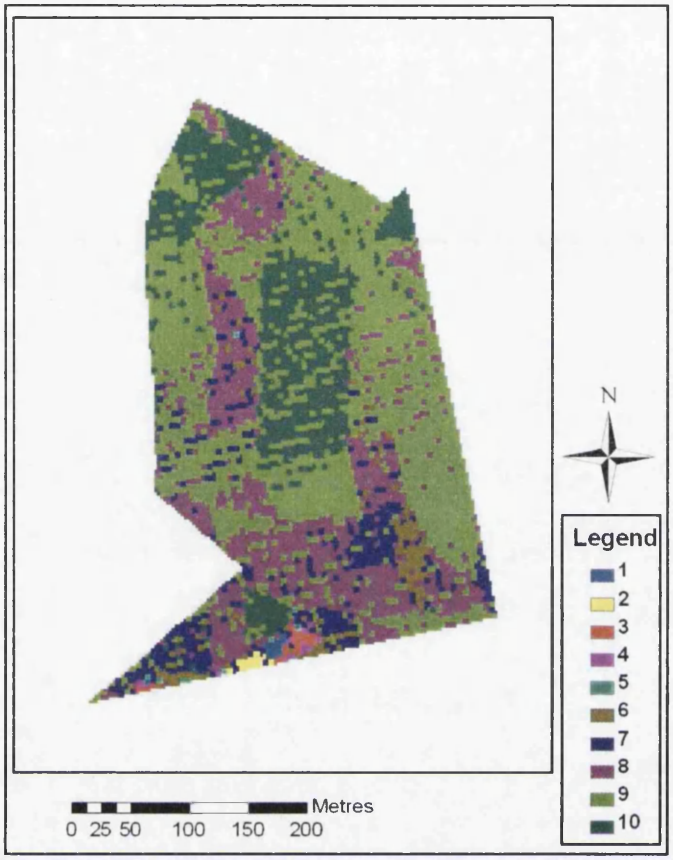


Figure 6.9: Re-classification of the potential soil loss data into ten discrete classes based on the relative suitability for road construction.

distance to river and steep-slope buffer zones 0.1 or 10 %

potential for soil loss 0.3 or 30 %.

The above percentage are chosen to start with the simplest model. 30 % is chosen for the three layers because all three are equally important whereas distance to river and steep-slope buffer zones layer is less important as the river and steep-slope have already been buffered. Each of the data sets is then multiplied by its weighting factor and the results are combined additively using the Raster Calculator in the Spatial Analyst tool, i.e.

$$\text{suitability} = \mathrm{w}_{\text{slope}}.\mathrm{f}_{\text{slope}} + \mathrm{w}_{\text{tree distance}}.\mathrm{f}_{\text{tree distance}} + \mathrm{w}_{\text{river}}.\mathrm{f}_{\text{river buffer}} + \mathrm{w}_{\text{soil loss}}.\mathrm{f}_{\text{soil loss}} \tag{6.1}$$

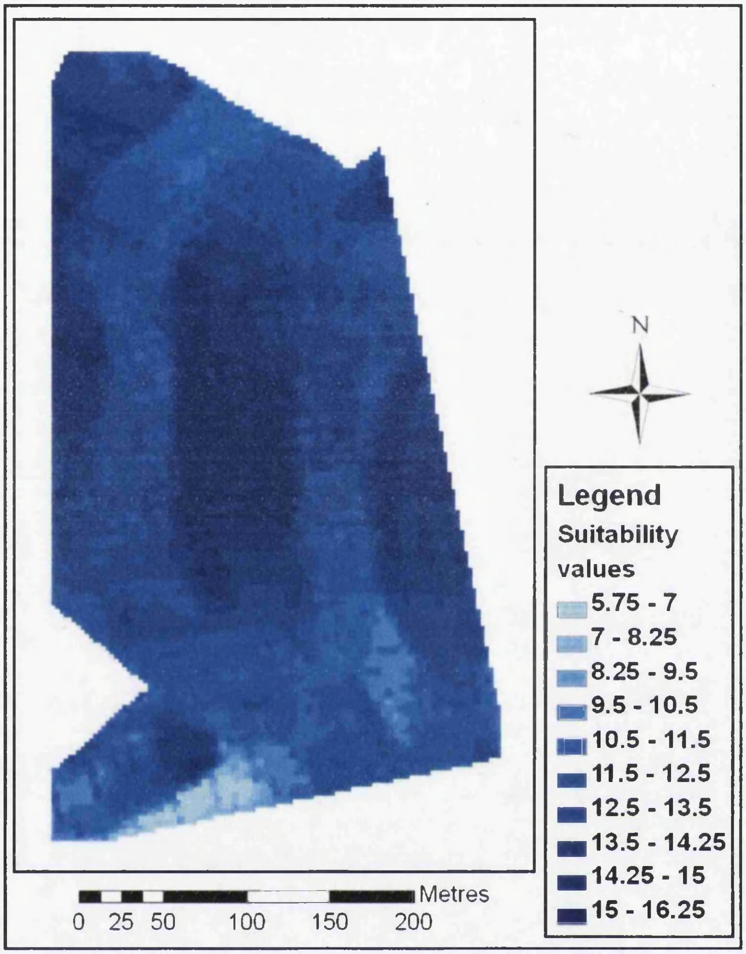


Figure 6.10: Relative suitability of land for logging road construction.

where f_i is factor *i* and w_i is the weight assigned to that factor, and suitability is the relative suitability of that land for road construction. The output is presented in Figure 6.10. This figure shows how suitable each location is in terms of constructing the logging road, according to the criteria set in the suitability model. Higher values (dark blue) indicate locations that are more suitable.

Finally, the best route for the logging road has to be evaluated. First, the cost data sets have to be created by deciding which datasets are required, reclassifying them to a common scale, weighting and combining them. Then the cost weighted distance using Source and Cost datasets are performed which created a raster where the value of each cell is the accumulated cost of traveling from each cell back to the source. To find the shortest path, a Direction dataset is needed, which can be created as an additional dataset from the cost weighted function. This resulted in a raster of the direction of the least costly path from each cell back to the source. This function finds the least accumulative cost for migrating from each cell of the resistance layer to the nearest, cheapest source. The explaining method of the Cost Weighted Distance tool is the least-cost algorithm. To move from cell N_i to cell N_{i+1}, the cumulative resistance is calculated as the resistance to reach cell N_i plus the average resistance to move through cell N_i and N_{i+1}. The function is based on an eight-neighbour-cell algorithm. As a result, also diagonal movements are allowed. In case of diagonal directions, the cost is multiplied by $\sqrt{2}$ to compensate for the longer distance (Dedecker et al., 2007).

First, the so-called 'source' and 'cost' data sets have to be created, so that they can be used as input into a cost weighting function. In this study, the source data set indicates where the road construction starts and the destination data set indicates where the road finishes which is in this case the groups of harvestable trees, and this can be generated from the suitability map shown in Figure 6.11. Then, a data set of the 'cost' of constructing the road, based on the fact that it is more costly to construct road on steep slopes and at the same time avoiding areas of high erosion. Therefore the slope and the soil loss data sets are reclassified. However, unlike the re-classification performed for the suitability model where steep slopes and high erosion areas were given classification value of 1, this time the steep slopes and high soil loss values are given high classification values of 10 because both features would need high cost to build roads on. The results of the two re-classifications are shown in Figure 6.12 and Figure 6.13, respectively.

Combining the two results described above by adding their rasters, produces a single data set of the cost of building logging road at each location, in terms of the steepness of the terrain slope and the potential for soil loss. Here, equal weights are applied unlike the suitability model because both slope and soil loss datasets are equally important. There-

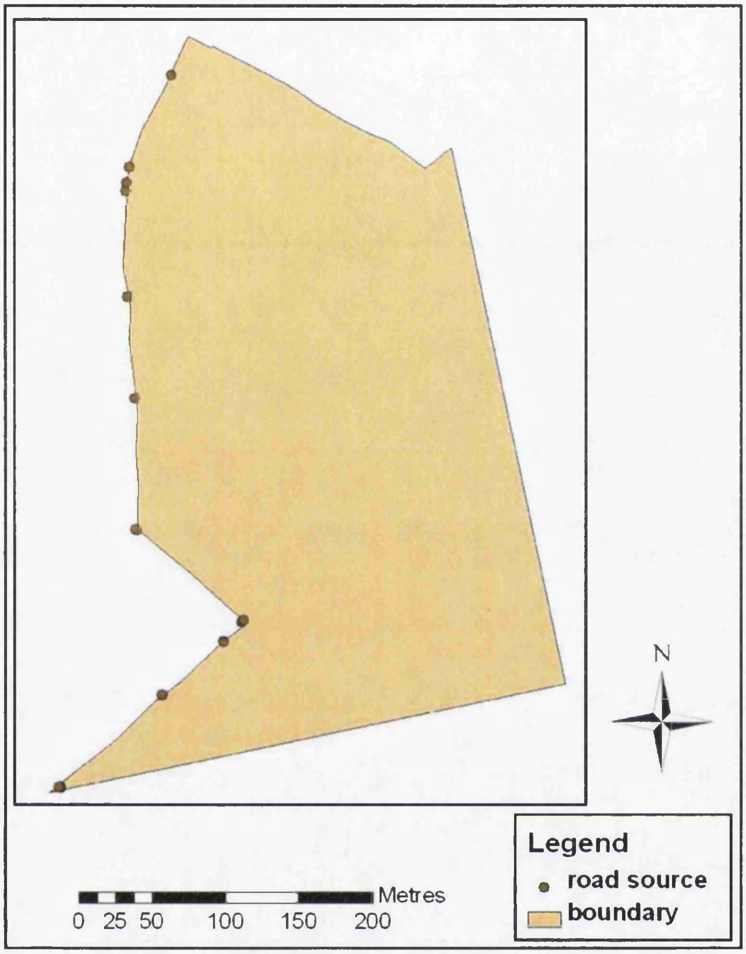


Figure 6.11: Source data set for cost weighted distance.

fore, in this model, both data sets have equal weighting, so it is not necessary to apply weights as was performed with the suitability model. Using Raster Math in Spatial Analyst Tool, the two data sets are combined additively to produce the cost data set shown in Figure 6.14. This figure shows locations for which the relative cost of road construction is likely to be low.

Using the cost and the source data sets and the Cost Weighted Distance algorithm in the Spatial Analyst tools, two further data sets are created, namely distance and direction. Each cell in the distance data sets (Figure 6.15) contains a value representing the accumulated least cost of constructing a logging road to the harvestable trees, while the direction

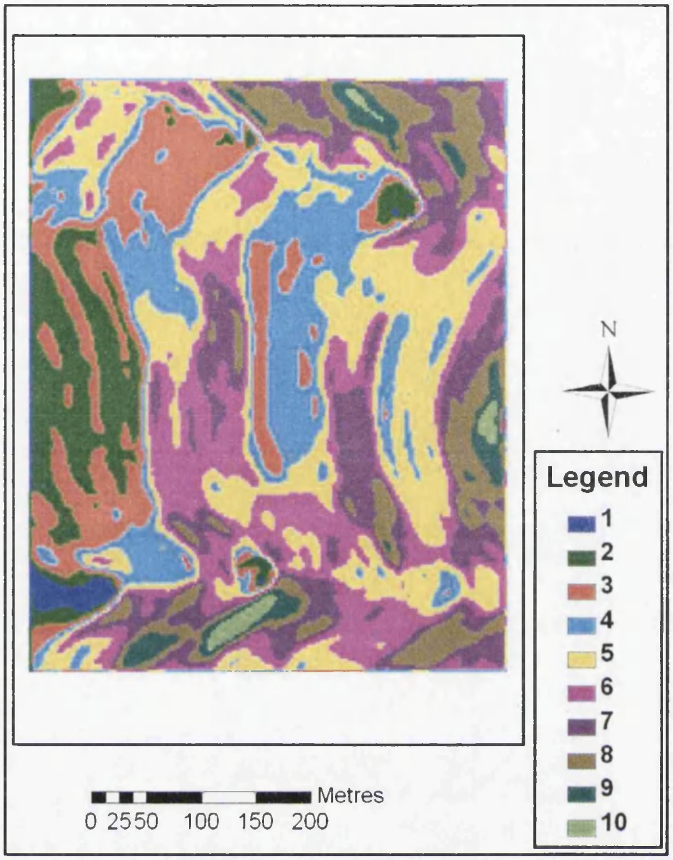


Figure 6.12: Reclassification of the terrain slope (gradient) data set to show the relative cost of road construction.

data set (Figure 6.16) gives the direction of the least-cost path from each cell back to the source.

To find the shortest path from the source to the harvestable trees, a destination data set has to be created. In this case, the destination is the buffered group of harvestable trees. When this is overlaid with the cost weighted distance data sets, the optimum area for the logging road can be visualized as in Figure 6.17. The best area is the one coloured grey, followed by red and orange. The cost distance to build roads to the harvestable trees ranges between 0 and 155.85. This information is vital to the forest managers as they can know how much allowance they could give to the loggers during the road construction. When the shortest path is performed in this study, the result did not produce the expected

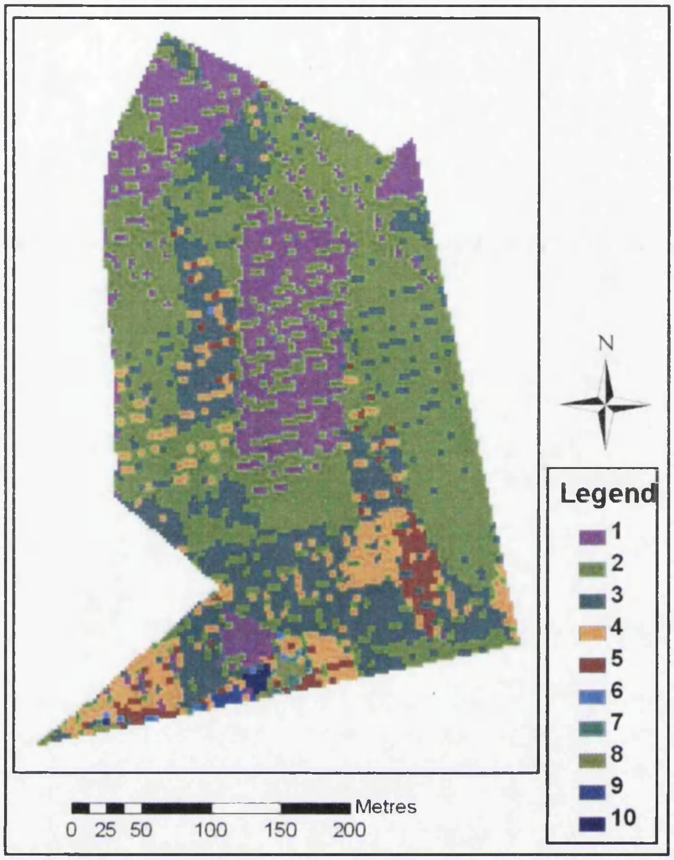


Figure 6.13: Re-classification of the potential soil loss data set to show the relative cost of road construction.

result. The shortest path was computed only for a small part at the southwest of the study area as shown in Figure 6.18. Therefore, based on result in Figure 6.17, a sample of an optimum logging road are digitized as presented in Figure 6.19(a). As much as possible the road is digitized in the grey area, however if need be, the road can be digitized on the red or orange area like for crossing or etc. This analysis is not constrained by pre-existing logging road access to the study area and hence, entry could be made from any angle. However, in real operations there would have to be a link to external access that might affect part of the road layout.

As a comparison, road built by loggers during the harvesting phase is shown in Figure 6.19(b). The figure indicates clearly the difference of the road aligned using GIS and the

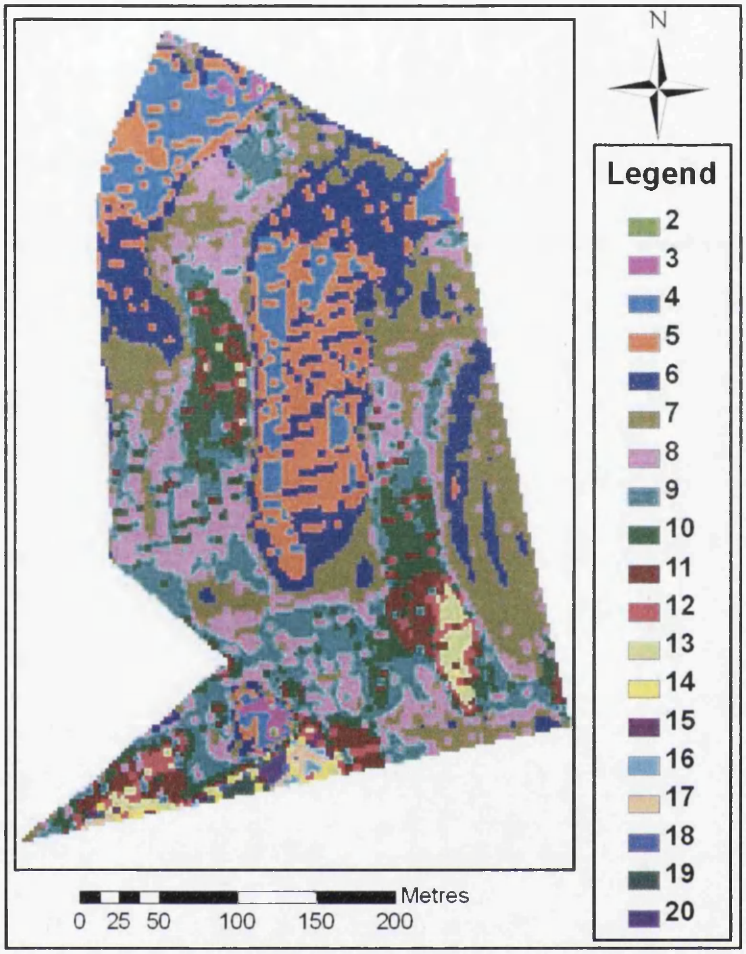


Figure 6.14: Cost for building logging road in the study area.

road built by loggers, without using the GIS. The road built by the loggers passed through the steep slopes which should be avoided and also passed through the centre of group of harvestable trees. These are the examples of monitoring of the loggers' harvesting activities by the forest managers. With this information, the forest managers could easily make decision whether the loggers have been carrying out the timber harvesting wisely and sustainably or not.

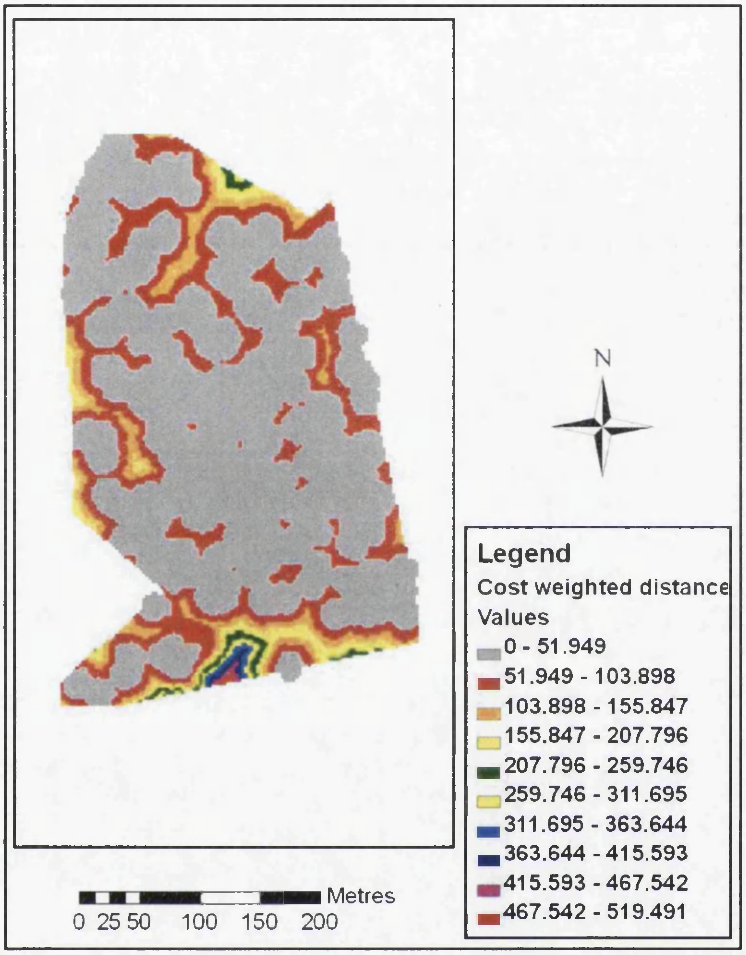


Figure 6.15: Cost weighted distance to the harvestable tree buffer.

6.4 Summary

This chapter has demonstrated how logging roads can be designed and aligned using ArcGIS 9^{TM} Spatial Analyst tools based on the soil erosion and harvestable tree datasets obtained in Chapter 4 and 5. The optimization of forest logging road location is the third component of the development of a GIS-based timber harvesting plan for Bubu FR and therefore completed harvesting plan for the study area. Although the exact road alignment could not be obtained automatically using Spatial Analyst tools, the optimum areas for logging road construction has been acquired which helps forest managers in the monitoring and enforcement of harvesting and road construction activities.

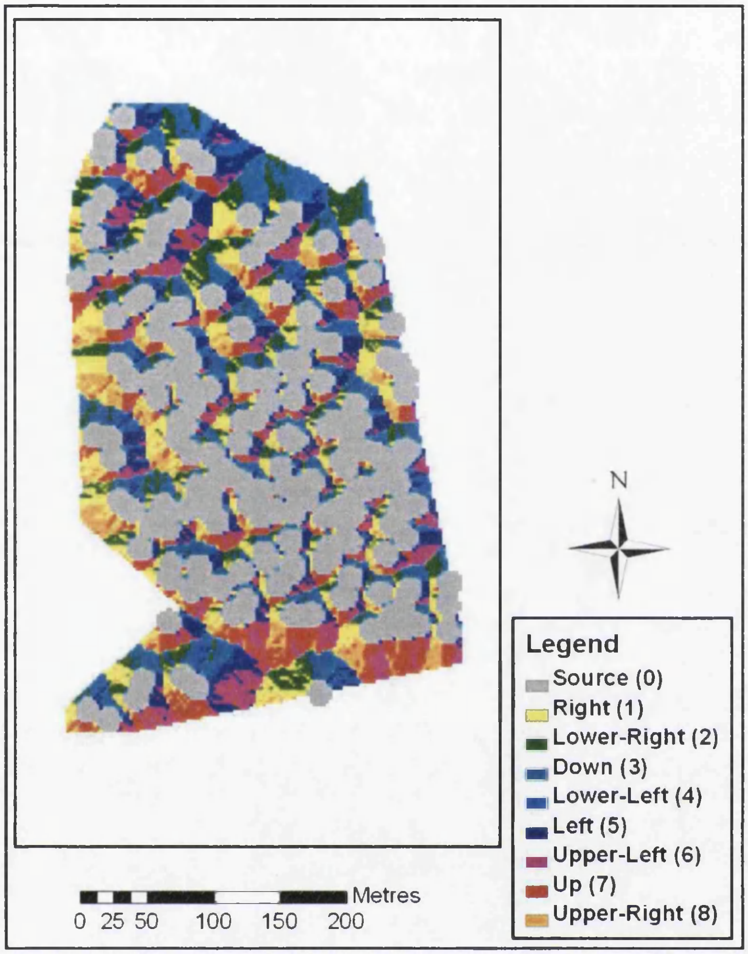


Figure 6.16: Cost weighted direction to harvestable tree buffer.

There are several indirect observations that can be derived from the results obtained in the previous section. The main aim of the study in this chapter is to align the optimum logging road in the study area. However, along the process, there are other advantages captured. For example, before the logging road could be aligned, the areas suitable for building logging roads should be identified first in the suitability model. The result shows that the areas suitable for the logging road comply with low soil loss areas and not in buffered areas. Secondly, the cost of building the road is calculated by taking into account factors like steep slopes and high soil loss values which are the most obvious factors that will increase the road-building cost. In reality, the slope steepness might be taken into

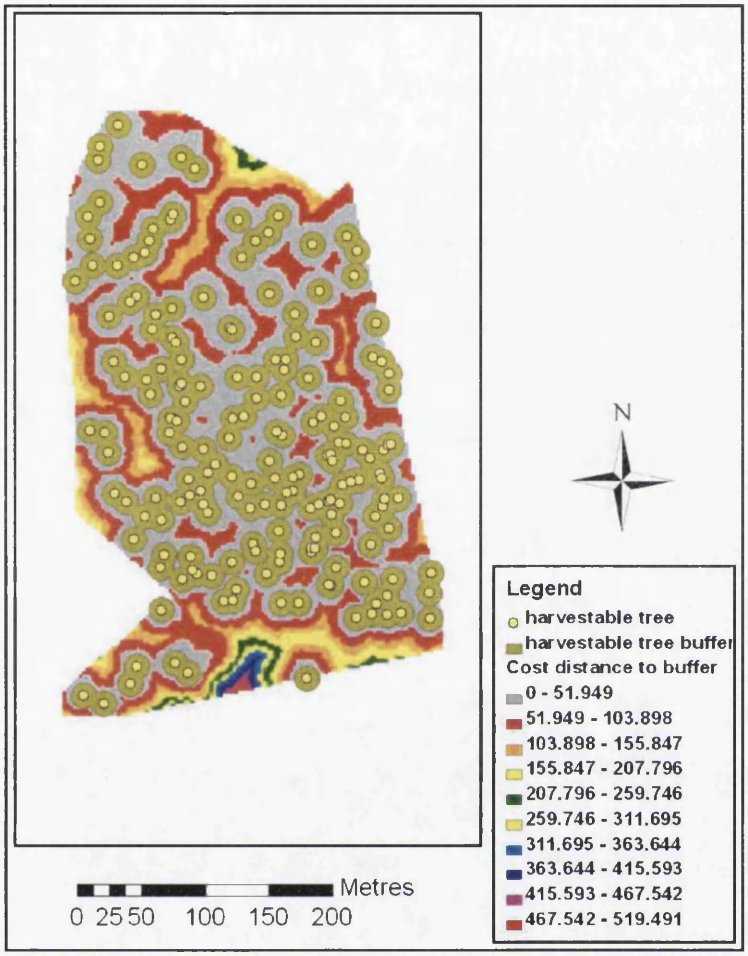


Figure 6.17: Optimum area for logging road.

account when constructing the road because it can be easily visualized, however, it is not easy to consider the soil loss factor. Thirdly, the shortest path or the optimum road can be drawn easily in the map of the study area as to compared to the manual drawing of the logging road. Although it did not really work in this study, the cost weighted distance presented an optimum area for logging road construction. More has to be explored in future work for the shortest path analysis tool to be able to apply.

In future, another method which can be explored is that by using the morphological filter, known as erosion, a cluster point can be established. The logging road can be aligned by passing through the centre point which accommodates trees at both sides, then

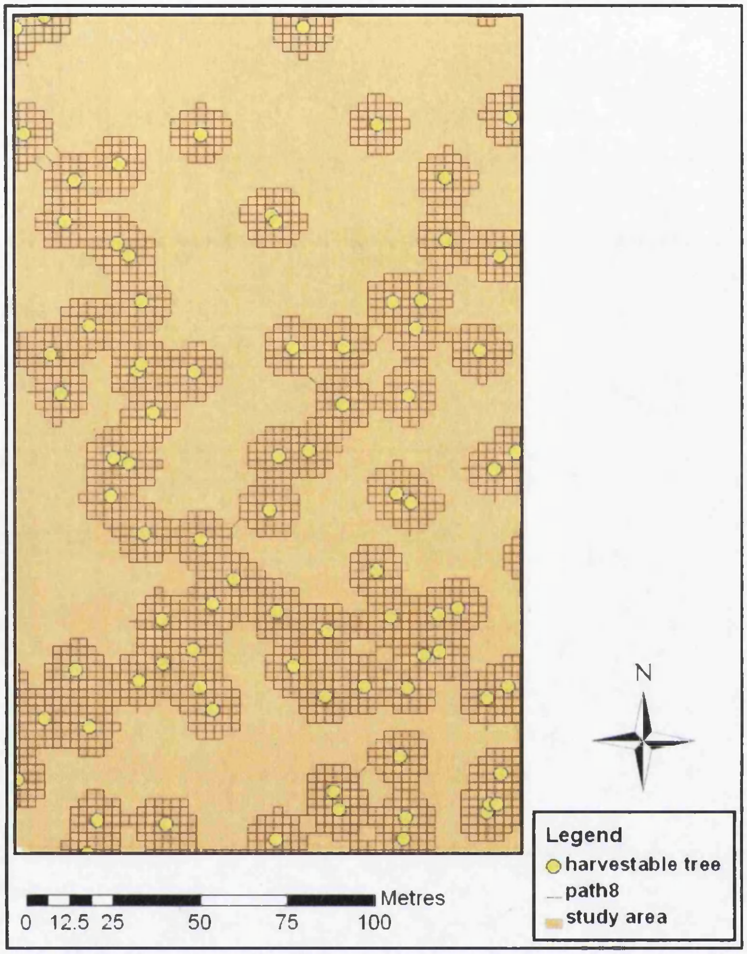
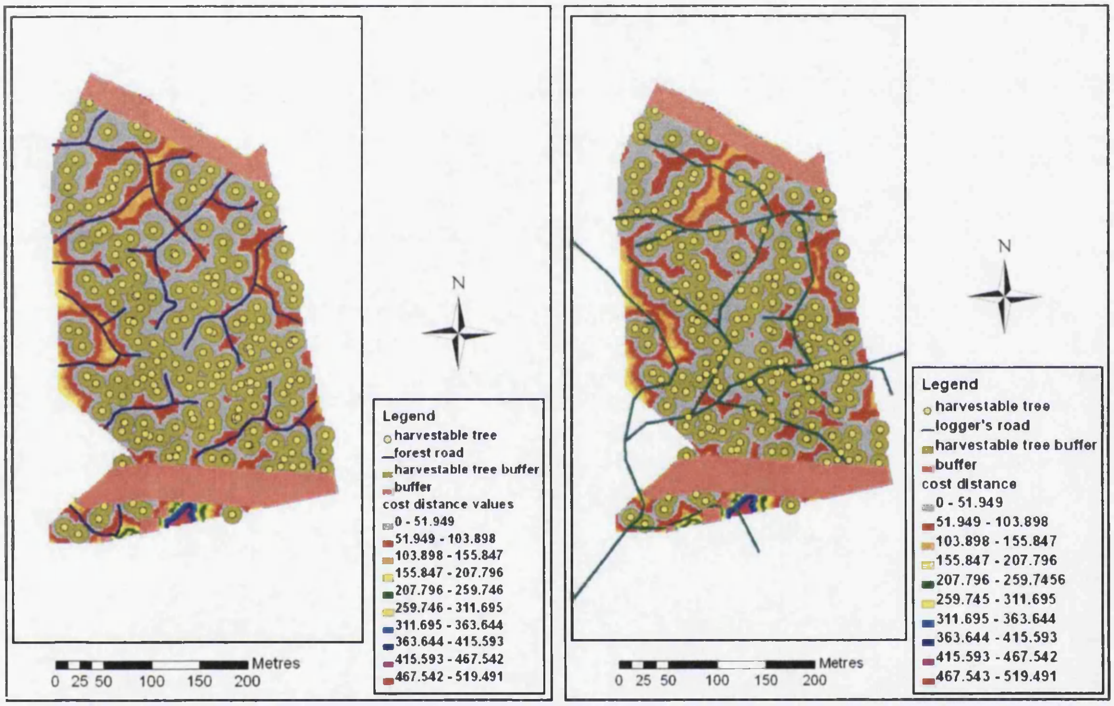


Figure 6.18: Shortest path for the study area.

go on to another centre point and finally forest road network could be formed.



(a) Sample road

(b) Logger's road

Figure 6.19: Sample of an optimum logging road for the study area.

Chapter 7

Discussion and Conclusion

Overview Summaries of the results from the development of a GIS-based timber harvesting plan are presented in this chapter. The work consists of three research components, namely (i) the determination of the net production area and the identification of the harvestable trees, (ii) the prediction of potential soil loss and its flow direction, and (iii) the optimisation of the forest road network. The benefits arising from this study, as well as its limitations in terms of its practicality for implementation, are also discussed. A section on the potential for future work is also included, before the overall conclusions based on the objectives of the study is presented.

7.1 Summary of results

A procedure for forest harvesting planning in Malaysia, as required under the SMS guidelines, has been discussed in some detail with the aim of developing a practical and pragmatic GIS-based timber harvesting plan. The thesis also demonstrates how these guidelines might be implemented and applied within a functional GIS, specifically ArcGIS 9$^{\mathrm{TM}}$, for a 10 ha study area in the Bubu FR, Taiping, Perak, Peninsula Malaysia. The results of the analysis are summarised below.

7.1.1 NPA and selection of harvestable trees

The NPA and selection of harvestable trees analysis carried out in Chapter 4 shows how the standard planning rules embodied in the SMS can be integrated successfully into a GIS to determine areas suitable for harvesting, to delineate areas for conservation, such as water bodies, and to identify trees that have to be protected either for the next harvesting cycle, or for conservation purposes, or for seeding purposes. Apart from analysing the physical geographical features, such as the presence of steep slopes and the courses of rivers and streams, the GIS software used here provides a powerful tool to locate the trees relevant to the tree-cutting regime, including residual trees, conservation trees, different tree species and harvestable trees. From this information, the timber-volume extraction calculations can be derived. In this study area, this methodology is applied, which suggests that the timber-volume extraction figures are $32.36\,\mathrm{m^3ha^{-1}}$ for dipterocarp species and $37.53\,\mathrm{m^3ha^{-1}}$ for non-dipterocarp species for the 10 ha sample area considered here. The status of the forest, whether it is species-rich or species-poor is another vital piece of information that can be derived from the analysis and this also helps to inform the DBH for the cutting limit of the forest.

Besides the demonstration of the integration and deterministic implementation of the SMS rules within the GIS, a simple form of sensitivity analysis was performed. This involved varying the allowable buffer zone distances, the DBH cutting-limit values and the maximum slope angles on which felling is permitted. This part of the study was carried out to demonstrate the potential of the GIS to model simple 'what if' questions, and in recognition of the fact that, ultimately, the SMS rules are applied in the field by human beings, with the associated tolerances and uncertainties that are involved (i.e. the decision as to whether to harvest a tree does not rest upon whether the slope is *exactly* 30°). This aspect of the GIS enables forest managers to manipulate and change the criteria underlying the SMS and then run the process again. The ability to answer 'what if?' questions in this way should increase the efficiencies of the management and planning of forest harvesting. Hence, a more precise, graphical and up-to-date decision-making process, which provides more accurate and consistent results than the conventional manual method, might be more readily established. When a link is established between a given locality and other districts, states or the headquarters office, a more sytematic and integrated forest harvesting system could be developed which would be very useful for monitoring, management and enforcement purposes.

7.1.2 Soil erosion prediction and its flow direction

A further benefit of the GIS, outlined above, is that it can also be used to measure the potential for soil loss in different parts of the study area. In fact, it has still more advantages because the result can be displayed spatially, which makes it easier for the forest managers to visualise areas with high potential for soil erosion risk. These areas are usually very sensitive environmentally and have to be protected; however, if they need to be developed, extra measures can be taken, but this, too, can be predicted using the GIS. In this study, the MSLE is used to indicate the relative likelihood of soil erosion in different parts of the study area. Thus, the intention is not to estimate precise values of soil movement, but to highlight those parts of the study area that are more susceptible to soil erosion than others. The former would indicate areas where timber harvesting might be avoided or reduced; the latter would indicate areas in which timber harvesting could perhaps proceed. Here, all of the parameters of the MSLE, with the exception of the slope length factor (LS) have been calculated in advance using specific formula and entered into the GIS for soil loss prediction. The LS factor cannot be entered directly because there are some spatial analysis processes that have to be carried out, like creating a TIN from the elevation contour data, the conversion of the resulting TIN to raster format, and the creation of a DEM from the raster data, before computing the LS value for every grid cell in the study area. Once the local LS factor has been obtained, the potential soil loss value, A, can be calculated. The results presented in this study suggest that the highest soil loss in the area occurs, unsurprisingly, on the steepest slopes (40°), where the predicted soil loss is 1.068 metric ton$\cdot$ha$^{-1}\cdot$yr^{-1}. The results of the soil erosion analysis presented in Chapter 5 clearly demonstrate that with some modifications and bespoke programming, the GIS can be used to predict the relative potential for soil loss in forested areas. The advantage of knowing the likelihood of soil loss before harvesting is that forest managers are able to substitute harvestable trees located in high soil-loss areas with trees located in low soil-loss areas.

In terms of the direction of soil flow, ArcGIS 9$^{\text{TM}}$ has a complete set of tools to generate the flow direction and flow accumulation which shows the movement of soil loss. However, to estimate the value of soil loss and soil gain in each gridcell within the study area, some bespoke programs had to be created in the Gawk programming language, using concepts taken from TOPMODEL. The results produced using this approach provide a first indication of where soils are depleted or accumulate within the study area.

7.1.3 Road alignment

Using the Spatial Analyst tools in ArcGIS 9$^{\text{TM}}$, an attempt is made in this thesis to identify the area suitable for logging road construction in the study area. A suitability model is constructed, based on considerations of terrain slope (gradient), proximity to the harvestable trees and the potential for localised soil erosion. This suitability model is combined with practical factors that influence the cost of building logging roads using a Cost Weighted Distance approach to find the most suitable routes for the logging roads. However, when the Shortest Path method was used to identify the optimum alignment of the logging roads in the area, only a small portion of the logging road network anticipated was created. Despite many attempts to overcome this problem, this part of the thesis objectives was ultimately unsuccessful in the time available. It is thought that this might be due to the inability of the software to handle paths from multiple different points in the source and destination data sets. Despite this, the GIS was used to produce a fall-back product which indicated general areas that are suitable for forest road construction throughout the study area. This more limited product nevertheless would help forest managers to monitor the activities of the loggers.

7.2 Benefit

Traditionally, the pre-F inventory is facilitated by analysing large harvesting databases, but spatial analysis of such data sets is limited because the work is often difficult and time-consuming to accomplish. However, the results of this study demontrate that GIS can provide accessible tools to conduct spatial analyst in an effective, rapid way, where some type of geographical referencing is included in the data set. These data are stored in a systematic, proper and orderly arrangement, which makes acquisition of data effortless; likewise, if one needs to modify the existing data or to add new data to it in future. Moreover, once the data have been installed in the GIS, it becomes a rich, diversified and detailed source of data on harvesting. In short, the advantages of using a GIS-based harvesting plan are as follows: (i) the possibility of rapidly producing input maps (soil maps, land use maps etc.) for the assessment of alternative land management scenarios; (ii) the possibility of displaying model results as maps; and (iii) the ability to analyze large forests in fine detail, so that the forest can be investigated in a comprehensive and detailed fashion.

Forest data is often used by different levels of management in a timber-producing country like Malaysia. The management levels range from the highest, such as the policy makers, to the lowest, such as the operational harvesting team. Therefore, information and data need to be shared and exchanged regularly and frequently to accomodate different needs. Similarly, two-way data sharing and exchanging is expected with respect to the FD Headquarters, State FDs and District FDs. By employing the GIS-based timber harvesting plan developed in this study and modified it accordingly, data sharing and exchanging is more readily attainable. The integrated systems would link the various District FDs, State FDs and the FD Headquarters.

Another benefit that could be gained from this study is that the forest inventory data could be linked to other environmental hazard and socio-economic geo-spatial data sets. Linking this information aids forest planners in identifying potential environmental hazards, such as forest fire hot-spots and in evaluating alternative treatment options.

Although the study was carried out using a case study in the Malaysian forest concession, the methods described in this thesis can be transferred to other forest concessions in the state or in other tropical countries, where they need to be modified slightly to address local conditions and needs. Furthermore, the approach could also be adapted for other aspects of forestry studies, like plantation, economic value, rehabilitation, conservation of the forest or timber industries. Besides, the analysis could be extended into a more integral and comprehensive analysis.

Despite the high cost of software installation and training, both the access to data and the types of spatial analysis that can be carried out and results produced would be very much improved. The time taken to retrieve, store, analyse and make changes to the database would also be shortened. In addition, the databases could be utilised to carry out different analyses in near real-time, especially ‘what if’ queries, with the results obtained in the time frame of the planning and forest operations process. Errors that arise during processing and analysis can also be detected and corrected faster than might otherwise be the case. This would definitely speed up the process of decision-making by the forest management, which would ultimately have benefits in terms of time and cost. A preliminary consideration of the environmental, economic and local community issues prior to GIS-based analysis on timber harvesting also suggest that the system developed here would offer benefits for environmental conservation and for the indigenous communities. Consequently, the forestry sector is expected to modernise and upgrade their expertise and capabilities in information technology to meet the industrial demands and future challenges.

7.3 Limitations

Management of information technologies is now undoubtedly an essential part of forest management. Forest managers must understand the strategic and tactical implications of these technologies and must be ready to make fundamental changes in their organizations in order to take advantage of the potential that can be provided by timely, accurate information. Nearly all of these technologies will require substantial new investments, not only in the technologies themselves but also in the training of personnel and the acquisition and verification of data. A strong and active commitment of managers at the highest levels in the organization is therefore essential if the new technologies are to be implemented to the organization's advantage (Dykstra, 1997). GIS will be useful for forestry analysis, only if the foresters use it. In order to ensure competency of staff in the use of software and techniques required for analysing the data, appropriate GIS training should be arranged. This means that all professional forestry staff including top-level managers should receive at least an 'awareness' training in GIS, and those who will use the system to extract information and carry out analysis should receive in-depth technical training. In relation to this, not many authorities are prepared to provide their staff time with away from their daily job to attend the training, especially the private timber concessions.

Similarly, sufficient hardware and software must also be provided and installed as a networking from country level to district level so that each professional who will be using the GIS has convenient access to it. In most cases, the GIS will reside on a high-performance computer workstation, and individual users will connect to it through a network accessed from their desktop personal computers. Apart from the staff who use the software, there also has to be a technician to manage the smooth running of computer workstation or to solve any computer problem that might occur.

Installation of the hardware and software involves huge amount of money and needs some financial allocation and support from the private and Government sectors. On the other hand, the advantages acquired from the investment are incomparable. In Malaysia, there is already a practice where the levy money collected from timber industries is given back to the industries for its benefit by funding some urgent, essential and critical research. Hence, the same could be done to provide computer facilities for the timber industries so that the management could be improved and modernised through information technology (IT).

7.4 Future Research

GIS, GPS, remote sensing, image processing and models are tools to assist spatial forest planning efforts, although are more frequently used to acquire or provide spatial data for the planning processes. However, the vital function of GIS is the ability to answer geographical questions based on the information in digital maps with associated attribute database. It has traditionally been used in forestry to store maps in electronic form and to make calculations, such as area and distance. More recently, its use has been extended to analyse potential and complex problems which have spatial context (Davis et al., 2001) i.e. prediction of habitats, ecosystem associations and species richness from forest site classification and current data, such as elevation, topography, proximity to roads and buildings, forest cover, soil maps and climate. Nevertheless, GIS can be used in producing an altenative forest planning by means of solving forestry problems and decision making process. The GIS-based timber harvesting plan developed in this study would be more efficient if it is integrated with remote sensing, which is very useful in the forestry studies as it allows large areas to be outlined and monitored in a short time. Integration with airborne high resolution remote sensing images such as radar and LiDAR would enable multi temporal images comparison be carried out to detect environmental changes at macro and micro scales and also to observe any forest gaps resulted from harvesting. Radar, which utilizes the microwave portion of the spectrum can provide important additional information of terrain surfaces and vegetation canopies. Longer radar waves can penetrate vegetation canopy more deeply than optical wavelengths. This additional information may be able to facilitate differentiation between forest cover types that optical and infrared sensor sustems are not able to accomplish (Stellingwerf and Hussin, 1997). LiDAR instruments could also generate canopy height models that subsequently provide accurate estimations of important forest parameters such as canopy heights, stand volume, and the vertical structure of the forest canopy (Suarez et al., 2004).

Besides that, GPS could be used in acquiring and verifying spatial data like the boundaries, rivers, contours, roads and other physical features. These images and spatial data could be mapped and stored in the database using GIS software, hence, enable future modification and easy retrieval of data. Moreover, it can act as the basis for upgrading the GIS-based timber harvesting plan to a Intelligent Knowledge-Based System (IKBS) or expert system or artificial intelligence (AI) of timber harvesting planning.

IKBS are computer programs for organizing and managing the database and they may be constructed using any of, or a combination of, the hierarchical, network, relational, and object-oriented structures. The aim of the IKBS is to make data quickly available to a group of users whilst still maintaining its integrity, to protect the data against deletion and corruption, and to facilitate the addition, removal, and updating of data as necessary. Hence, all information and results obtained from research tasks carried out in this study i.e. determination of net production area, selection of harvestable trees, prediction of soil loss and its flow direction, and optimisation of logging road and skid trail could be stored in this forest information database. Then, the expert system component will be developed and manipulated.

Expert system refers to a category of computer programs that are encoded with and apply the knowledge of specific areas of expertise to provide solutions to problems within specialized domains of understanding. As a problem-solving device, an expert system interprets information and reasons toward a conclusion obtaining the same results that the human expert would arrive at if presented with a comparable task (Suttipong et al., 1998). Consequently, if IKBS or expert system for this study could be developed, they would provide added enhancement, increase effectiveness and improve the quality of the developed timber harvesting plan. This approach also enhances the methodology for timber harvesting plan through the derivation of probabilistic maps. These maps can be used as a decision support tool in forest management and planning.

A dynamic monitoring and managing process is critical to effective harvesting management. To facilitate this and at the same time enhance the timber harvesting system, the WebGIS software package, which is based on the ArcIMS^{TM} software could be used. The back-end database uses Oracle 9.01^{TM} to store spatial data in an integrative and relational database management system through ArcSDE-Spatial Data Engine^{TM}, a middleware between ArcIMS^{TM} and Oracle^{TM} database. ArcSDE^{TM} is a server software product used to access massively large multiuser geographic databases stored in database management systems. It is an integrated part of ArcGIS^{TM} and a core element of any enterprise GIS solution. Its primary role is to act as the GIS gateway to spatial data stored in a Database Management System (DBMS) (Huang et al., 2004).

So far this study has only considered the rule-set as stated in the SMS. In order for the developed GIS-based timber harvesting plan to be more practically operationalised and more widely applied, other rule-sets or criteria and indicators or regulations should also be included like those in MC&I or EIA. Furthermore, as discussed in 7.2, this study could be applied to other aspect of forestry like plantation, economic, rehabilitation, conservation or timber industries. These could be done by integrating GIS, high spatial resolution remote sensing image and MCA.

Another soil erosion prediction method that can be explored is the Unit Stream Power Erosion and Deposition (USPED) model which is a 3-dimensional enhancement to the

USLE. The USPED model differs from other USLE-based models in the manner in which it handles the influence of topography on the erosion process. As a result, the USPED model predicts both erosion and deposition, while most other USLE-based models are limited to predictions of erosion only. In terms of measuring the sediment yield from the road network to streams in a forest watershed, a GIS-based sediment prediction model, the SEDMODL can be used. GIS techniques were used to provide required data layers such as topography, streams, roads, geology, and average precipitation. The results indicated that the SEDMODL model integrated with GIS techniques can assist road managers to estimate total sediment yield quickly and effectively. Besides, critical road sections with high sediment yield potential can be identified and the efficiencies of various sediment control measures can be evaluated for these sections.

In the aspect of forest economy, the results of the study could be used further to estimate the economic output of the timber harvesting based on number of trees harvested. With knowledge on the DBH of harvestable trees and number of trees that can be harvested, the number of logs per ha can be obtained.

7.5 Conclusion

Over the last decades, impacts of forest management operations on water pollution, erosion, landscape aesthetics and biodiversity have increased and becoming major environmental and public concerns in Malaysia. Hence, various forest planning and management approaches like SFM and RIL have been conceptualized and implemented to minimise the problem. Various forest planning and analytical decision-making techniques have been used such as simulation, mathematical optimization and meta-heuristic techniques to solve the spatial forest management problem.

Since ecological and environmental considerations are important for both society and individual forest-owners or decision makers, there is an increasing need to analyze the development of spatial structure of forests and to develop means by which spatial objectives can be explicitly included in forest planning. Hence, the aim of this study is to develop a GIS-based timber harvesting plan using tropical forest inventory information and to analyse spatially the results with the available ground data after the harvesting has been carried out on the field. This aim can be achieved through the following objectives:

- To determine the net production area in a forest concession
- To select suitable trees to be harvest
- To anticipate the soil loss using MSLE before harvesting
- To predict the soil loss flow direction
- To optimise the forest road network in the net production area

As stated earlier, this study aims to achieved the GIS-based timber harvesting plan, where a more sustainable, reduced-disturbance, knowledge-based and intelligence-guided harvesting system can be produced. Firstly, the study proved that the SMS rules embodied in the SMS pertaining to the NPA and selection of harvesting trees can be directly and successfully implemented in ArcGIS 9^{TM}. Secondly, for the soil erosion prediction and soil flow direction, the method used cannot be computed directly in ArcGIS 9^{TM} but has to be supported with Gawk programming. Related to this aspect, other soil erosion techniques should also be explored in future to enhance the timber harvesting system. Thirdly, the Suitability model in ArcGIS 9^{TM} can be used to show areas suitable for forest road construction, although it could not align the forest road network for the study area. Probably more ArcGIS 9^{TM} tools have to be examine to align the forest road network in the study area.

As a conclusion, a forest company or agency that does not have up-to-date, accurate information about its forests would not be able to make quick, effective and strategic decisions. This includes detailed information on forest boundaries, site quality, age classes, conditions of topography and soils and the location and condition of infrastructure. Increasingly, non-timber resource information such as recreation potential and the condition of wildlife habitat is also becoming important for strategic planning. Therefore, continuously improved timber inventories and harvesting plans are very essential to develop as well as models for projecting growth and yield in the future so that strategy alternatives could be tested using computer simulation models and strategic planning could be constructed.

Appendix A

Acronyms and Abbreviations

AAC	Annual Allowable Cut
ASCII	American Standard Code for Information Interchange
ASL	Above Sea Level
CoC	Chain of Custody
C&I	Criteria and Indicators
DBH	Diameter at Breast Height
DBMS	Database Management System
DEM	Digital Elevation Model
DFO	District Forestry Officer
DID	Drainage and Irrigation Department
DOA	Department of Agriculture
DTM	Digital Terrain Model
EIA	Environmental Impact Assessment

FAO	Food and Agriculture Organization
FD	Forestry Department
FDPM	Forestry Department Peninsular Malaysia
FMP	Forest Management Plan
FMU	Forest Management Unit
FR	Forest Reserve
FRIM	Forest Research Institute Malaysia
FSC	Forest Stewardship Council
GIS	Geographic Information System
GPS	Global Positioning System
IKBS	Intelligent Knowledge-Based System
ITTO	International Tropical Timber Organization
IUFRO	International Union of Forest Research Organizations
IUCN	International Union for the Conservation of Nature and Natural Resources
LDD	Local Drainage Direction
LES	Linear Engineering Structures
MC&I	Malaysian Criteria, Indicators, Activities and Management Specifications for Forest Management Certification
MCA	Multi Criteria Analysis
MCDM	Multi Criteria Decision Making

MIS	Management Information System
MMD	Malaysia Meteorological Department
MTC	Malaysian Timber Council
MTCC	Malaysian Timber Certification Council
MSLE	Modified Soil Loss Equation
MUS	Malayan Uniform System
NFC	National Forestry Council
NFI	National Forest Inventory
NFP	National Forestry Policy
NPA	Net Production Area
PFE	Permanent Forest Estate
PRF	Permanent Reserved Forest
P&C	Principles and Criteria
pre-F	pre-felling
post-F	post-felling
RDBMS	Relational Database Management Systems
RIL	Reduced Impact Logging
RM	Ringgit Malaysia
RUSLE	Revised Universal Soil Loss Equation

SAR	Radarsat Synthetic Aperture Radar
SFM	Sustainable Forest Management
SMS	Selective Management System
SOPs	Standard of Performance
TIN	Triangular Irregular Network
TOPMODEL	TOPography based hydrological MODEL
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
US$	United States Dollar
USLE	Universal Soil Loss Equation

Bibliography

Adeel, Z. and Pomeroy, R. (2002), Assessment and management of mangrove ecosystems in developing countries. *Trees-Structure and Function*, 16(2-3), pp. 235–238.

Ahmad, C. A. S., Abdul Rahim, N., Baharuddin, K., and Rohati, S. (2002), Application of GPS and GIS to map main logging road features in Peninsular Malaysia. In *Proceedings of 12th ISCO Conference*, Ministry of Water Resources, People's Republic of China, Beijing: Tsinghua University Press.

Ahris, Y., Foziah, J., Susilawati, S., Ruslin, H., and Abdul Rashid, I. (2003), GIS and development control system for a local authority in Malaysia. *Habitat International*, 27(4), pp. 683–696.

Akay, A. E., Orhan, E., Reis, M., and Yuksel, A. (in press), Estimating sediment yield from a forest road network by using a sediment prediction model and GIS techniques. *Building and Environment*, Corrected Proof, Last accessed 4 Sep 2007.

Akay, A. E. and Sessions, J. (2005), Applying the decision support system, TRACER, to forest design. *Western Journal of Applied Forestry*, 20(3), pp. 184–191.

Ali, H., Shui, L. T., and Walker, W. R. (2003), Optimal water management for reservoir based irrigation projects using geographic information system. *Journal of Irrigation and Drainage Engineering-ASCE*, 129(1), pp. 1–10.

Anon (1999), Tropical forest mapping and monitoring in Malaysia. Background paper presented at Global Observation of Forest Cover Workshop (GOFC), Washington D.C., USA.

Anon (2001), *Report of Malaysia's primary commodities. Technical report*, Ministry of Primary Industries, Kuala Lumpur.

Anon (2003), *Public summary of assessment of Perak FMU for forest management certification. Technical report*, Malaysian Timber Certification Council, Kuala Lumpur.

Appanah, S. (2001), Trends and issues in tropical forest management: setting the agenda for Malaysia. In *Proceedings of Conference on Forestry and Forest Products Research 1999 Series*, Forest Research Institute Malaysia, Kuala Lumpur: FRIM.

Arima, E. Y., Walker, R. T., Perz, S. G., and Caldas, M. (2005), Loggers and forest fragmentation: behavioral models of road building in the Amazon basin. *Annals of the Association of American Geographers*, 95(3), pp. 525–541.

Baban, S. M. J. and Yusof, K. W. (2001a), Mapping land use/cover distribution on a mountainous tropical island using remote sensing and GIS. *International Journal of Remote Sensing*, 22(10), pp. 1909–1918.

Baban, S. M. J. and Yusof, K. W. (2001b), Modeling soil erosion in tropical environments using remote sensing and geographical information systems. *Hydrological Sciences Journal*, 46(2), pp. 191–198.

Baharuddin, K., Zulkifli, Y., and Abdul Rahim, N. (1999), *FRIM Technical Information Handbook. A guide for estimating surface soil loss using the Modified Soil Loss Equation (MSLE) on forest land.* 25, Kuala Lumpur: FRIM, 24 pp.

Baskent, E. Z. and Keles, S. (2005), Spatial forest planning: A review. *Ecological Modeling*, 188(2-4), pp. 145–173.

Bawa, K. S. and Seidler, R. (1998), Natural forest management and conservation of biodiversity in tropical forests. *Conservation Biology*, 12(1), pp. 46–55.

Beven, K. (1997), TOPMODEL: A critique. *Hydrological Processes*, 11, pp. 1069–1085.

Beven, K. (2001), How far can we go in distributed hydrological modelling? *Hydrological Earth System Science*, 5, pp. 1–12.

Beven, K. and Kirkby, M. J. (1979), A physically based variable contributing area model of catchment hydrology. *Hydrological Science Bulletin*, 24, pp. 43–69.

Boot, R. G. A. and Gullison, R. E. (1995), Approaches to developing sustainable extraction systems for tropical forest products. *Ecological Applications*, 5, pp. 896–903.

Boyle, T. J. B. and Sayer, J. A. (1995), Measuring, monitoring and conserving biodiversity in managed tropical forests. *Commonwealth Forestry Review*, 74, pp. 20–25.

Brans, J. P. and Vincke, P. H. (1985), A preference ranking organisation method: the PROMETHEE method for MCDM. *Management Science*, 31(6), pp. 647–656.

Brooks, E. S., Boll, J., Elliot, W. J., and Detcher, T. (2006), Global positioning system/GIS-based approach for modeling erosion from large road networks. *Journal of Hydrological Engineering*, 11(5), pp. 418–426.

Brooks, S. M., Richards, K. S., and Spencer, T. (1993), Tropical rainforest logging: modeling slope processes and soil erosion in Sabah, East Malaysia. *Singapore Journal of Tropical Geography*, 14, pp. 14–27.

Brooks, S. M. and Spencer, T. (1997), Changing soil hydrology due to rain forest logging: an example from Sabah, Malaysia. *Journal of Environmental Management*, 49, pp. 297–310.

Brown, N. D. (1998), *Tropical rain forest: a wider perspective*. London: Chapman & Hall.

Brown, S., Iverson, L.R., and Lugo, A. E. (1994), Land-use and biomass changes of forests in Peninsular Malaysia from 1972 to 1982: a GIS approach. *Ecological Studies*, 101, pp. 117–143.

Cannon, C. H., Peart, D. R., Leighton, M., and Kartawinata, K. (1994), The structure of lowland rainforest after selective logging in West Kalimantan, Indonesia. *Forest Ecology ad Management*, 67, pp. 49–68.

Cedergren, J., Falck, J., Garcia, A., Goh, F., and Hagner, M. (1996), Pre-alignment of skid trails and directional felling to improve residual stand in tropical rain forest. In *Proceedings of the Seminar on Harvesting Technologies and Standards for Sustainable Forest Management in Sabah*, Forestry Department, Sabah, Sabah, Malaysia: Forestry Department, Sabah.

Chan, L. T. (2002a), Effect of selective logging on the genetic diversity of *Scaphium macropodum*. *Biological Conservation*, 104, pp. 107–118.

Chan, L.H. (2002b), The impact of present forest policies on sustainable forest management in Malaysia. In *Forest policies and forest policy reviews*, edited by T. Enters and R. N. Leslie, Bangkok, Thailand: FAO, pp. 38–43.

Chan, N. W. (1998), Environmental hazards associated with hill land development in Penang Island, Malaysia: some recomendations on effective management. *Disaster Prevention and Management: An International Journal*, 7(4), pp. 305–318.

Chappell, N. A., Yusop, Z., Rahim, N. A., Tych, W., and Kasran, B. (2004a), Spatially significant effects of selective tropical forestry on water, nutrient and sediment flows: a modeling-supported review. In *Forests, Water and People in the Humid Tropics*, edited by M. Bonnell and A. Bruinjzeel, Cambridge University Press, pp. 29–48.

Chappell, N.A., Douglas, I., Jamal, M.H., and Tych, W. (2004b), Sources of suspended sediment within a tropical catchment recovering from selective logging. *Hydrological Processes*, 18(4), pp. 685–701.

Chappell, N.A., Vongtanaboon, S., Jiang, Y., and Tangtham, N. (2006), Return-flow prediction and buffer designation in two rainforest headwaters. *Forest Ecology and Management*, 224, pp. 131–146.

CIA (2006), *The World Factbook*. http://www.cia.gov/cia/publications/factbook/geos/my.html.

Clarke, M.A. and Walsh, R.P.D. (2006), Long-term erosion and surface roughness change of rain-forest terrain following selective logging, Danum Valley, Sabah, Malaysia. *Catena*, 68 (2-3), pp. 109–123.

Commonwealth Secretariat (2006), Country Profiles Home - Malaysia. http://www.thecommonwealth.org/Templates/YearbookInternal.asp?NodeID=138658.

Condit, R., Ashton, P. S., Baker, P., Bunyavejchewin, S., Gunatilleke, N., Hubbell, S. P., Foster, R. B., Itoh, A., LaFrankie, J. V., Lee, H. S., Losos, E., Manokaran, N., Sukumar, R., and Yamakura, T. (2000), Spatial patterns in the distribution of tropical tree species. *Science*, 288, pp. 1414–1418.

Croke, J. and Nethery, M. (2006), Modelling runoff and soil erosion in logged forests: Scope and application of some existing models. *Catena*, 67, pp. 35–49.

Davis, L. S., Johnson, K. N., Bettinger, P., and Howard, T.E. (2001), *Forest Management: To sustain ecological, economic and social values*. Boston: McGraw-Hill, 804 pp.

Dawkins, H. C. and Phillip, M. S. (1998), *Tropical moist silviculture and management: a historical study of success and failure*. Wallingford: CAB International.

Dedecker, A.P., Van Melchebeke, K., Goethals, P.L.M., and De Pauw, N. (2007), Development of migration models for macroinvertebrates in the Zwalm river basin (Flanders, Belgium) as tools for restoration management. *Ecological Modelling*, 203, pp. 72–86.

Densham, P. J. (1991), Spatial decision support system, geographical information system. In *Principle and Applications*, edited by Goodchild M. S. Maguire, D. J. and D. W. Rhind, London: Longman, pp. 403–412.

Desmet, P.J.J. and Govers, G. (1996), Comparison of routing algorithms for digital elevation models and their implications for predicting ephemeral gullies. *International Journal of Geographic Information Systems*, 10, pp. 311–331.

Dissmeyer, G. E. and Foster, G. R. (1980), *A guide for predicting sheet and rill erosion of forest land. Technical Publication. Technical Report SA-TPPII*, United States Department of Agriculture, Washington, D. C.

Ditzer, T., Glauner, R., Forster, M., Kohler, P., and Huth, A. (2000), The process-based stand growth model Formix 3-Q applied in a GIS environment for growth and yield analysis in a tropical rain forest. *Tree Physiology*, 20(5-6), pp. 367–381.

Douglas, I. (1969), The efficiency of humid tropical denudation systems. *Transactions of the Institute of British Geographers*, 40, pp. 1–16.

Douglas, I. (2003), Predicting road erosion rates in selectively logged tropical rain forests. In *Erosion Prediction in Ungauged Basins: Integrating Methods and Techniques*, edited by D.H. DeBoer, W. Froehlich, T. Mizuyama, and A. Pietroniro, IAHS Press, pp. 199–205.

Douglas, I., Bidin, K., Balamurugan, G., Chappell, N. A., Walsh, R. P. D., Greer, T., and Sinun, W. (1999), The role of extreme events in the impacts of selective tropical forestry on erosion during harvesting and recovery phases at Danum Valley, Sabah. *Philosophical Transactions of the Royal Society B*, 354, pp. 1749–1761.

Dykstra, D.P. (1997), Information system in Forestry. *Unasylva*, 48, pp. 263–288.

Engel, V.C., Stieglitz, M., Williams, M., and Griffin, K.L. (2002), Forest canopy hydraulic properties and catchment water balance: observations and modeling. *Ecological Applications*, 154, pp. 263–288.

Enters, T. and Leslie, R.N. (2002), *Information and analysis for sustainable forest management: linking national and international efforts in south and southeast Asia. Technical report*, EC-FAO.

Environmental Systems Research Institute (1991), *Arc/Info User's Guide V. 6.0, Arc/Info Data Model, Concept & Key*. Redlands, California, USA: ESRI.

Epstein, R., Weintraub, A., Sapunar, P., Nieto, E., Sessions, J. B., Sessions, J., Bustamante, F., and Musante, H. (2006), A Combinatorial Heuristic Approach for Solving Real-Size Machinery Location and Road Design Problems in Forestry Planning. *Operation Research*, 54(6), pp. 1017–1027.

Farabi, H. (2003), Risk Based Approach Using Terrain Attributes to Control Water Quality Impacts Caused by Forest Roads. In *MODSIM 2003 Integrative Modelling of Biophysical, Social and Economic Systems for Resource Management Solutions*, edited by D. A. Post, volume 2, Modelling and Simulation Society of Australia and New Zealand, pp. 479–484.

Fedra, K. (1994), A computer-based approach to environmental impact assessment. In *Proceedings of the Indicator and Indices for Environmental Impact Assessment and Risk Analysis.*, Italy: Joint Research Centre, Ispra, pp. 11–40.

Fedra, K. (1995), Decision support for natural resources management: models, GIS and expert systems. *AI Applications*, 9, pp. 3–19.

Food and Agriculture Organization (1997), *Asia-Pacific Forestry Sector Outlook Study: Country Report - Malaysia.* Bangkok: FAO.

Food and Agriculture Organization (2001), FRA2000 - Comparison of forest area and forest area change estimates derived from FRA1990 and FRA2000. *FAO Forestry Paper*, (59), ftp://ftp.fao.org/docrep/fao/006/ad068e/AD068E.pdf.

Food and Agriculture Organization (2006a), Gateway to land and water information. http://www.fao.org/ag/AGL/swlwpnr/reports/y_ta/z_my/my.htm#overview.

Food and Agriculture Organization (2006b), Global forest resource assessment 2005 - progress towards sustainable forest management. *FAO Forestry Paper*, (147), www.fao.org/forestry/fo/fra/main/index.jsp.

Forestry Department (1997), *Manual Kerja Luar: Sistem Pengurusan Memilih (Selective Management System).* Kuala Lumpur: JPSM.

Forestry Department Peninsular Malaysia (1999), *Specification of Forest Roads for Peninsular Malaysia.* Kuala Lumpur: Forestry Department Peninsular Malaysia.

Forshed, O., Udarbe, T., Karlsson, A., and Falck, J. (2006), Initial impact of supervised logging and prelogging climber cutting compared with conventional logging in a dipterocarp rainforest in Sabah, Malaysia. *Forest Ecology and Management*, 221(1-3), pp. 233–240.

Fujisawa, H. (2004), The forest planning system in relation to the forest resource and forestry policies. *Journal of Forest Research*, 9, pp. 1–5.

Ghulam, M. H., Ciesiolka, C. A. A., Yusoff, W. A., Nafis, A. W., Radzali, M., Rose, C. W., and Coughlan, K. J. (1995), Soil erosion processes in sloping land in the east coast of Peninsular Malaysia. *Soil Technology*, 8, pp. 215–233.

Gomi, T., Sidle, R. C., Noguchi, S., Negishi, J. N., Abdul Rahim, N., and Sasaki, S. (2006), Sediment and wood accumulations in humid tropical headwater streams: Effects of logging and riparian buffers. *Forest Ecology and Management*, 224, pp. 166–175.

Gullison, R. E. and Hardner, J. J. (1993), The effects of road design and harvest intensity on forest damage caused by selective logging: empirical results and a simulation model from the Bosque Chimanes, Bolivia. *Forest Ecology and Management*, 59, pp. 1–14.

Hanson, D. L., Steenhuis, T.S., Walter, M. F., and Boll, J. (2004), Effects of soil degradation and management practises on the surface water dynamics in the Talgua River watershed in Honduras. *Land Degradation and Development*, 15, pp. 367–381.

He, F. L., Legendre, P., and LaFrankie, J. V. (1996), Spatial pattern of diversity in a tropical rain forest in Malaysia. *Biogeography*, 23, pp. 57–74.

Hill-Rowley, R., Kirton, L., Ratnam, L., and Appanah, S. (1996), The use of a grid-based geographic information system to examine ecological relationships within the Pasoh 50-ha research plot. *Journal of Tropical Forest Science*, 8(4), pp. 570–572.

Ho, W. S., Ratnam, W., Shukor, M. N., and C., Mahani M. (2004), The effects of the timing and method of logging on forest structure in Peninsular Malaysia. *Forest Ecology and Management*, 203, pp. 209–228.

Hogberg, P. and Wester, J. (1998), Root biomass and symbioses in *Acacia mangium* replacing tropical forest after logging. *Forest Ecology and Management*, 102, pp. 333–338.

Huang, J., Wu, B., Xu, W., Zhou, Y., Tian, Y., and Huang, W. (2004), WebGIS for monitoring soil erosion in Miyun reservoir area. *IEEE International*, 7, pp. 4843–4845.

Hubbell, P. S. (1979), Tree dispersion, abundance and diversity in a tropical dry forest. *Science*, 203, pp. 1299–1309.

Hubbell, P. S. and Foster, R. B. (1983), Diversity of canopy trees in a Neotropical forest and implications for conservation. In *Tropical rain forest: ecology and management*, edited by L. C. Sutton, T. C. Whitmore, and A. C. Chadwick, Oxford: Blackwell Science, pp. 25–41.

Hubbell, P. S. and Foster, R. B. (1987), The spatial context of regeneration in neotropical forest. In *Colonization, succession and stability*, edited by A. J. Gray, M. J. Crawley, and P. J. Edwards, Oxford: Blackwell Science, pp. 395–412.

Huth, A., Drechslera, M., and Kohler, P. (2005), Using multicriteria decision analysis and a forest growth model to assess impacts of tree harvesting in Dipterocarp lowland rain forests. *Forest Ecology and Management*, 207, pp. 215–232.

Hyung, T. C. and Beven, K. (2007), Multi-period and multi-criteria model conditioning to reduce prediction uncertainty in an application of TOPMODEL within the GLUE framework. *Journal of Hydrology*, 332, pp. 316–336.

International Tropical Timber Organization (2004a), *Annual review and assessment of the world timber situation 2004. Technical report*, International Tropical Timber Organization, Yokohama.

International Tropical Timber Organization (2004b), *Report on forest law enforcement and governance in Malaysia in the context of sustainable forest management. Technical report*, International Tropical Timber Organization, Yokohama.

Iwan, S., Mahmud, A. R., Mansor, S., Mohamed Shariff, A. R., and Nuruddin, A.A. (2004), GIS grid-based and multi-criteria analysis for identifying and mapping peat swamp forest fire hazard in Pahang, Malaysia. *Disaster Prevention and Management: An International Journal*, 13(5), pp. 379–386.

Jenson, S. K. and Domingue, J. O. (1988), Extracting topographic structure from Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing*, 54(11), pp. 1593–1600.

John, J., Barreto, P., and Uhl, C. (1996), Logging damage in planned and unplanned logging operations and its implications for sustainable timber production in the eastern Amazon. *Forest Ecology and Management*, 89, pp. 59–77.

Johns, A. D. (1988), Effects of 'selective' timber extraction on rain forest structure and composition and some consequences for frugivores and folivores. *Biotropica*, 20, pp. 31–37.

Johnson, N. and Cabarle, B. (1993), *Surviving the Cut: Natural Forest Management in the Humid Tropics*. World Resources Institute.

Jumat, A. (2004), Ramin trade practises. Paper presented at the Tri-national Ramin Workshop - Trade in the commercial timber species Gonystylus spp., Kuala Lumpur, Malaysia, April 15-16, 2004.

Jurgens, C. and Fander, M. (1993), Soil erosion assessment by means of LANDSAT-TM and ancillary digital data in relation to water quality. *Soil Technology*, 6, pp. 215–223.

Jusoff, K. and DŚouza, G. (1996), Quantifying disturbed hill dipterocarp forest lands in Ulu Tembeling, Malaysia with HRV/SPOT images. *Journal of Photogrammetry and Remote Sensing*, 51(1), pp. 39–48.

Jusoff, K. and Mustafa, N. M. S. N. (1996), *Forest Codes and Practice. Guidelines on logging practices for the hill forest of Peninsular Malaysia. FAO Forestry Paper No. 133. Technical report*, FAO, Rome.

Jusoff, K. and Senthavy, S. (2003), Land use change detection using remote sensing and geographical information system (GIS) in Gua Musang district, Kelantan, Malaysia. *Journal of Tropical Science*, 15 (2), pp. 303–312.

Jusoff, K. and Setiawan, I. (2003), Quantifying deforestation in a permanent forest reserve using vectorised Landsat TM. *Journal of Tropical Science*, 15 (4), pp. 570–582.

Karlsson, J., Ronngvist, M., and Frisk, M. (2006), RoadOpt: A decision support system for road upgrading in forestry. *Scandinavian Journal of Forest Research*, 21, pp. 5–15.

Kellomaki, S. (2000), Forests of the boreal region: gaps in knowledge and research needs. *Forest Ecology and Management*, 132, pp. 63–71.

Kenny, F., Matthews, B., and Todd, K. (2005), A methodology for routing overland flow through sinks and flats. In *GIS and Spatial Analysis*, edited by Q. Cheng and G. BonhamCarter, Toronto, Canada: York University, pp. 1311–1316.

Khali Aziz, H. (2001), Remote sensing, GIS and GPS as a tool to support precision forestry practices in Malaysia. In *Proc. ACRS 2001 - 22nd Asian Conference on Remote Sensing*, volume 1, Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore (NUS), Singapore Institute of Surveyors and Valuers (SISV) and Asian Association on Remote Sensing (AARS), Singapore: CRISP, pp. 562–566.

Kochummen, K. M., LaFrankie, J. V., and Manokaran, N. (1991), Floristic composition of Pasoh Forest Reserve, a lowland rain forest in Peninsular Malaysia. *Tropical Forest Science*, 3, pp. 1–13.

Lal, R. (1994), Soil erosion by wind and water: problems and prospects. In *Soil erosion research methods*, edited by R. Lal, Florida, USA: Soil and Water Conservation Society and St. Lucie Press, pp. 1–9.

Lee, S. (2005), Application of logistic regression model and its validation for landslide susceptibility mapping using GIS and remote sensing data journals. *International Journal of Remote Sensing*, 26(7), pp. 1477–1491.

Lee, S. and Talib, J. A. (2005), Probabilistic landslide susceptibility and factor effect analysis. *Environmental Geology*, 47(7), pp. 982–990.

Legues, A. D., Ferland, J.A., Ribeiro, C.C., Vera, J. R., and Weintraub, A. (2007), A tabu search approach for solving a difficult forest harvesting machine location problem. *European Journal of Operational Research*, 179, pp. 788–805.

Li, H., Chen, Z., Yong, L., and Kong, S. C. W. (2005), Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency. *Automation in Construction*, 14(3), pp. 323–332.

Ludwig, K., Kohler, P., and Huth, A. (2001), Sustainable timber harvesting in Venezuela: a modeling approach. *Journal of Applied Ecology*, 38, pp. 756–770.

Lund, G. H. (1998), *IUFRO guidelines for designing multipurpose resource inventories: a project of IUFRO research group 4.02.02. Technical report*, IUFRO, Vienna.

Malaysian Timber Certification Council (2001), *Malaysian Criteria, Indicators, Activities and Standards of Performance for Forest Management Certification (MC&I).* Malaysian Timber Certification Council, Kuala Lumpur.

Malaysian Timber Council (1997), *The Malaysian Timber Certification Manual - Part 1.* Malaysian Timber Council, Kuala Lumpur.

Malaysian Timber Council (2001), Management specifications for assessing the implementation of the 84 activities for sustainable forest management at the FMU level on a state basis. http://www.mtc.com.my/forestry/fmustate2.htm., NPA determination.

Malaysian Timber Council (2004), 2004 Statistics on timber industries. http://www.mtc.com.my/statistic/2004_statistic.htm., Forest Statistic.

Malmer, H. and Grip, H. (1990), Soil disturbance and loss of infiltrability caused by mechanical and manual extraction of tropical rainforest in Sabah, Malaysia. *Forest Ecology and Management*, 38, pp. 1–12.

Marey Perez, M. F., Rodriguez Vicente, V., and Crecente Maseda, R. (2006), Using GIS to measure changes in the temporal and spatial dynamics of forestland: experiences from north-west Spain. *Forestry*, 79(4), pp. 409–423.

Mark, D. M. (1988), *Network Models in Geomorphology. Modelling in Geomorphological Systems*. Chichester: John Wiley.

Mitasova, H., Mitas, L., Brown, W. M., and Johnston, D. M. (1998), *Multidimensional soil erosion/deposition modeling and visualization using GIS. Technical report*, Geographic Modeling and Systems Laboratory, University of Illinois at Urbana-Champaign.

Moehansyah, B. L., Maheshwari, B. L., and Armstrong, J. (2004), Field evaluation of selected soil erosion models for catchment management in Indonesia. *Biosystems Engineering*, 88, pp. 491–506.

Montoro, J. A., Silla, R. O., and Garcia, M. M. (1988), Evaluation and mapping of erosion risks: An example from S.E. Spain. *Soil Technology*, 1, pp. 77–87.

Morgan, R.P.C. (1974), Estimating regional variations in soil erosion hazards in Peninsula Malaysia. *Malayan Nature Journal*, 28, pp. 94–106.

Morgan, R.P.C. (2005), *Soil erosion and conservation*. Third edition, Oxford, UK: Blackwell Publishing Ltd., 304 pp.

Morgan, R.P.C., Rickson, R. J., McIntyre, K., Brewer, T. R., and Altshul, H. J. (1997), Soil erosion survey of the central part of the Swaziland Middleveld. *Soil Technology*, 11, pp. 263–289.

Musa, M. K. A. (2004), Accuracy assessment between DEM generated by hypsographic data and RADARSAT stereo images in the production of hilly forest road alignment map. In *Proceedings of the 25th Asian Conference of Remote Sensing (ACRS 2004)*, Chiang Mai, Thailand: AARS,GISTDA, IIAS and ITC, pp. 197–203.

Musa, M. K. A. and Mohamed, A. N. (2002), Alignment and locating forest road network by best-path modeling method. In *Proceedings of the Asian Conference of Remote Sensing (ACRS 2002)*, Kathmandu, Nepal: Asian Association on Remote Sensing (AARS) and Survey Department, Nepal.

Naáman, J. (2002), Recent forest policy reviews in Peninsular Malaysia. In *Forest policies and forest policy reviews*, edited by T. Enters and R. N. Leslie, Bangkok, Thailand: FAO, pp. 75–78.

Naoki, A., Nur Supardi, M. N., Mazlan, H., Mahdan, B., and Toshinori, O. (2001), An analysis of land use changes in Pasoh Forest Reserve: an application of remote sensing & GIS techniques. In *Tropical forestry research in the new millennium: meeting demands and challenges. Proceedings of the International Conference on Forestry and Forest Products Research (CFFPR 2001)*, Kuala Lumpur, Malaysia: Forest Research Institute Malaysia (FRIM).

Narimah, S. (2006), Characterizing the scale sensitivity of the cellular automata simulated urban growth: A case study of the Seberang Perai region, Penang State, Malaysia. *Computers, Environment and Urban Systems*, 30(6), pp. 905–920.

Newberry, D. M., Renshaw, E., and Brunig, E.F. (1986), Spatial pattern of trees in Kerangas forest, Sarawak. *Vegetatio*, 65, pp. 77–89.

Nezry, E., Yakam-Simen, F., Romeijn, P.and Supit I., and Demargne, L. (2000), Advanced remote sensing techniques for forestry applications: an application case in Sarawak (Malaysia). In *Symposium on Remote Sensing (EUROPTO VII), Proceedings of SPIE*, EOSSPIE, Barcelona, Spain: EOSSPIE.

Niiyama, K., Abd Rahman, K., Kimura, K., Tange, T., Iida, S., Quah, E. S., Chan, Y. C., Aziz, R., and Appanah, S. (1999), *Design and Method for the Study on Tree Demography in a Hill Dipterocarp Forest at Semangkom Forest Reserve, Peninsular Malaysia.* Research Pamphlet 123, Kuala Lumpur: FRIM, 11 pp.

Noss, R. F. (1999), Assessing and monitoring forest biodiversity: a suggested framework and indicators. *Forest Ecology and Management*, 115, pp. 135–146.

Novotny, V. and Chesters, G. (1981), *Handbook of Nonpoint Pollution Sources and Management. Technical report*, Van Nostrand Reinhold Co., New York.

Phua, M. H. and Minowa, M. (2005), A GIS-based multi-criteria decision making approach to forest conservation planning at a landscape scale: a case study in the Kinabalu area, Sabah, Malaysia. *Landscape and Urban Planning*, 71(2-4), pp. 207–222.

Pinard, M. A., Barker, M. G., and Tay, J. (2000), Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia. *Forest Ecology and Management*, 130(13), pp. 213–225.

Pinard, M. A. and Putz, F. E. (1996), Retaining forest biomass by reducing logging damage. *Biotropica*, 28, pp. 278–295.

Poore, D., Burgess, P., Plamer, J., Rietbergen, S., and Synnot, T. (1989), *No timber without trees: a study for ITTO*. Earthscan Publications, London.

Poore, M. E. D. (1968), Studies in Malaysian rain forest. 1. The forest on triassic sediments in Jengka Forest Reserve. *Ecology*, 56, pp. 143–196.

Potts, M. D., Abd. Rahman, K., Nur Supardi, M. N., and Tan, W. H. (2005), Sampling tree diversity in Malaysian tropical forests: an evaluation of a pre-felling inventory. *Forest Ecology and Management*, 205, pp. 385–395.

Putz, F. E. (1994), Towards a sustainable forest. How can forests be managed in a way that satisfies criteria of sustainability? *International Tropical Timber Organization Tropical Forestry Update*, 4, pp. 7–9.

Putz, F. E., Dykstra, D. P., and Heinrich, R (2000), Why poor logging practices persist in the tropics. *Conservation Biology*, 14(4), pp. 951–956.

Renard, K. G., Foster, G. R., Weesies, G. A., and Porter, J.P. (1991), RUSLE:Revised Universal Soil Loss Equation. *Journal of Soil and Water Conservation*, 46, pp. 30–33.

Rice, B. and Westoby, M. (1982), Plant species richness at the 0.1 hectare scale in Australian vegetation compared to other continents. *Vegetatio*, 52, pp. 129–140.

Richards, P. W. (1996), *The tropical rain forest: an ecological study*. Cambridge University Press.

Roslan, Z.A., Amir Hashim, A.K., and Tew, K.H. (1997), Remote sensing application in determination of land use management factors of the USLE. In *Proceedings of Asian Conference of Remote Sensing*, Asian Association on Remote Sensing, Kuala Lumpur: Macres & AARS.

Roslinah, S. and Norizan, A. P. (1997), Soil erosion and hydrological study of the Bakun Dam catchment area, Sarawak using remote sensing and geographic information system (GIS). In *Proceedings of Asian Conference of Remote Sensing*, Asian Association on Remote Sensing, Kuala Lumpur: Macres & AARS.

Rowshon, M. K., Kwok, C. Y., and Lee, T. S. (2003), GIS-based scheduling and monitoring of irrigation delivery for rice irrigation system: Part 1. Scheduling. *Agricultural Water Management*, 62(2), pp. 105–116.

Ruslan, R. (2004), Estimating sediment yield using Agricultural Non-Point Sources (AGNPS) model: the effects of slope information from different GIS software. *Journal of Spatial Hydrology*, 4(2), pp. 1–20.

Sadeghi, S. H. R., Mizuyama, T., Miyata, S., Gomi, T., Kosugi, K., Mizugaki, S., and Onda, Y. (2007), Is MUSLE apt to small steeply reforested watershed? *Journal of Forest Research*, 12(4), pp. 270–277.

Safiah Yusmah, M. Y. (1998), *Soil erosion risk assessment in a humid tropical catchment: Bukit Tinggi, Bentong, Pahang Darul Makmur*. Master's thesis, Faculty of Science, University Malaya, Kuala Lumpur, Malaysia, unpublished M. Sc. thesis.

Safiah Yusmah, M. Y., Khali Aziz, H., and Raja Barizan, R. S.and Abd. Azhan, S. I. (2003), Operational use of remote sensing and GIS for forest rehabilitation planning. *RAP Publication*, (14), pp. 277–284.

Saket, M. (2002), Gaps in national-level information on forests and trees in developing countries. *Unasylva 201*, 53, pp. 24–27.

Samsudin, M., Abd. Rahman, K., Safiah, M.Y., and Shamsudin, I. (2003), *Assessing the status of logged-over production forests the development of a rapid appraisal technique*. *Technical report*, Food and Agriculture Organization.

Sayed Jamaludin, S. A. (2002), Assessing the performance of GIS techniques in environmental impact assessment studies. *Management Information Systems*, 4, pp. 155–164.

Sharifah, N. S. O., Jeber, F. K. M., and Shattri, M. (2004), GIS/RS for landslides zonation in Pos Slim-Cameron Highlands district, Peninsular Malaysia. *Disaster Prevention and Management*, 13(1), pp. 24–32.

Sharma, V. P. (1997), Use and misuse of the Universal Soil Loss Equation. *Tropical Medicine and International Health*, 2, pp. 508–510.

Shattri, M., Mohammed, A. S., Billa, L., Iwan, S., and Faisal, J. (2004), Spatial technology for natural risk management. *Disaster Prevention and Management*, 13, pp. 364–373.

She, T. H., Aouad, G., and Sarshar, M. (1999), A geographic information system (GIS)-based bridge management system. *Computer-Aided Civil and Infrastructure Engineering*, 14(6), pp. 417–427.

Sidle, R. C., Sasaki, S., Otsuki, M., Noguchi, S., and Nik, A. R. (2004), Sediment pathways in a tropical forest: effects of logging roads and skid trails. *Hydrological Processes*, 18(4), pp. 703–720.

Sist, P., Dykstra, D., and Fimbel, R. (1998), *Reduced-Impact Logging Guidelines for Lowland and Hill Dipterocarp Forests in Indonesia. Technical Report Occasional Paper No. 15*, Center for International Forestry Research.

Sist, P., Fimble, R., Sheil, D., Nasi, R., and Chevallier, M. (2003), Towards sustainable management of mixed dipterocarp forests of Southeast Asia: moving beyond minimum diameter cutting limits. *Environmental Conservation*, 30(4), pp. 364–374.

Spinelli, R. and Marchi, E. (1998), A literature review of the environmental impacts of forest road construction. In *Proceedings of the Seminar on Environmentally Sound Forest Roads and Wood Transport*, FAO, Rome: FAO.

Stellingwerf, D. A. and Hussin, Y. A. (1997), *Measurements and Estimations of Forest Stand Parameters Using Remote Sensing*. The Netherlands: VSP, 270 pp.

Suarez, J. C., Ontiveros, C., Smith, S., and Snape, S. (2004), The use of airborne LiDAR and aerial photography in the estimation of individual tree heights in forestry. Paper presented at 7th AGILE Conference on Geographic Information Science, Heraklion, Greece, 29 Apr-1 May, 2004.

Sugumaran, R. (2000), *Development of a Range Management Decision Support System (RAMDSS) for forest planning in the Banavasi Range of the Western Ghats, India.* Ph.D. thesis, Geography Department, University of Edinburgh, Edinburgh.

Sulong, I., Mohd Lokman, H., Mohd Tarmizi, K., and Ismail, A. (2002), Mangrove mapping using LANDSAT imagery and aerial photographs: Kemaman District, Terengganu, Malaysia. *Environment Development and Sustainability*, 4, pp. 135–152.

Suttipong, P., M., Daud, Zohadie, M., and Jusop, S. (1998), Expert system for predicting flash flood due to development in urban areas. *Tronburi Research and Development Journal*, 21, pp. 88–100.

Tarboton, D. G., Bras, R. L., and Rodriguez-Iturbe, I. (1991), On the extraction of channel networks from digital elevation data. *Hydrological Processes*, 5, pp. 81–100.

Thang, H. C. (1987), Forest management systems for tropical high forest with special reference to Peninsular Malaysia. *Forest Ecology and Management*, 21, pp. 3–20.

Thuresson, T. (2002), Value of flow-intensity field sampling in national forest inventories. *Unasylva 210*, 53, pp. 19–23.

Uhl, C. and Vieira, I. C. G. (1989), Ecological impacts of selective logging in the Brazilian Amazon: a case study from the Paragominas region of the state of Pará. *Biotropica*, 21(2), pp. 98–106.

Unit Pengurusan Hutan (1996), *Senarai Kod Pokok-pokok bagi Kajian Growth Plots'.* Kuala Lumpur: JPSM.

van Bueren, E. L. and Blom, E. (1996), *Hierarchical Framework for the Formulation of Sustainable Forest Management Standards*. Wageningen, The Netherlands: The Tropenbos Foundation.

Warrington, G.E., Knapp, K.L., Klock, G.O., Foster, G.R., and Beasley, R.S. (1980), An approach to water resources evaluation of non-point silvicultural sources. In *A Procedural Handbook*, edited by L.A. Mulkey, Washington D.C.: Forest Service USDA.

Whitmore, T.C. (1998), *An introduction to tropical rain forests*. Second edition, Oxford: Oxford University Press.

Whyte, G. (1999), Inventory, modeling and auditing systems for planning and controlling forestry operations. *International Journal of Forest Engineering*, 10(2), pp. 27–31.

Winkler, N. (1997), *Environmentally sound forest harvesting: testing the applicability of the FAO Model Code in the Amazon in Brazil. Forest harvesting case study 8. Technical report*, Food and Agriculture Organisation, Rome.

Wischmeier, W. H. (1975), Estimating the soil loss equarion's cover and management factor for undisturbed areas. In *Present and prospective technology for predicting sediment yields and sources. Proceedings Sediment-yields Workshop*, United States Department of Agriculture, Washington D.C.: USDA.

Wischmeier, W. H. (1976), Use and misuse of the Universal Soil Loss Equation. *Journal of Soil and Water Conservation*, 31(1), pp. 5–9.

Wischmeier, W.H. and Smith, D.D. (1978), *Predicting rainfall erosion losses. A Guide to Conservation Planning*. Agricultural Handbook No. 537, USDA.

World Resources Institute (2006), EarthTrends: The environmental information portal. "http://earthtrends.wri.org/text/forests-grasslands-drylands/country-profile-114.html", forest Statistic.

Worrell, R. and Hampson, A. (1997), The influence of some forest operations on the sustainable management of forest soils - review. *Forestry*, 70(1), pp. 61–85.

Wyatt-Smith, J. (1987), Manual of Malayan silviculture for inland forest: red meranti-keruing forest.

Yaakup, A., Johar, F., Sulaiman, S., Hassan, R., and Ibrahim, A. R. (2003), GIS and development control system for a local authority in Malaysia. *Habitat International,*, 27(4), pp. 683–696.

Yaakup, A. B., Healey, R. G., and Hughes, C. G. (1990), The application of geographic information systems for urban land-use planning and monitoring - a case-study of low-cost housing development in Kuala Lumpur, Malaysia. *Environment and Planning B: Planning and Design*, 17(4), pp. 385–393.

Yildirim, V., Nisanci, R., and Reis, S. (2006), A GIS Based Route Determination in Linear Engineering Structures Information Management. Poster presented at Shaping the Change XXIII FIG Congress, Munich, Germany, October 8-13, 2006.

Yoder, D. and Lown, J. (1995), The future of RUSLE: Inside the new Revised Universal Soil Loss Equation. *Journal of Soil and Water Conservation*, 50(5), pp. 484–489.

Yoshimura, T. and Kanzaki, K. (1998), Fuzzy expert system laying out forest roads based on the risk assessment. In *Proceedings of the Seminar on Environmentally Sound Forest Roads and Wood Transport*, FAO, Rome: FAO.

Young, I.T., Gerbrands, J.J., and van Vliet, L.J (2003), Image Processing Fundamentals. http://www.ph.tn.tudelft.nl/Courses/FIP/noframes/fip.html.

Young, R., Onstad, C. A., Bosch, D. D., and Anderson, W. P. (1987), AGNPS - A Nonpoint-source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation*, 44(2), pp. 168–173.

Zhang, Q. F., Justice, C. O., Jiang, M. X., Brunner, J., and Wilkie, D. S. (2006), A GIS-based assessment on the vulnerability and future extent of the tropical forests of the Congo Basin. *Environmental Monitoring and Assessment*, 114(1-3), pp. 107–121.

Ziegler, A. D., Negishi, J. N., Sidle, R. C., Noguchi, S., and Abdul Rahim, N. (2006), Impacts of logging disturbance on hillslope saturated hydraulic conductivity in a tropical forest in Peninsular Malaysia. *CATENA*, 67, pp. 89–104.