The Integration Of Remote Sensing And GIS To Facilitate Sustainable Urban Environmental Management: The Case of Bangkok, Thailand

by

Neil W. Malcolm

A thesis
presented to the University of Waterloo
in fulfillment of the requirements
for the degree of
Masters of Environmental Studies
in Planning

Waterloo, Ontario, Canada, 2002

AUTHOR'S DECLARATION:

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

The Integration Of RS And GIS To Facilitate Sustainable Urban Environmental Management: The Case of Bangkok, Thailand

ABSTRACT

Cities in developing countries are facing serious problems as a result of rapid urban population growth. Not the least of these problems is the creation of environmental stresses at the rural-urban fringe of these cities as they increase in area and envelop fertile surrounding agricultural lands. Because of this rapid rate of growth, sustainable urban environmental management (SUEM) policies and practices are often difficult to develop and implement proactively. This thesis argues that rapid population growth and subsequent urban expansion occurs such that urban form and function are built around the transportation network. In this context, a basic requirement for the facilitation of SUEM is the ability to be able to detect and extract indicators of urban expansion, in particular the road network, from available satellite remote sensing (RS) data. Subsequently, the indictors of growth derived from RS imagery can be integrated into a multi-source GIS database with ground-based census data to facilitate potential environmental stress analysis. The extraction of useful data from RS imagery for GIS-based analysis of urban growth is achieved through an integrated conceptual and operational framework presented in the thesis. This framework allows for environmental stress analysis at the urban periphery that can assist with the design of policies to contain urban growth.

ACKNOWLEDGMENTS

There are many individuals and organizations that deserve thanks for having provided contributions and support in the development of this thesis. First and foremost, I would like to thank my advisor, Dr. G. Brent Hall, for his valuable input, motivation, time, edits, ideas ... and the list goes on and on. Without his boundless support this thesis would not have been possible.

I would also like to thank Drs. Joe Piwowar and Jim Bater for their useful input in terms of imagery analysis (Joe), edits and suggestions that helped polish the final document into its current form. Thank you also to my other reader, Dr. Rob Feick, for his excellent and positive advise as I worked through my degree.

A large thank you goes to the Canadian University Consortium – Asian Institute of Technology (CUC-AIT) for awarding me with the Travel Award that facilitated my field research in Thailand. Without this opportunity, my work in Bangkok would not have been possible. A special thanks goes to Jim Bater, Chair of the CUC Board of Directors, Walter Jamieson, Director of the CUC-AIT Training and Technology Transfer Program, and all of the staff at the CUC office at AIT for all their assistance during my stay. Also, many thanks to the staff at the Asian Centre for Research on Remote Sensing (ACRoRS) at AIT, in particular Drs. Kiyoshi Honda and Lal Samarakoon, for providing me with imagery, data and a place to work while at AIT.

I would also like to offer thanks to two fellow grad students: Dan Crouse and Chris Close, who were both available at any time to discuss methods of analysis or, more importantly, to make bodum coffee (Chris) and provide distraction for periods of relaxation.

Last, but certainly not least, I would like to thank my family for their continued support of my desire to stay in school. In particular, my wife, Linda, deserves the greatest thanks for putting up with my long hours in the lab and late nights in front of the computer. Linda has always pushed me to work harder and accomplish my goals by setting the example, so it is to her that this thesis is dedicated. Thanks and I love you!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The need for access to accurate, up-to-date land use information is especially important for urban land use management in developing nations. Extensive and rapid growth of urban areas in these countries has created numerous urban environmental problems such as pollution, degradation of potable water, loss of valuable peri-urban and surrounding agricultural land, and traffic congestion, among others. To help develop policies targeted at ameliorating these problems and facilitating environmentally sound development, planners are increasingly turning to the use of spatial information technologies such as remote sensing (RS) and Geographic Information Systems (GIS). These tools are now starting to become widely used in both developed and developing countries. However, in both contexts there is a dislocation between policy development and planning, relative to the potential contribution offered by spatial information technologies. This is especially true in the realm of sustainable urban environmental management (SUEM). SUEM can be best defined by breaking it down into its separate parts, namely sustainable development and urban management in conjunction with social and economic development. Combined, these parts provide a basis for sustainable development through management of urban environments. This thesis explores some of the needs of SUEM through the use of spatial information technologies. The tools of RS and GIS are combined in a temporal analysis to demonstrate their use for the identification of potential environmental stress indicators in targeting problem areas on the rural-urban fringe of Bangkok, Thailand.

1.1 Problem Statement

The rapid and often disorganised sprawl of large cities, especially those in developing countries, causes many difficulties for their inhabitants and makes the task of providing urban infrastructure and services a major challenge for planners. Traditionally, the means for determining the location and nature of new urban development has been through extensive *in-situ* fieldwork. Following this, new developments are planned and urban areas spread outwards incrementally from their initial development. However, ground-based fieldwork is both time consuming and of questionable benefit in developing countries, as the rate of change is often rapid and adherence to formal urban planning principles in infrastructure and service provision is, at best, *ad hoc*. Reliable and timely data about the location, form and morphology of urban land use change is often lacking and, given this, it is difficult to facilitate proper policy development and decision-making in regard to urban service planning and sustainable management.

The types of data required to achieve SUEM objectives in large cities in developing countries are wide ranging and include physiographic, demographic and land-use data, among others. SUEM typifies the need for growth management that provides for a sustainable environment, while continuing to enable focussed and prosperous urban growth to occur. In this thesis, the need for SUEM is addressed in terms of how best to create the information technology context required for SUEM to occur as a city grows. To facilitate properly managed development, many types of up-to-date information are required. One widely used method of obtaining timely information about the morphology of rapidly changing urban areas is through the use of space-borne satellite imagery. High-resolution satellite imagery has the ability to provide relatively inexpensive land-cover data for mapping, inventory, and change detection at short time intervals. Satellite images provide a good overall ‘picture’ of an urban area and provide a great deal of spectral information regarding land-use over extended areas. However, satellite imagery does have limitations and it is not, in and of itself, sufficient to derive useful information concerning the morphology and land-use structure of large cities. Accordingly, one of the main purposes of this thesis is to demonstrate the ability to transform this imagery into usable data within a multipurpose GIS environment. Once transformed into this format and combined with other ground-based information, the combined data are used to identify ‘triggers’ that characterize the location of zones of potential environmental stress that require management strategies to cope with subsequent urban growth. Temporal analysis of the urban periphery in search of such zones is integral to this study.

1.2 Objectives of the Thesis

As developing countries attempt to bridge the gap between their current social and economic status and the western world's levels of development, often defined through improvements in living standards and more equitable incomes and alleviation of poverty, the natural environment often bears the brunt of any attained growth. Economic growth through rapid industrialization always brings about expansion of urban centres that consume often-fertile surrounding agricultural land. The analysis of land-use morphology through the integration of RS data with ground-based data stored in a GIS offers improved insights into both land structure and the process of land-use change.

This thesis focuses on this integration to facilitate the study of land use change signals, especially at the urban periphery. The general objective is to develop an operational methodology for use by planners and others employing the tools of RS and GIS to identify areas of potential environmental stress associated with impending rapid urban growth at the rural-urban periphery. The specific objectives of the thesis are:

(i) to develop an integrated conceptual framework based on the concepts of sustainable development and urban environmental management for the achievement of SUEM in cities in developing countries,

(ii) to operationalise this conceptual framework through the integration of RS and GIS spatial information technologies,

(iii) to extract roads and classify adjacent land uses from temporal RS imagery and, subsequently, to put these features into a GIS for further temporal analysis with ground-based data to analyse land use at the rural-urban fringe, and

(iv) to detect land use change and subsequent indicators of potential environmental stresses.

The case study for the research is Bangkok, Thailand. Potential environmental stresses such as the appearance of informal settlements, road densification, increased vehicular congestion as a result of more roadways, and increased housing density that may lead to increased air and water pollution, are all characteristic of many cities in developing countries, including Bangkok (Bishop et al, 2000). In this context, indicators of stress, which are identifiable using both RS and GIS technologies, are used to signify the process of urbanization and potential locations for the incidence of environmental stresses.

Specifically in this research roadway construction is regarded as the initial trigger for generalised land use change around which urban growth follows. The main notion here is that any urban sprawl must initially begin with some form of path or roadway to allow for greater access and mobility. Consequently, where roads develop, people soon follow as areas that were formally inaccessible to vehicular traffic are opened up. Increased population then leads to the need for improved infrastructure provision and other urban goods and services. In this sense, roads are identified as the initial indicator of urban growth that 'trigger' further development. Additional triggers include densification of buildings, decreases in land under agricultural production and increased population and numbers of households.

To achieve the overall objectives of the thesis, a procedure is developed for extracting trigger-related features from imagery and converting these features to data structures that can be used with a GIS for urban environmental management. Emphasis is placed initially on transportation networks, followed by the incorporation of other indicators within a multipurpose GIS. Because this analysis is completed at two different points in time, the second specific aspect of the contribution made by this thesis is to provide a temporal breakdown of land cover change along the Northern Corridor of the Bangkok Metropolitan Area, in the provinces of Pathum Thani and Nonthaburi. This change is examined through an integrated analysis of several indicators of environmental stress. The extraction of useful data from RS imagery for GIS-based analysis of urban growth at the periphery allows the results to be fed back into policies that facilitate urban growth management. Through this, SUEM practice can be either initiated or improved further at the urban periphery of Bangkok.

1.3 Structure of the Thesis

In Chapter 2, literature on sustainable development, urban environmental management and their intersections is reviewed. This discussion comprises multiple aspects of the concept and principles of SUEM. The review further considers the role of spatial information technologies in fostering SUEM in developing countries. The literature review combines the use of satellite remote sensing and GIS information technologies to make operational the conceptual model of SUEM.

Chapter 3 builds from Chapter 2 by presenting a detailed description of the research design for the thesis. The study areas selected in the Northern Corridor of Metropolitan Bangkok are discussed and the methods of analysis used in the thesis are summarized.

Chapter 4 presents and discusses the results. The accuracy of the remote sensing (RS) imagery analysis, including road feature extraction and temporal land use change analysis, is assessed and the subsequent integration of the extracted image features is analyzed with socio-economic data derived from the latest census of Thailand. This allows assessment of the effectiveness of the combination of RS data and GIS to detect land use change and subsequent indictors of potential environmental stresses at the rural-urban fringe.

Chapter 5 presents the conclusions derived from the results of the thesis. Some recommendations for further research are presented pertaining to the methods and the overall effectiveness of the process.

CHAPTER 2

SUSTAINABLE URBAN ENVIRONMENTAL MANAGEMENT & SPATIAL INFORMATION TECHNOLOGY

This chapter first discusses the concept of sustainable development. The role of sustainable development in policy and planning at various levels is then discussed, with a focus on how the concept is applied in developing countries. Next the concept of urban environmental management is explored. Subsequently, both concepts are combined into a unitary entity termed sustainable urban environmental management (SUEM). This new concept is then developed in the context of modern information technologies, especially those that focus on visualizing and analyzing spatial data relative to urban environmental stress.

The processes of making the concept of SUEM operational utilizing spatial information technologies (SIT) are discussed next. The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) is first reviewed, with subsequent individual focus for each in terms of their use in developing countries. In particular, the use of RS for skeletal road extraction is reviewed in detail. From these two data sources, the generation of a multi-purpose, multi-source GIS database is discussed.

To unite the main components of the preceding review, an integrated model for the role of SIT in SUEM is presented. This overall model demonstrates the linkages between SUEM and SIT by building on the concepts of sustainable development, urban environmental management and SUEM and defining the lineage between these concepts and the use of SIT to operationalize the process of environmental stress detection. Lastly, based on the operational portion of this model, a related operational model for the use of SIT in implementing the concepts of SUEM is presented and discussed. The use of potential indicators of environmental stress derived from RS and ground-based GIS data are then reviewed in accordance with their use in this model.

2.1 Sustainable Development (SD)

The term development started to appear in common parlance shortly after the Second World War when attempts were first made to bring economically under-developed countries in line with more prosperous nations. Tjatera (1994) defines the type of development occurring at this time as an attempt to eliminate differences in living standards between people living in developed and developing regions of the world. Typically, each country would strive for prosperity with little regard for any potential impacts of this progression on other countries. In accordance with Tjatera's definition, many methods of 'development', including monetary and fiscal policies and importation of foreign methods of production, were attempted in order to bring lagging countries up to the standards set by developed nations. However, inequities related to financial prosperity and rates of development inevitably appeared within regions in developing countries. Many of these inequities were later attributed to causing environmental degradation, disease, and increases in uncontrolled human migration in certain areas, as non-equivalent access to resources left some regions in better economic condition than others (Zha, 2000; Tjatera, 1994). After several decades of attempting to import varying western growth models of development based on industrial production, it became clear that something more was needed to ensure that development would occur in a more environmentally sound manner.

Since the early-to-mid-1980s, when the environmental awareness movement came to the forefront in western society, the concept of sustainable development (SD) has become an overriding principle in the development of nations. The concept of SD was introduced by the International Union for the Conservation of Nature in 1980 when they revealed their framework for world conservation (Portnov and Pearlmutter, 1999). SD can be defined as a shift from singular economic policies designed simply for maximizing economic growth to policies designed to reflect the need to consider 'sustaining' natural resources and taking into account social and cumulative impacts of development (Tjatera, 1994). The United Nations (1996) defines SD as a process that meets the needs of the present without compromising the ability of future generations to meet their own needs. Based on both Tjatera and the United Nations (UN) definitions, it is easy to see the need for such policies in guiding urban development, particularly in developing countries, where the needs of future generations have infrequently been taken into account in the search for economic growth and prosperity.

The publication ‘Our Common Future’, by The World Commission on Environment and Development in 1987, has become the definitive statement on global sustainable development and the environment. The report notes that few city governments in the developing world have the power, resources, and trained personnel to provide their rapidly growing populations with the land, services, and facilities for an adequate quality of life. The report also states that in terms of deteriorating infrastructure, environmental degradation and sustainable development, urban centres in developing countries are in a state of crisis. The commission recommends seven strategic imperatives designed to allow nations to move away from destructive processes of growth and development and to follow a path of SD that allows environmental policies and development strategies to be integrated. These include:

1) reviving growth;
2) changing the quality of growth;
3) meeting essential needs for jobs, food, energy, water, and sanitation;
4) ensuring a sustainable level of population;
5) conserving and enhancing the resource base;
6) reorienting technology and managing risk; and
7) merging environment and economies in decision making.

(WCED, 1987)

Ultimately, because SD often only occurs with painful opportunity costs its procurement must rest on the political will of governing bodies. In the broadest sense, the strategy for SD endorsed by the World Commission sought to promote harmony between humanity and nature. In the pursuit of SD, and to meet the strategic imperatives noted above, they specifically noted the need for improved technological capabilities in DC. The use of IT (specifically SIT) in DC is addressed in a subsequent section of this chapter.

The concept of SD can be divided into its two parts, sustainability and development. Portnov and Pearlmutter (1999) further subdivide sustainability into literal, ecological, and social aspects. These aspects respectively represent the sustainability of anything that comprises the ecological basis of human life and the social basis of human life respectively. In the same manner, they sub-divide development into process, growth and change and objectives. Process and growth and change can be interpreted as sustaining growth while objectives represent the attainment of basic needs, both in terms of the semantics of sustainable development. The concepts of SD addressed here provide the framework necessary for practising sustainable urban development. These include environmental, economic and socio-demographic dimensions. Each of these dimensions must be addressed for SD to occur in a developing country context.

Considerable progress has been made in the last ten years on innovation and implementation of policy in regard to the goals of SD. This is partially evidenced in the economic growth and substantial investments in health and education by countries in Asia and the Americas (CIDA-c, 1997). However, there is a lag in moving towards SD policies in cities in most developing countries. The ability to assess cities in terms of their sustainability and their adherence to growth goals that subscribe to the principles of sustainability is difficult. To assist with this, Satterthwaite (1999) outlines five broad categories of environmental action within which the performance of all cities should be assessed. These include:

1) controlling infectious disease and the health burden they impose on urban populations;
2) reducing chemical and physical hazards within the home, workplace, and wider city;
3) achieving a high quality urban environment for all urban inhabitants (e.g. park space);
4) minimizing the transfer of environmental costs to the inhabitants and ecosystems surrounding the city; and
5) ensuring process towards sustainable consumption (this can be defined as ensuring people's consumption needs without undermining environmental capital).

The first three points fall under the realm of meeting urban residential needs, while the latter two are more problematic in that they have environmental impacts and are difficult to administer through the conventional mandate of local authorities (Satterthwaite, 1999). These five indicators, while useful, are still difficult to use. The primary reason for this lies with the unavailability of data of sufficient quality required to undertake the type analyses required. For SD development to occur, areas of potential environmental stress that may emerge at the urban fringe need to be detected quickly and accurately analysed (see Figure 2-1). The rapid population growth occurring in DC and the subsequent modification that occurs in terms of new and existing urban infrastructure to support this population growth, is the driving force behind the creation of these areas of potential environmental stress. Hence, SD is needed in cities in DC to ensure that once areas of environmental stress are detected, proper planning and development policies can be applied to these areas to promote orderly development and prevent social and environmental degradation.

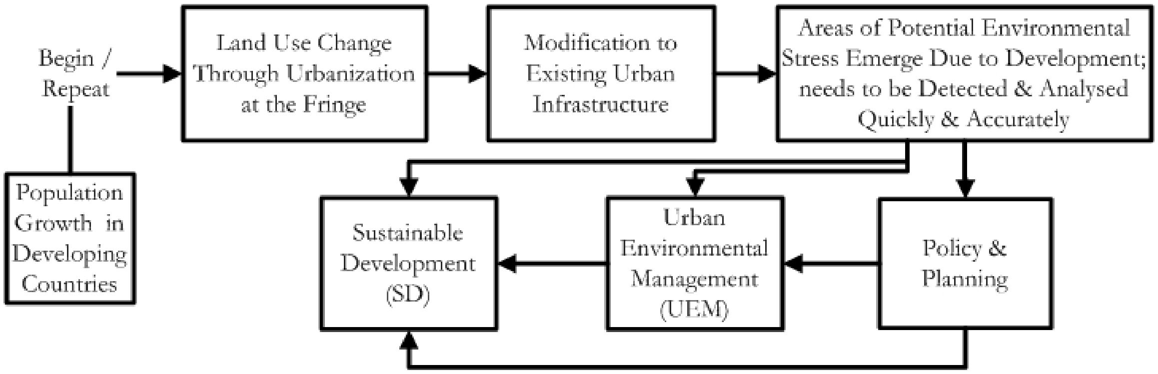


Figure 2-1: SD within the Integrated Framework

2.1.1 Future Sustainable Development Strategies

Future strategies for SD will more than likely continue to emphasize the recent focus on forms of management that are based on information and knowledge. In this context, the Canadian International Development Agency (CIDA) identifies in its agenda for SD strategies for the next three years, a goal to establish itself as a leading international knowledge-based organisation (CIDA, 2001). Their strategy includes designing approaches to capture and share knowledge and expertise between the organization, agencies and partners in developing countries (CIDA, 2001). This type of strategy has been, and will continue to be, important to the implementation of SD practices in developing countries, particularly in terms of providing knowledge and technological expertise. If organizations such as CIDA can continue their hands-on involvement with institutions and non-government organizations, SD will have a better chance of success. This is evident through the tremendous changes that have occurred in DC over the past fifty years due to the unprecedented development cooperation administered by organizations such as CIDA (CIDA, 2001). In terms of sustainability and livelihood, de Roo and Miller (2000) note in their argument for compact cities and SD that the effect of undesirable environmental activities are not limited to the location in which the activity occurs. Over time they will spread to affect sustainability in larger areas.

2.2 Urban Environmental Management in Cities in Developing Countries

Historically, the interaction between the many participants involved in urban environmental management (UEM), including local government, citizens, industry and planners, has been weak and ineffective (Srinivas, 1997). More specifically, as these participants attempt to implement policies and plans, their general goal is the management of urban growth with respect to environmental problems and their causes and effects. In attempting to provide protection for the natural environment in the face of urban growth, sound growth management involves many layers of management policies. For example, many priorities need to be taken into consideration, including depletion of natural resources, human-environment interactions, environmental degradation, health and productivity or resource stocks when attempting UEM (Srinivas, 1997). Unfortunately, to make encompassing and broadly applicable decisions in terms of urban growth, while respecting the limiting factors of each of these priority items, is nearly impossible.

The urban environment is represented by a broad range of heterogeneous land use and land cover classifications. Attempts at managing the urban environment in DC with sound planning, similar to that found in most cities in North America, have been practiced in DC for decades. However, these management attempts have, in many cases, been unsuccessful. In general, the reasons for the failure of policies and programs in these cities are not hard to find. Laquian (2000) notes that the economic and social forces favouring urban growth have been too strong to allow for urban planners and residents to negotiate successfully the scale of development that has occurred over the last several decades. Often, in many Asian countries, just to deal with the rapid development, planning policies have channeled urban sprawl into specified development nodes rather that attempting to restrict development. Because of this, a serious problem concerning the loss of rich agricultural lands surrounding mega-urban developments has become apparent (Laquian, 2000).

It has been demonstrated that the processes that constitute urban activity have far-reaching and long-term effects not only on the immediate boundaries of cities, but also on surrounding region(s). Basically, the urban environment consists of two components: resources and processes. Resources include land, water, energy and human components while processes include industry, transportation, migration, construction, and residence

(GDRC, 2001). As processes occur that transform resources into other useable products and services, or as humans migrate, several different ramifications are possible. These effects can be either positive, such as practical products that create economic growth, education and an increased knowledge base, or negative, such as pollution and waste generation. Management of these processes becomes the focus where the natural environment meets the urban environment and it is these geographic interface areas where side effects tend to occur. UEM needs to be the focal point for many government policies in cities in DC. The objectives of UEM need to facilitate the management of

1) the urban working and living environment,
2) environmentally-sound urban growth and development,
3) conservation and protection of urban natural and cultural environments,
4) the prevention of environmental deterioration,
5) the evaluation and mitigation of impacts of urbanization,
6) urban transportation,
7) health and safety in urban areas,
8) urban waste, and
9) monitoring of changes in urban environments.

(UEM, 2001)

The objectives of UEM and its subsequent policy generation fit into the framework of this thesis as shown in Figure 2-2. As with SD, the need to identify areas of potential environmental stress that has emerged due to development must be completed through UEM because UEM is more likely to occur if policy and planning guidelines are designed to meet the objectives of UEM outlined above. To facilitate the creation of these policy and planning guidelines, both quantitative data and qualitative information is required. Data enable planners and others involved with managing growth to make decisions regarding issues, including the loss of natural resources and the controlling of pollution, from a more informed vantage point. Further, the effectiveness of an urban management policy must also be measured in terms of the effectiveness of information dissemination (Srinivas, 1997). Without public education and liberal support from the necessary stakeholder groups, the provision of UEM to ensure the prevention or detection of potential environmental stress cannot be achieved.

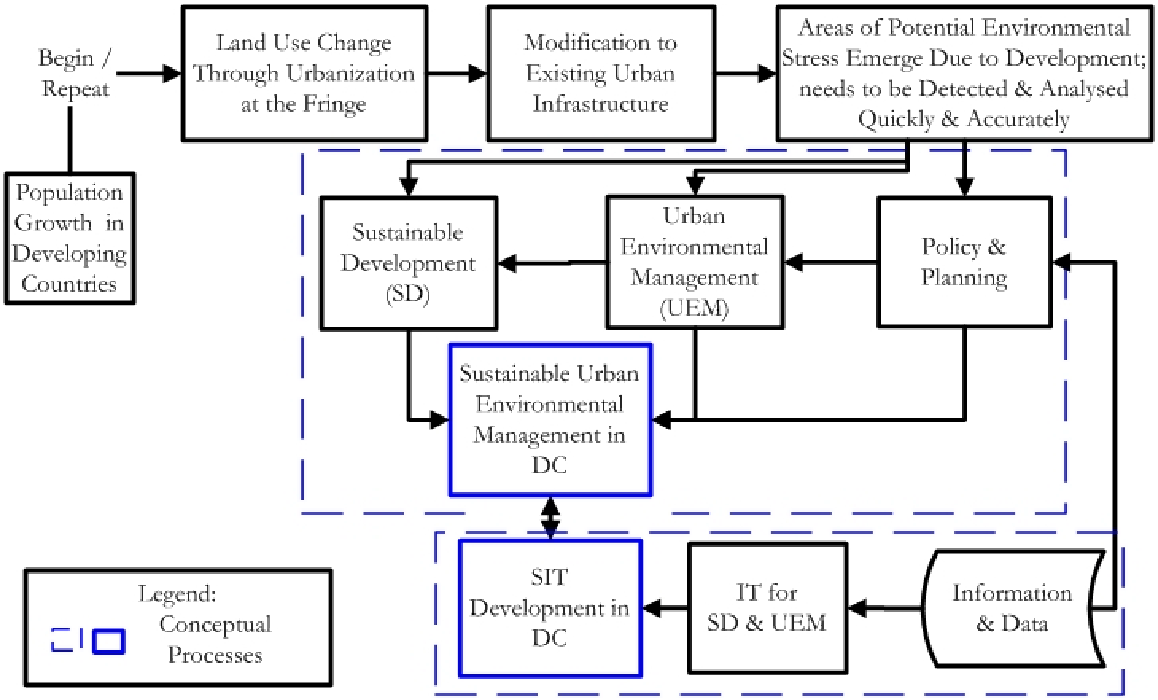


Figure 2-2: Location of UEM in Integrated Framework

In the face of rapid expansion, the need to plan cities in developing countries is cause for concern, especially in terms of environmental sustainability and UEM. This is because many cities in these areas do not have the resources, financial and human, to facilitate sustainable environmental management. Additionally, growth in DC cities is too often being driven by a strong desire for economic prosperity and increased productivity. The reason for the drive to increase productivity is, simply stated, profitability. Castells (1996) develops this theory in more detail by discussing how a company's desire for profit maximization and profitability often far outweighs its desire for productivity. To remain, and more often to become, profitable in the global economy, increased productivity becomes necessary for companies in developing countries. However, more often than not, this increased productivity is achieved through impacts on natural resources and the environment.

In a situation where information is integral to facilitate planning decision making, planners in developing countries have limited resources at their disposal (Masser and Campbell, 1989). A problem such as the bureaucratic inability to share resources leaves many individuals and groups information poor (Nghi and Kammeier, 2001). Given this reality, the key to realizing effective planning and urban management becomes the development of effective strategic planning. In an attempt to achieve this, UEM in the past has often come in the form of importing urban planning practises from developed countries. For example, Ngwainmbi (1999) notes that the exportation of technology to developing countries can be appropriate, but only when the technology causes social and infrastructural change. He continues to note that since the Second World War, industries in developing countries have focussed on the transfer and creation of value-oriented technology. However, this has not been successful in many cases, as the technology was rendered useless because its function was not predetermined. More often than not these imported technologies, which have been relatively successfully in cities in developed nations, are not nearly as effective in the context of a developing city. Because of this, new and innovative solutions involving information technology have been tried frequently in cities in DC in an attempt to compensate for unsuccessful planning practice (Bishop *et al.*, 2000).

2.3 Sustainable Urban Environmental Management (SUEM)

The concepts of SD and UEM are, in some ways, interchangeable in their meanings and principles. However, in the context of this thesis, environmental management is identified as a primary component of SD, and as such, it is encompassed within the concept of sustainable urban environmental management (SUEM).

There are many new challenges facing city planners and those responsible for urban policies, as the rate of urbanization continues to increase (Neilson, 1999). Within the integrated framework proposed in this thesis, SD and UEM are linked to produce SUEM, as shown in Figure 2-2. If the escalating population growth in DC is to be met with planning and policy frameworks that will provide for viable socio-economic futures, both SD and UEM, as defined separately above, must be included in this framework. The resulting rapid increases in demand for employment, natural resources, land and basic urban necessities make urban management attempts to improve living standards and to protect the natural environment more difficult, but at the same time, more crucial. This immediate need to support SD and UEM must be met through an integrated approach to ensure that cities and countries move towards SUEM if there is to be a sustainable future. A means of assisting the move towards SUEM in developing countries, as outlined in the following section, is through the use of data and information technologies.

2.4 Role of Information Technologies in Facilitating the Goals of SUEM

To achieve SUEM simultaneously with development, urban planners in developing countries need to acquire new planning skills and techniques. These skills must enable planners to recognize and analyse the spatial element of urban development. Based on the Agenda 21 (United Nations, 1992) goals and activities discussed earlier, Low *et al.* (2000) provide an assessment of the impact of communication infrastructure on SD and the urban environment. Their conclusions point to the fact that only some cities around the world have adopted programmes for ecologically sound SD. Although the fact that some cities have formulated programs to facilitate ecologically SD is laudable, the rates at which the remaining cities make progress towards achieving Agenda 21's goals and activities will substantially determine the world's future ecological state (Low *et al.*, 2000).

The inherent differences between cities in developing countries and those in developed nations underline why many difficulties exist in the implementation of IT in the former. Bishop *et al.* (2000) provide seven characteristics of cities in developing countries that affect their ability to adopt IT (in general the same factors apply equally to SIT). These include:

1) rapid growth not being matched by growth in delivery of infrastructure;
2) urban development often uncoordinated as growth is driven by market forces and speculation;
3) uncoordinated land management and planning laws;
4) adoption of a prescriptive form of land use planning resulting in longer term land uses that are less market sensitive and often not adhered to;
5) large amounts of squatter settlements and slums resulting from a lack of adequate housing;
6) unplanned developments that present difficulties in providing utilities at a later date; and
7) a complete lack of spatial information infrastructure (and lack of data).

In this context, appropriate technology for SD planning, UEM, and ultimately, SUEM, comes down to what is *suitable* and *accessible* (Cartwright, 1992). Quite often in the past, a technology proven to be appropriate for application deployment in a developed country has been introduced into developing countries with no consideration of the possibility that it may not be as effective in this context as in the other. Unfortunately, different levels of data availability and quality, cultural, and planning needs and requirements in these countries have often rendered imported innovations unsuccessful. Ramasubramanian (1999) notes that successful or unsuccessful implementation of SIT in developing countries can be attributed to many factors, not all limited to the actual use of the technology itself. These might include resource constraints, technical constraints, cultural and language barriers, and structural problems (Ramasubramanian, 1999). Further, even though the rate of adoption of information technologies in developing countries has been increasing steadily for several decades, questions of their actual penetration and effectiveness remain. The key issue here lies in whether or not the services that are provided are relevant and appropriate for developing countries (Menou, 1993).

To this end, the seven characteristics identified above by Bishop *et al.* (2000) provide starting points for understanding how IT can contribute to, and improve upon, planning and policy formulation. In particular, IT can assist in improving the infrastructure necessary for the management of urban growth, which in turn aids the process of SD planning and UEM. This potentially includes the processes of managing resources, human and other, that convert these resources into various other useable products and services in an environmentally sound manner.

If an effective implementation and deployment of IT can ultimately take place, the technology can be effective in rectifying some of the negative side effects of urban growth. For example, in the case of SIT, because the rapid growth of cities in developing countries cannot be matched by timely infrastructure provision, Hall *et al* (2001) have shown that an integration of RS and GIS technologies can be used to locate and target areas that require improved funding for infrastructure provision and, hence, improved quality of life. In the context of this thesis, the processes of utilizing IT in developing countries for SD, UEM, and ultimately, SUEM (Figure 2-2), figure prominently in the framework proposed to achieve sustainable growth through the use of spatial information technology. The model demonstrates that IT is utilized in conjunction with timely and accurate data. These data are also used in the creation of new urban planning policies. Subsequently, these policies and implemented practices are used in DC to achieve UEM and SD, which are integrated, as outlined in the previous section, to form SUEM. In parallel to these processes, data and IT are also required for SD, UEM and finally, SUEM. The use of IT in developing countries has reciprocal flows with SUEM in developing countries in terms of the notion that IT can be used to achieve SUEM. At the same time, SUEM is also the catalyst for the implementation of IT in DC.

When attempting to implement IT to facilitate SUEM to address aspects of growth in a developing city, many factors need to be taken into account. The first factor that must be considered is whether or not the IT in question is, in fact, an appropriate technology.

Darrow and Pam (1978) define eleven principles of appropriate technology, namely:

1) be low in capital costs
2) use local materials wherever possible
3) create jobs, using local skills & labour
4) small scale to be affordable by a small group of farmers
5) understandable, controllable and maintained by villagers without high levels of education
6) be produced in a small fabricating shop, if not in a village itself
7) facilitate communal work, recognizing that in most of the world decisions are made by groups rather than by individuals
8) use renewable energy resources
9) make the technology understandable to the people who are using it and thus suggest ideas that can be used for further innovations
10) be flexible so it can continue to be used or adapted to fit changing circumstances
11) be free of patents, royalties, consulting fees, import duties or financial incumberances so that practical plans can be obtained free or at low cost and no further payment is required.

Given a typical lack of capital, the need to create jobs and utilize local skilled labour, and the need to make technology understandable to the people using it, many of these principles are still applicable. However, it can be argued that their usefulness may not be directly applicable to SIT. In particular, where SIT is being used to facilitate SD, UEM, and SUEM, Darrow and Pam's principles require further scrutiny. This is addressed in the following section.

2.5 Role of Spatial Information Technology in Facilitating the Goals of SUEM

Urban development and land management are also processes that, if implemented properly, can benefit from the use of RS and GIS technologies. Specifically, Bishop *et al*

(2000) point to the success of small strategic applications that can help to establish the value of GIS in developing countries. Small, targeted applications are often more successful than a complex and comprehensive GIS due to the lack of well trained and educated persons in planning roles in some developing countries. With targeted applications, such as the extraction of road features from RS imagery and ancillary data analysis for growth detection and potential urban stress identification, the process and results are produced more quickly than an encompassing land information system designed to incorporate too many items at too many levels of analysis.

As noted by Elkington and Shopley (1988), information is the ultimate renewable and therefore sustainable resource. However, as already observed, without adequate and accurate information, urban planners in developing countries have difficultly making important decisions. In terms of planning-related issues, spatial information is fundamental to accurate decision-making. To this end, the use of IT in planning has not been fully realized in a developing country context. While communication and information technologies are targeted to assist in solving development problems including illiteracy, disease and poverty, to name but a few, it is ultimately up to many different individuals, organizations, and levels of government to ensure that information processing tools and basic information are made available in these contexts (Hanson and Narula, 1990). Because of this, it is important first to understand the level of penetration of SIT in developing countries before subsequent projects should be implemented.

As noted in the previous section, IT, SIT, and their implementation in DC feed the process of SUEM while, in turn, SUEM contributes to the processes involved in implementing SIT in a DC context (Figure 2-2). This process is now addressed.

2.5.1 Information Technology for SD and UEM

In recent years, advancements in microelectronics-based information and communication technologies have contributed to economic growth in both developed and developing countries (UNCSTD, 1998). However, many gaps still exist. Agenda 21 (United Nations, 1992) outlines the gap between available data quantity and quality in regards to the desire to achieve more cost effective and relevant data collection. Further, Agenda 21 notes the need to strengthen the capacity of data collection and decision-making, to develop a means of ensuring planning for sustainable development, and finally, to make relevant information accessible. In general, these are desirable, yet very broad goals. While considerable amounts of data do exist, the majority of these data are not useful in many cases due to uncertainties related to data validity and accuracy.

Five activities were identified in Agenda 21 to assist in the achievement of the above goals. These activities include the development of a set of suitable SD indicators; the improvement of data collection and use; the improvement of data assessment and analysis techniques; the development of an information framework, and the encouragement of traditional and indigenous knowledge wherever possible (UNCED, 1992). Breheny and Rookwood (1997) list four key areas that form the basis for developing a strategy to ensure future urban sustainability, namely natural resources, land use and transport, energy, and pollution and waste management. However, relatively little is being done in terms of using these as indicators to monitor SD. Bishop *et* al (2000) note evidence of this inactivity in many cities in developing countries in terms of sprawl of informal settlements, increases in congestion, air and water pollution, poor infrastructure, and housing decay.

Additionally, Agenda 21 notes the need for improved data collection to facilitate more robust methods of data assessment and analysis. One method of data collection that has been employed for several decades is satellite remote sensing (RS). However, its effectiveness in an urban setting has been limited in the past by the low spatial resolution imagery. As spatial resolution increases, the morphological structure of cities in terms of density, textural form, and spread become more visible and hence, theoretically, more easily detectible and extractible from satellite imagery. In terms of data analysis in developing countries, Agenda 21 recommends new SIT to fulfil the needs of analysis of data from satellite sources. A review of the literature pertaining to existing use of RS in an urban setting is addressed in a subsequent section.

2.5.2 Spatial Information Technology Penetration

IT, and particularly SIT, is readily utilized in developing countries. However, the *effective* implementation and use of SIT is not nearly as extensive. Many pre- and post-conditions must be in place before SIT penetration can be effective. In terms of preconditions and SIT, Hall (1993) suggests that Darrow and Pam's (1978) eleven principles of appropriate technology, discussed earlier, are not satisfied in most contexts. For SIT to penetrate into emerging economies, it first needs to be able to make use of local materials and persons whenever possible. This is often difficult with GIS, as a large amount of training is required to make users proficient with the software. Ramasubramanian (1999), Burrough (1992), and Taylor (1991) note a lack of trained personnel as one of the key barriers to GIS implementation in developing countries.

In some cases, the symbolic value of owning a GIS and its associated social status also plays a role in effective implementation and use (de Man, 2000). This can have two effects. First, the social status may be more important than the actual use and results achieved from the GIS. de Man (2000) points out that this and other non-concrete results from GIS implementation can have a significant and positive effect on organizations. Second, the associated status can also be used as motivation to derive results from the GIS implementation.

Hall (1993) goes on to note that a relatively high cost and performance requirements of hardware and software is required for a spatial information system to render the technology 'socially' inappropriate in most developing countries. Burrough (1992) confirms this viewpoint stating that the costs of computer hardware and software, costs of training, and costs of data acquisition, can make these activities economically prohibitive. Given the financial constraints alone, Darrow and Pam's (1978) requirements of being low in capital costs and being free of patents, royalties, consulting fees, import duties or financial encumbrances, it seems unlikely that a GIS is an appropriate technology for many developing countries, further impeding the case for the use of SIT in achieving the goals of SUEM.

Finally, it should be noted that Hall (1993) qualifies the above statements by noting the fact that these principles of appropriate technology focus mainly on production technology. In this sense, while the Darrow and Pam's (1978) principles are applicable only in some ways rather than completely to the implementation of SIT. It is possible that the differences in production technology and SIT may be too great to allow for a direct comparison in this manner. Other factors including initial expenses, capital costs, and import duties may also render the comparison somewhat fallacious.

Given the relatively limited productive use of SIT in developing countries, it is important to understand how SIT has been used in the past to facilitate better development policies and planning in terms of SUEM.

2.5.3 Local SIT Development for SUEM

According to the Latin American Demographic Centre (CELADE), there are six key functions that technology must facilitate when employed at the local level in a developing country. These include:

1. processing of census microdata for user-defined small-areas;
2. multi-sector databases;
3. utilization of present with past censuses;
4. digitized census cartography;
5. spatial display and analysis of the data on maps; and
6. small-area population estimations and projections.

(CELADE, 1995)

However, several barriers persist in realising these functions, especially in terms of data collection processes and data validity. The processing of census microdata for user defined small areas is only now being realized in the relatively more developed of the developing countries around the world. For example, The Information Processing Institute for Education and Development at Thammasat University, Bangkok, Thailand, has been developing a village level database of socio-economic characteristics since the early 1990s. While the collection of these data has been proceeding for several years, it is unclear whether they have been fully processed and put to their full potential by any persons or organizations. Further, the data are only currently available from Thammasat University in a large dBase (dbf) file that has several different elements of information in one field within the database. Because of this, the data require time-consuming pre-processing before they are useful for any actual analysis.

This type of problem is not uncommon in most developing countries. The United Nations (1996) noted that for the process of development to occur in a sustainable manner, data integrity is crucial and that currently in developing countries, there is a need to improve on the lack of quality data for decision support analysis. Inconsistencies in much of the data currently available in developing countries and a virtual absence of any metadata only compound the inability to determine the validity and/or accurateness of these data.

In addition to problems with data quality and availability is the fact that GIS technology may not fully meet the information needs of planning or SUEM. Couclelis (1991) lists four basic functions in this regard, namely operational, management, strategic, and communication and she states that it is possible that the concept of geographic space that underlies underlying GIS technology may be quite different to the notion of space embodied in managing urban areas. She notes that planning's notion of space can include spatial and non-spatial frameworks, such as legal and fiscal matters, as well as quantitative (census data) and qualitative (verbal descriptions) spatial information. Within this context, important differences between site and situation are addressed. While site represents the attributes of a specific location, situation "is what characterizes a location by virtue of its being part of a spatial structure involving other locations" (Couclelis, 1991). Current SIT can address site effectively using its spatial and location linkages (GPS, co-ordinate systems, etc.). However, it is limited in its ability to provide the descriptive characteristics of a given situation. Until situational factors, such as neighbourhood type, political conditions, and local perspectives can be included in the decision making process, no level of site analysis can be entirely accurate or conclusive. Because of this, the next step in the development of SIT in both developed and developing countries should incorporate both site and situation into analyses.

To address these points in more detail, the past and present operational use of SIT in developing countries needs to be thoroughly reviewed. As such, the next four sections review the operational use of SIT to achieve SUEM from RS, GIS and integrated analysis perspectives.

2.5.4 Operationalizing SUEM with SIT

As noted in the previous section, the process of operationalizing SUEM continues to be fraught with difficulties in many developing countries. However, it is argued here that, when used appropriately, IT and SIT tools can make an important contribution in making the concepts of SD and SUEM operational. In this context, one of the main objectives of this thesis is to create a reliable process of road network identification, extraction and subsequent integration within a multi-source and multipurpose GIS database to help facilitate SUEM. To date, this is something that does not currently exist within a developing country context. There is, however, quite widespread use of SIT to address related issues and the following sections review the use of existing RS and GIS applications and their findings. The purpose of this is to show the lack of an adequate process of integrating RS imagery and ground-based socio-economic GIS data to generate indicators of areas of potential environmental stress.

The inclusions of RS and GIS for SUEM, shown in Figure 2-3, flow from the need to utilize SIT in DC to achieve SUEM, as addressed in Sections 2.2 through 2.5.3. The left hand side of the figure outlines proposed temporal RS analysis steps in the detection of land use change and subsequent integration with continued GIS analyses. The right hand side follows parallel temporal analysis of GIS based socio-economic data, which, as noted above, is integrated with the RS change detection to derive the locations of potential environmental stress. The results of this integration are further used to select an area(s) for continued RS analysis in the form of transportation feature detection and extraction. Through closer examination of existing RS and GIS applications in the next three sections (2.5.5 through 2.5.7), evidence of the need for improved processes of analysis and subsequent integration of the two technologies is further revealed.

2.5.5 Remote Sensing (RS)

Since their inception, RS technologies have provided researchers and practitioners with the ability to produce land cover mapping. The first tangible combination of space exploration and remote sensing took place after World War II when cameras were attached to rockets and launched from New Mexico (Lillesand and Kiefer, 1994). These images were not of high quality, but they did initiate the interest of researchers in taking pictures from space. Following this, in the early 1960s, weather satellites captured images of clouds with the coarse earth's surface as the background. Since then, many satellites with various sensors have been put into use by many countries for the general purpose of earth observation.

Two of the most successful and influential satellite programs include the Landsat program in the United States and the SPOT (Systeme pour l'Observation de la Terre) program in France. The first Landsat Mission was in 1975 and since then seven missions have been completed, all but one successfully. The SPOT program has produced four satellites since 1986 with a fifth scheduled for launch before the end of 2002. Both the

Landsat and SPOT programs have improved and refined their data collection methods since the original launches and today are amongst the leaders in breadth of wavelength coverage and improved image spatial resolution. Most recently, the launch of the private satellite IKONOS by Space Imaging Inc. in 1999 marks the availability of the world's first commercial high-resolution (< 2 meters) satellite imagery (Tanaka and Sugimura, 2001). Also, the launch of *QuickBird* on October 18th 2001 by DigitalGlobe, which offers resolutions similar to IKONOS, will bring competition to the high-resolution commercial satellite market.

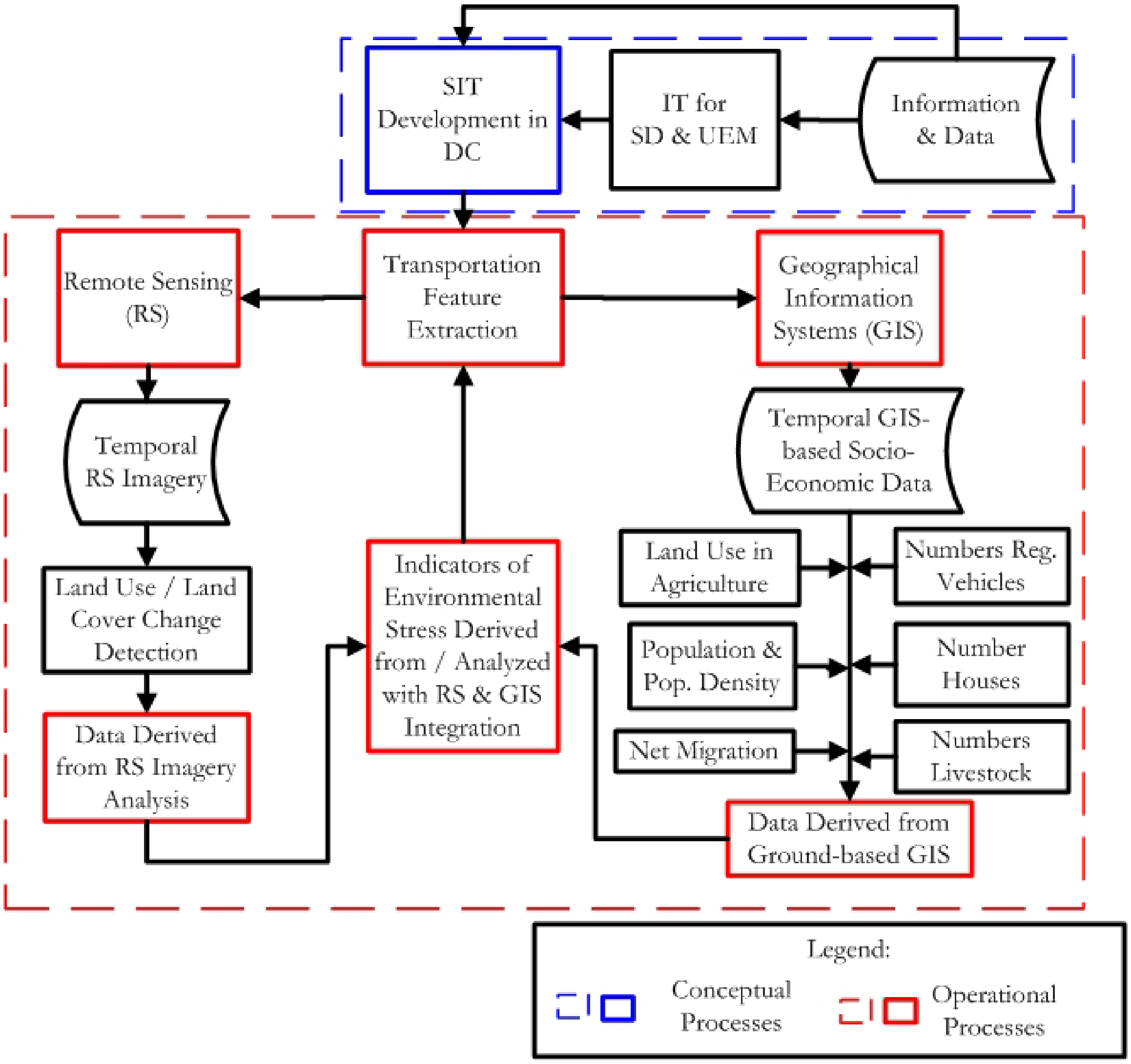


Figure 2-3: Integration of RS and GIS Technologies for SUEM

Morain (1998) lists the following items as the motivational forces behind the development of remote sensing technologies:

1) need for better information about the earth's surface
    - spatial distribution of natural resources
    - effective management of renewable and nonrenewable resources
2) national security
    - assets for maintaining security through observation
3) commercial opportunities
    - still being tested via recent launches of privately owned satellites
4) international co-operation
    - co-operation to better understand, manage, share, and protect earth's resources
5) international law
    - to ensure the facilitation of free and open exchanges of data and information.

These points outline the main uses of data collected via RS since its inception and subsequent development. These uses are applicable to planning and policy making needs in cities in developing countries. Because RS can provide land cover data relatively swiftly and efficiently, it can be concluded that it is a suitable vehicle for planning and policy development (Ulbricht *et al.*, 1995). Using RS, planners can better understand the urban environments they work in, thereby assisting in problem solving and decision-making processes. In this context, Da Costa and Cintra (1999), in their paper addressing the use of RS for metropolitan environmental analysis in Brazil, note the abilities of SPOT and Landsat imagery in the areas of research support, analysis of spatial dynamics and urban morphology. They further note that the methodology, which includes the use of RS analysis, permits the study of urban environments in a complete, rapid and precise manner, all at a relatively low cost (Da Costa and Cintra, 1999).

RS has been extensively used in the study of land cover and land use change across the globe. While this work has had the common goal of facilitating identification, classification and changes in the distribution of land cover and land use, approaches and data sources have varied. Land cover can be defined as the physical composition of the land under examination, or what can be recognized from the air, while land use is the actual usage or productive application of the land. For example, land cover could be forest, grassed vegetation, or water body whereas a land use would be agriculture, urban infrastructure, or hydroelectric reservoir. Because of the many satellites and sensors that are currently orbiting the earth, researchers have several options when it comes to selecting the sensor that best targets the location and needs they are interested in. For example, Martinez-Casasnovas (2000) implemented a cartographic and database approach for land cover/use mapping in Spain. His approach began with the development of a hierarchy of terrain object classes to support classification results. The results of this hierarchy were then transformed into basic mapping generalizations, which were in turn translated into a relational database focused on structuring data in order of data element relationships. He concluded that this approach to image classification can be viewed as advantageous from the user's point of view since land cover / use classes were structurally broken down into basic mapping units that could be used in a variety of planning applications.

Similarly, Makarovic (1995) discussed image-based mapping, listing image interpretation and feature extraction, stereomodel orientations, sampling and digitizing, geometric transformations and field completion as the five main mapping techniques. The technique of particular interest in his paper was image interpretation and feature extraction. Makarovic indicated that feature extraction was easier and more effective when high-quality (higher resolution) images were utilized. Because of this, image-based mapping was best suited to semi-detailed and coarse thematic mapping, where high accuracy was not required. This continues to be the case with even higher resolution satellite imagery.

Not all RS image analysis involves straightforward classification processes. Several computing algorithms including edge detectors, neural networks, and dynamic programming techniques have been developed to analyze land cover with RS data. For example, Kalluri *et al.* (2000) used a hierarchical connected components algorithm to undertake image segmentation by clustering pixels into homogeneous regions. They then connected these components relative to uniform pixel reflectances. Kalluri *et al.* (2000), conclude in their discussion that recent developments in faster, high-end servers and workstations allowed the development of complex mapping and computational processes that were cumbersome to implement in the past. They recommend the use of multiple processors in data processing for the computationally intensive tasks of image enhancement and segmentation and they noted that new processing technologies will ensure the implementation of remote sensing algorithms to study land cover dynamics at a global scale (Kalluri *et al.*, 2000).

Population analysis using RS can also provide valuable information about urban growth dynamics. In this context, Entwisle and Walsh (1998) examined the interrelationships between population and environment in northeast Thailand by strengthening the union of social and spatial data, techniques, and perspectives. To facilitate this, imagery from Landsat MSS and TM sensors were used as well as the SPOT multi-spectral and panchromatic sensors covering an approximately twenty-year period from the mid 1970s to 1990s. Their findings suggest that RS data can provide a valuable perspective on land cover and land use change. Using multi-source and multi-temporal RS imagery, they were able to examine inter-seasonal variations of the landscape that were otherwise difficult to assemble and acquire. The data allowed enhancement of the overall perspective of their study when integrated with the ground-based population surveys. However, for temporal analysis, several limitations affect remote international locations. For example, archived data are often difficult to find, assemble and acquire and few alternate views of the landscape are offered from the commonly available satellite systems (Entwisle and Walsh, 1998).

In a related study, Dutra and Huber (1999) examined feature extraction for land use classification using Earth Resources Satellite Synthetic Aperture Radar (ERS SAR) data. They confirmed the notion that specific feature extraction in a land cover classification is inherently difficult given that it is both dependent on the input data and on the classifier used. Their method involved feature selection followed by classification using the maximum-likelihood classifier and an artificial neural network. Because of their use of SAR data, they were forced to employ a refining Lee filter to remove the speckle inherent in the image, a technique often employed with SAR data (Hall *et al*, 2001). Ultimately, Dutra and Huber (1999) found that their classification accuracy, similar to most classification methods, was excellent in terms of the training set, but worse for the validation set and subsequently for the complete image.

This brief review suggests in general that the use of RS technologies in developing countries is viable, thus affirming the general approach adopted in this thesis. However, Foody (1995) noted that the full potential of using RS as a source for land cover data has not been fully realized to date, particularly in terms of the integration of this data source with GIS. The integration of RS technologies with ground-based GIS to analyze land use at the rural-urban fringe, specifically in order to detect land use change and subsequent indicators of potential environmental stresses, is now considered in more detail. The primary landscape feature used to identify new urban development in this research is the transportation network. Hence, research on the detection and extraction of roads from RS imagery is reviewed in the following section.

2.5.6 Skeletal Road Extraction

O'Sullivan (2000) stated that mobility, defined as the ability of people to travel over distances, increases due to the necessity of people to move to and from homes, places of employment, retail outlets and leisure facilities. Further, he noted that as these localities become more geographically dispersed, the impacts on and requirements of, the existing transportation network increases, precipitating growth in the network. Because transport and transportation networks are in need of major improvements in cities in DC, there exists a necessity for being able to locate and map the road networks in a more timely and efficient manner. This not only includes existing routes, but must also include the need for better planning of new routes as well as the need to detect and monitor new roads as they develop (O'Sullivan, 2000). This temporal examination of old and new roads is necessary to facilitate the analysis of land use change over time as secondary urban infrastructure grows around the developing transportation network. As noted above, these needs form the fundamental basis for this thesis.

Automated extraction of man-made and natural objects from aerial photography and satellite imagery is one of the fundamental tasks in image analysis (Kim and Muller, 1995). Attempts to extract specific features automatically from digital images have been in practice for more than fifteen years using many different methods and algorithms (Gruen, 1995). The desire (and need) to extract linear features has been of interest in the private sector, government and the military. A basic objective of this thesis is to establish an operational process of linear (road) feature identification from RS source imagery and subsequently to extract these features into a GIS. The term 'extraction' itself can be vague at times (Doucette *et al.*, 2001). Here, the task of road extraction addresses the issues of both road identification and subsequent delineation. Once extracted, these features are then added to a multi-source GIS database for analysis in conjunction with other indicators of urban growth. This database allows potential environmental stress locations of growth and change to be identified. While various processes of linear feature extraction are well documented, as reviewed below, the ability to identify and extract features and automatically input them into a GIS for analysis is not thoroughly addressed in current research.

Several researchers have examined the possibilities of extraction and classification of man-made features in urban environments including, for example, buildings and roads (Trinder, 1995; Haala and Brenner, 1999; Shettigara *et al.*, 1995; Sowmya and Trinder, 2000; Guindon, 2000; and Baltsavias, 1996). Shettigara *et al.* (1995) defined the terms 'artificial' and 'man-made' as objects that have been artificially created using synthetic or natural materials. Before any extraction and/or classification of such features from RS imagery can take place, the geographic context of the images must be understood. Context, in this sense, can be defined to include, using Couclelis (1999) terms, the site and situational dimensions, as well as the spectral and spatial resolutions of the source imagery. The differences between site and situation were addressed earlier. However, this can be an important consideration in terms of representing inherent or local knowledge in the context of RS images. Factors such as the size of the object in question with respect to the image pixels under examination influence the ability to extract and classify man-made features from other information contained in the image. Even after understanding and accounting for these factors, specific feature extraction has traditionally been completed only via manual or semi-automated methods (Sowmya and Trinder, 2000). Hence, recent attempts have been made by researchers at automating the feature extraction process.

Methods used include object recognition models using spatial/spectral/contextual attribute combinations in high resolution imagery for recognition of such features as roads and buildings (Guidon, 2000); digital ortho-photos through 3-D extraction from stereo pairs (Baltsavias, 1996); finding edges of man-made objects and extracting them by mapping the boundaries between the man-made and adjacent natural objects (Shettigara *et al.*, 1995); and using laser scanners to classify and extract buildings and trees from urban environments (Haala and Brenner, 1999). The success of these methods has been varied. However, each has achieved the extraction of features via either manual or semi-automated techniques.

As more methods are developed for data acquisition via successful identification and extraction of features for digital mapping and GIS, knowledge representation modeling skills are used to adapt methods to particular characteristics of the image (Sowmya and Trinder, 2000). In particular, the extraction of linear features has received a great deal of attention and, subsequently, different methods of road extraction have been developed and tested. These include, but are not limited to, map-image modeling, edge detection and filtering, dynamic programming, LSB-Snakes, neural networks, laser scanning, and 3-D edge detection. These techniques are now described.

Land development and hence land use change from one state to another, typically occurring around existing built-up areas and along roads (Yeh and Li, 2001). As these changes are invoked, they become the triggers for further development through a cyclical process that is both temporally and spatially variable. As roads appear, typical urban landscapes develop naturally along and adjacent to the roads. Consequently, this feature represents the catalyst for new urban development. Hence, the extraction and analysis of linear features such as roads and the edges of areas of land use change from digital imagery is centrally important in the processes of SUEM.

As noted above, the analysis of satellite imagery for linear feature extraction has been extensively researched (Mayer and Steger, 1998; Steger *et al.*, 1995); Fiset *et al.*, 1998; Jedynak and Roze, 1995; and Barzohar and Cooper, 1995). Modeling methods such as abstraction, defined by Mayer and Steger (1998) as the increase in the degree of simplification and emphasis, are used to detect relatively homogeneous regions in an image. In the case of roads, their surface and reflectance is typically homogeneous and of a different brightness than the surrounding areas. Using this assumption, Steger *et al.* (1995) extracted a partial road network. However, shadows present in the image produced erroneous road segments in some areas.

Fiset *et al.* (1998) modeled map-image matching for road network updating. Because the updating of topographic maps is traditionally a tedious and time-consuming task, they sought to automate the process. Their process began with the rasterization of the existing road network. The rasterized road network map was then matched to a classified image to locate potential new roads that could be derived from the image. The matching process used two algorithms. The first sought to match the rasterized map-road with the corresponding image-road network. The second algorithm was designed to search automatically for new road segments, which were added to the existing road map. The two main problems that were encountered using this approach included the tendency for the second algorithm to confuse road pixels with the spectral signature of buildings adjacent to the road segments and missing segments that result in too few relevant pixels in certain parts of the image. To match effectively the new road segments with the existing network, a supplementary step was used to trace the segments with a seven by seven search window at each intersection coordinate in the database. This supplementary pixel analysis, in conjunction with the map-image mapping process provided results that were far better than either method singularly. This process represented an effective and efficient means of road detection and map updating.

Edge detection and filtering have also been used for linear feature extraction (Tripathi and Gokhale, 2000; Karimi *et al.*, 1999; and Vosselman and de Knecht, 1995). The process of roadway feature extraction consists of three main tasks, including image acquisition, feature extraction, and input to database management systems. Karimi *et al.* (1999) used the *Thin and Robust Zero-Crossing* edge detector for this purpose. First, roadways in high-resolution images were manually seeded. Seeding was defined as the process of human input and interpretation during the extraction process to provide the classifying computer algorithm with information pertaining to accurate road location. Seeded segments were then processed with the edge detector to locate and extract road features in a semi-automatic manner. This research using high-resolution imagery (1 metre) showed promise as a means of road feature extraction. However, before it could be fully automated and implemented effectively, several aspects needed to be refined. These included:

1) image intensity to noise across road surfaces;
2) shadows cast by buildings, trees, etc.;
3) barriers like bridges and overpasses;
4) occlusion due to vegetation and topography;
5) confusion between roads and other man-made construction;
6) markings on the road;
7) differences in road materials used;
8) traffic pattern differences on road;
9) position errors caused by elevation change; and
10) limitation of the information content on the images.

(Karimi *et al.*, 1999)

These problems are not only applicable to the application of edge detection algorithms. They also cause problems and inconsistencies for all methods of feature identification and extraction and need to be researched further before fully automated processes can be realized. Because the extraction of detailed roadway features from satellite imagery for input into a database management systems, especially a GIS, has not been extensively reported in the literature, it represents a gap in the research and an area that deserves further exploration (Karimi *et al,* 1999).

Since fully automated methods, with no human assistance, for conversion of remotely sensed images to digital maps are still generally unfeasible, semi-automatic methods that involve computer and human interaction are the most viable alternative (Vosselman and de Knecht, 1995). In this context, road identification by filtering can be used to estimate the parameters that describe a road by shape and position. Vosselman and de Knecht (1995) used a Kalman filter to detect and remove outliers in observed image feature characteristics to facilitate continuous feature mapping. They described road feature characteristics as typically being represented by the following characteristics:

1. roads are elongated;
2. roads have a maximum curvature;
3. the road surface is homogeneous;
4. the road surface often has a good contrast with the adjacent areas;
5. roads do not stop without reason;
6. roads intersect and build a network; and
7. higher roads may cast a shadow.

(Vosselman and de Knecht, 1995)

The Kalman filter was able to rule out pixels based on a set of predefined conventions and once it predicted the direction of the road, the human operator could then overrule algorithmic decisions based on the set of road characteristics.

Semi-automatic extraction of road networks using dynamic programming has been researched extensively by Gruen *et. al.* (1994, 1995) and Gruen and Li (1995, 1997). Their research defined a typical road extraction procedure as consisting of four steps including road sharpening, road finding, road tracking, and road linking. Using these stages, Gruen and his associates were able to detect and extract roads from single SPOT scenes and digital aerial photographs. Similarly to Vosselman and de Knecht (1995), they listed several generic properties of road features that were used for identification within the image. These features included the properties that a road pixel is lighter than its neighbours on both road sides, grey values along a road typically do not change within short distances, and a road is linear, smooth, and of generally consistent width. Dynamic programming was defined as a technique for solving optimization problems (Gruen and Li, 1995) as it can simultaneously evaluate unrelated road characteristics such as those outlined above. Optimization, in their context, was defined as a determination of the best multistage process for road extraction. By interactively inserting vertices into observable road segments in the image prior to processing, these seed points were then connected to form polygons. Results show that dynamic programming was successful, particularly in rural areas where the distinction between roads and the surrounding agricultural land use was very clear.

Use of Least Squares B-spline (LSB) Snakes is a further extension of the work done by Gruen and Li (1997). LSB-Snakes represent an approximation of the position and shape of a linear feature within a RS image or scanned aerial photograph. The methodology combined the tools of ordinary least-squares estimation with the determination of energy-minimizing functions. Using this approach, Gruen and Li (1997) were able to use only a few coarsely distributed seed points set by a human operator near the features of interest to extract features using least-squares regression. In their tests, the process was able to extract roads under difficult conditions including varying road widths and obstruction by buildings, trees, and cars. Based on their results, Gruen and Li (1997) concluded that the results clearly prove the success of this algorithm.

A different method of extraction, which dates back to the late 1980's, is the use of computational neural networks for the classification of remotely sensed imagery (Wilkinson, 1996). Since the potential of neural networks was first demonstrated in the context of feature extraction, there has been a quickly growing body of literature on this topic (see, for example, Benediktsson and Sveinsson 1997, Liu *et al.* 2000). In recent years, the number of successful applications of neural networks for image classification has been increasing. Liu *et al.* (2000) claimed that neural network classifications were more accurate than conventional approaches to remote sensing for several reasons:

> 1) neural network classifiers make no priori assumptions about data distributions (and they) are able to learn … patterns in the distribution classes;
> 2) neural networks can readily accommodate collateral data such as textual information, slope, aspect, elevation; and
> 3) neural networks are quite flexible and can be adapted to improve performance for particular problems.
>
> (Liu *et al.*, 2000)

Following from this, Liu *et al.* produced in MATLAB software several programs for the visualization and analysis of road network infrastructure. Similarly, Bendiktsson and Sveinsson (1997), used computational neural networks as an alternative to conventional classifiers for the classification of remote sensing data. Given the successes generated in the use of neural networks, it is likely that more research in this field will appear in the future. However, in terms of their commercial implementation, packages such as PCI's EASI/PACE Imaging Kit are just now including back-propagation neural network algorithms. Because of the expense of this package and the lack of knowledge on its use, a large gap currently exists, and will likely continue to exist, between research and software implementation (Liu *et al.*, 2000).

Alternatively, laser scanning is a relatively new (in this context) and independent technology, which has made a recent resurgence in the study of image feature extraction (Ackermann, 1999; Haala and Brenner, 1999; and Wehr and Lohr, 1999). Currently, laser scanning is only captured on airborne platforms rather than earth-orbiting satellites. However, the techniques of data gathering to measure the visible ground surface or objects on it make it useful for linear feature extraction. Ackermann (1999) pointed to laser scanning as a particularly interesting new application for the automatic capture of buildings and built-up urban areas within digital urban models. To this end, Haala and Brenner (1999) used airborne laser scanning to classify urban scenes and complete a subsequent process of building reconstruction into a 3-D visualization. Because the use of laser data proved to be successful for them in reconstructing urban environments, they suggested that airborne laser scanning was useful for the automatic generation of urban databases.

Finally, road reconstruction using 3-D edge extraction has recently been developed by Gruen and other collaborating researchers (Zhang *et al.*, 2000; and Zhang and Baltsavias, 2000). The continued goals of Gruen and his team of researchers is to build an automatic and robust system to reconstruct road networks from aerial images with the aid of existing road databases and other data (Zhang and Baltsavias, 2000). In this case, they developed a new approach for automatic 3-D road network extraction by integrating known techniques for processing imagery with existing spatial databases. Their existing data for road networks included road type, class, width, length, topology information, and land cover. These ground-based data were then integrated with the imagery for 3-D road extraction. Zhang and Baltsavias (2000) tested several combinations of this integration and were able to extract successfully a road from a suburban setting. Zhang *et al.* (2000) found that the 3-D edge extraction method provided reliable results given the large amount of existing knowledge input into the process. Based on a visual interpretation of the imagery provided in Zhang *et al.* (2000), it would appear that this process, like previous research into road network extraction, has had far greater success in rural areas as compared to the more diverse and complex urban scenes.

The feature extraction tools reviewed above all have their strengths in terms of adequately extracting linear features for digital map creation and updating. However, none are able to provide a fully automated method with reliable results. Much more research is required in this area before this type of stand-alone method becomes routinely used for urban planning and land use management purposes. This thesis does not seek to improve upon the technical process of skeletal linear feature extraction. Rather, the integration of the extracted features with ancillary data for identification of areas of potential environmental stress is the objective. Once roads are successfully identified and extracted from RS source data, the question of how these data can be combined with other data sources to locate areas of potential environmental stress is addressed. While the road network can be viewed as the skeleton around which secondary urban development occurs, integration of this information with other indicators of change in a GIS (such as land cover classification and socio-economic data) allows for the pattern and process of land use change to be monitored and better understood. Thus, the roads are regarded as the integral indicator in terms of detecting and locating urban development and potential environmental stress in a temporal analysis process.

2.5.7 Geographical Information Systems (GIS)

In 1997, the GIS industry was valued at over US $2 billion (Mark et al., 1997). This figure says much about how the growth of the industry in North America over the past two decades, but little about the positive effects of GIS in developing countries, in particular their contribution to SUEM. Sui (1998) examined current practices, problems, and prospects of GIS-based urban modeling. He noted that conventional urban modeling is being used with GIS worldwide. However, he questioned the relevance of such conventional strategies, which tend to be more closely associated with industrial societies than today's information society. Models specifically targeting industrial cities have a primary goal of controlling land use and this is not necessarily the goal in terms of modeling cities in the information age. With the decline of the manufacturing base and the growth of multinational corporations, the global economy is becoming more diversified and a new urban reality is appearing where the basic manufacturing sector is disappearing thereby lessening the need for stringent land use controls. Sui noted in particular that the integration of GIS with urban modeling is currently technology driven and there is not necessarily adequate justification for the validity of models, nor is there a suitable spatial-temporal framework embedded in the current generation of GIS. In this context, new models of urban development, and specifically SUEM, must be developed to ensure proper urban growth in a sustainable manner. This can be achieved if the new models take into account indicators of urban growth and specifically indicators of environmental stress, to ensure sustainable growth patterns.

The recent research on GIS and urban structure and modeling outlined above leaves many gaps in terms of the provision of a model to ensure SUEM for cities as they grow and expand. The cities in DC are likely to experience stronger repercussions from the lack of a model for SUEM considering their ongoing rapid urbanization (Li and Yeh, 2000). The existing research points to the need for a new model of GIS analysis to facilitate urban growth simultaneously with the objectives and practice of SUEM in mind.

2.5.8 Integration of Remote Sensing and GIS

SIT technologies, especially RS and GIS, have much to benefit from each other (Foody, 1995). In fact, some software vendors, such as ESRI and ERDAS, claim the ability to provide seamless integration between products. However, practice has shown that the coupling of RS and GIS data formats is still some way from seamless. The integration is hampered by the use of differing data models and by the historical differences between these two data structures (Edwards, 1991). Data models in this context include raster, which represents features in a cell or regular grid based model, and vector, which uses points, lines and polygons to represent features.

Total SIT integration is defined by three classes of integration, namely 'separate but equal', 'seamless', and 'total integration' (Edwards, 1991). Separate but equal integration allows for separate software interfaces for image analysis and GIS with data exchange between each of the two, while seamless integration combines raster and vector systems into a single interface. Total integration involves a single system without the encumbrances of classes one and two noted above (Edwards, 1991). Several researchers have recently analyzed the current state of successful integration, at various levels, between RS and GIS (Gahegan and Ehlers 2000, Wilkinson 1996, Edwards 1991, Stow *et al.* 1991). Wilkinson (1996) proposed three main ways in which RS and GIS technologies are complementary to each other:

1) remote sensing can be used as a tool to gather datasets for use in GIS,
2) GIS datasets can be used as ancillary information to improve products derived from remote sensing, and
3) remote sensing data and GIS data can be used together in environmental modeling analysis.

The use of RS as a tool to gather datasets for analysis in a GIS is not new. However, improvements in image classification are making their integration with ground-based data more successful than ever before (Hall *et al.* 2001). New classification algorithms and innovations such as artificial neural networks are improving classification methods and results and trends in gathering and integrating analysis of RS and GIS data suggest a convergence of the technologies. Wilkinson (1996) suggested attribute analysis and classification of RS and GIS data, the use of very high dimensionality data from RS and GIS, and remote environmental mapping and object analysis / search in integrated RS and GIS datasets were commonplace analyses reported in the literature. However, within the field of remote sensing for mapping purposes, the fusion of multi-sensor, temporal data, while practiced for years, is still a complicated process. Environmental mapping requires the temporal component to be complete and relevant in terms of SUEM, whether for a geographically remote location or at the rural-urban fringe of a large developing city. Despite the advances, the processes involved in data fusion are still currently under development as much as at any point in the past decade. This situation is somewhat complicated by the constant introduction of new and different satellite remote sensors. Moreover, many types of different formats and structures continue to hamper this integration.

The updating of GIS data layers based on digital remote sensing has been extensively examined (Makarovic, 1995; Martinez-Casasnovas, 2000; Molenaar and Janssen, 1991). Stow *et al.* (1991) introduced a process that a regional planning agency can use to correct and update vector data using remotely sensed data. Using what they dubbed a "live link" between ERDAS image processing software and Arc/Info GIS software, remotely sensed data were successfully adopted to correct and update GIS land use layers. In the years since their research, software vendors have gone to great lengths to facilitate integration without the need for a "live link" between two separate interfaces. For example, many GIS currently support both raster and vector data structures and several image analysis packages promise a single interface capable of various merged functionalities, architectures, data structures, and ultimately, user experience.

In the context of this thesis, the integration of RS and GIS technologies is facilitated as follows. On the left hand side of Figure 2-3, RS imagery is proposed as a means to collect temporal land use change information. The results of this change detection form a dataset that can then be fed into a GIS for further integrated analysis. The temporal GIS-based socio-economic data analyses, shown on the right-hand side of Figure 2-3, are proposed as a source of ancillary information to improve the output of the RS change detection results. Together, the RS and GIS analyses in Figure 2-3 are used to derive the location of areas of potential environmental stress for further analysis and subsequent policy and planning. This type of environmental modeling demonstrates precisely Wilkinson's (1996) three ways that RS and GIS technologies are complementary.

Even with all of the improvements in the integration of RS and GIS data sets, some uncertainty still exists. Gahegan and Ehlers (2000), for example, suggested that transformation processes, which are integral in RS - GIS integration, contribute to the overall uncertainty that develops within the data. They expanded on this by noting that because data are abstracted from their 'raw' form to the higher representations used by GIS, they must be passed through a number of different data models using a series of transformations.

Current approaches to RS and GIS integration typically involve several stages of transformation including image classification, object formation, and data structure conversion. Image classification represents the replacement of the 'raw' image data with thematic interpretations to assist in the understanding of trend structures or content of the imagery. This process typically occurs on a per-pixel basis, however some pixels may be left unassigned or grouped into an 'unknown' class. Object formation is the conversion of a thematic model into an independent entity with a defined shape. Errors can occur in the object formation transformation process due to positional uncertainty and error. Finally, in terms of data structure, GIS data formats are typically software-specific (Huxhold and Levinsohn, 1995). Hence, to use data created or modified with one proprietary GIS always requires a data structure transformation for analysis with a different GIS. All of these transformations, alone or combined, can lead to uncertainty in the data.

It is possible that data characteristics may change during the transformation and it is difficult to determine to what extent the transformation method used may have affected the data (Gahegan and Ehlers, 2000). The types of uncertainty generated in the four models of geographic space, field, image, thematic, and object are shown in Table 2-1. These sources of uncertainty affect the completeness and consistency of data making them difficult to manage and account for during decision making. Given this, the current methodologies for RS and GIS integration are by no means perfect and the validity of results generated from processes, such as those shown in Figure 2-3, must be carefully scrutinized.

Several studies have been undertaken to examine the integration of RS and GIS (Molenaar and Janssen, 1991; Amissah-Arthur *et al.*, 2000; Yeh and Li, 2001; Huan, 1995; and Weimin, 1995). Subject to the caveats noted above, this integration has proven to be an effective and potentially powerful means of land use analysis and classification that can assist in the development of planning guidelines and policies. Techniques have included vector on

Type\Heading	**Field**	**Image**	**Thematic**	**Object**
Data or Value	Measurement error and precision	Quantisation of value in terms of spectral bands and dynamic range	Labeling uncertainly (classification error)	Identify error (incorrect assignment of object type), object definition uncertainty
Space	Locational error and precision	Registration error, sampling precision	Combination effects when data represented by different spatial properties combined	Object shape error, topological inconsistency, 'split and merge' errors
Time	Temporal error and precision	(Temporal error and precision are usually negligible for image data)	Combination effects when data representing different times are combined	Combination effects when data representing different times are combined
Consistency	Samples/readings collected or measure in an identical manner	Image is captured identically for each pixel, but medium between satellite and ground is not consistent; inconsistent sensing, light falloff; shadows	Classifer strategies are usually consistent in their treatment of a data set	Methods for object formation may be consistent, but often are not. Depends on extraction strategy
Completeness	Sampling strategy covers space, time, and attribute domains adequately	Image is complete, but parts of ground may be obscured	Completeness depends on the classification strategy. (Is all the data set classified or are only some classes extracted?)	Depends on the extraction strategy. Spatial and topological inconsistencies may arise as a result of object formation.

(Gahegan and Ehlers, 2000)

Table 2-1: Types of Uncertainty in Models of Geographic Space

raster superimposition, vector to raster conversion and vice versa as well as database level integration to reduce uncertainty in RS classification. Molenaar and Janssen (1991) suggested that to make the most out of the good monitoring of object dynamics, RS data should be linked directly to object information stored in a GIS. Objects, or entities, can then be more accurately identified and similarly, object information in the GIS database can be used to identify changes in the RS data. However, some uncertainty exists in this type of integration in part due to the fact that information derived from RS data can never be considered fully accurate since classifications are often done without full information. Therefore, classification results need to be analyzed in terms of variances and probabilities and can never be considered one hundred percent accurate (Molenaar and Janssen, 1991).

Two studies review the use of RS and GIS for urban growth monitoring in the rapidly growing city of Bangkok, Thailand (Weimin 1995, Huan 1995). Weimin's (1995) research focused on the use of synthetic aperture radar (SAR) and visible infrared radiometer (VIR) satellite imagery in combination with ancillary GIS data for post-classification sorting and accuracy assessment of land use change on the northern fringe of the city. Detected change was mostly caused by rapid industrialization and urbanization. The ancillary data used included soil and topographic maps, crop calendars, agricultural statistics reports and meteorological data. From the analysis of these data, Weimin was able to conclude that the integration of RS and GIS allowed analysis of land use change and its resulting effects on the infrastructure of unused lands. However, he noted that more GIS-based socio-economic data would be necessary to assess the environmental impacts of such rapid development in a city such as Bangkok.

Similar to Weimin, Huan's (1995) study also focused on the application of RS and GIS to evaluate urban development in the northern corridor of Bangkok. Huan (1995) concluded that RS and GIS databases should be institutionalized within the planning process in order to improve the location of urban infrastructure and to ensure proper planning and development of the northern corridor of Bangkok in the future. This conclusion serves to confirm further the applicability of the combined operational use of RS and GIS (Figure 2-3) to assist in facilitating improved planning practice and SUEM.

Relative to the above research, the rural-urban fringe of cities is a particularly important area in terms of land cover / land use analysis. Because of the rapid urban development and dramatic land use changes that occur at this location, the measurement and monitoring of change is crucial to the achievement of SUEM. In most cases, newly developed urban sprawl is on isolated tracts of land, separated from other areas of development by segments of vacant land use. Because RS is able to detect and measure many elements relating to the morphology of cities, including the amount, shape, density, textural form and spread of urban areas, its use is well suited to detecting and monitoring such isolated tracts. Given this, RS can be successfully used along the rural-urban fringe to locate and analyze the spread and extent of sprawl based on shapes and patterns of development.

It is evident from the above research that there currently exists a broad range of studies that integrate RS and GIS technologies to study aspects of urban land use. However, the lack of a seamless process of integration between the two technologies is also evident, especially in terms of facilitating development of a model of SUEM that can be used to achieve improved planning. Several recent studies have assessed the ability of integrating remotely sensed and socioeconomic data within a GIS to analyze landscapes and land use dynamics (Hall *et al.,* 2001; Thomson and Hardin, 2000; Yeh and Li, 2001; Amissah-Arthur *et al.*, 2000). With information derived from both RS and ground-based GIS data, a multi-source GIS database can be used to acquire timely and accurate source data for planning applications.

Currently, development and use of this form of GIS database creation has not been fully studied, which is surprising given the need for this type of resource in developing countries. In the context of urban analyses, and especially, the specific context within which this thesis operates, the process of combining data sources and facilitating temporal analyses within a multi-purpose / multi-source GIS is integral to the practice of SD, UEM, and subsequently, SUEM.

2.5.9 Conclusions on SIT Implementation in DC for SUEM

In light of the difficulties of IT and SIT penetrating and being successfully implemented in developing countries, some conclusions can be drawn regarding what must be done. Stanley *et al.* (1997) make several observations on the problem of IT use based on experiences with United Nation's (UN) projects in developing countries. First, they note that in too many cases, projects focus too much on simply making the project operational rather than developing applications to facilitate decision-making. This has resulted in the fact that very few projects have produced results that directly affect planning in the respective country. Contrary to their point, it must be noted that before the development of decision-making applications can be successful, they must first have a well-designed operational plan. If the process is not adequate or is incomplete, it is unlikely that any application will meet the needs of users.

Overall, the implementation of SIT in developing countries faces many barriers to success. Through this thesis, however, it is shown that the use of integrated SIT can result in improved information availability and processing, which, in turn, can help to facilitate better planning in the context of SD, UEM and SUEM. To this end, the combined elements discussed earlier in this chapter (Figures 2-1 to 2-3) provide the concepts through which urban fringe stress detection can be achieved. From this conceptual framework must come an operational model that effectively implements SIT.

2.6 Operational Model for SIT

To help facilitate SUEM under conditions of rapid urban growth, an operational process model has been developed to analyse urban development at the rural-urban fringe (Figure 2-4). The stages of development noted in the model are adapted from the United States Geological Survey (USGS) Land Use/Land Cover classification system designed for use with remote sensing data. The model is designed first to align the processes of road feature identification and extraction with the concepts of SUEM and subsequently with the other features and indictors under discussion. Hence, the model is an amplification of the later stages of Figure 2-3. Specifically, the model helps to facilitate the designation of land use and land use changes in the urban periphery of a growing city by analyzing emergent land conversion on a temporal scale. Priority is given to the road network, as subsequent development is expected to occur around this.

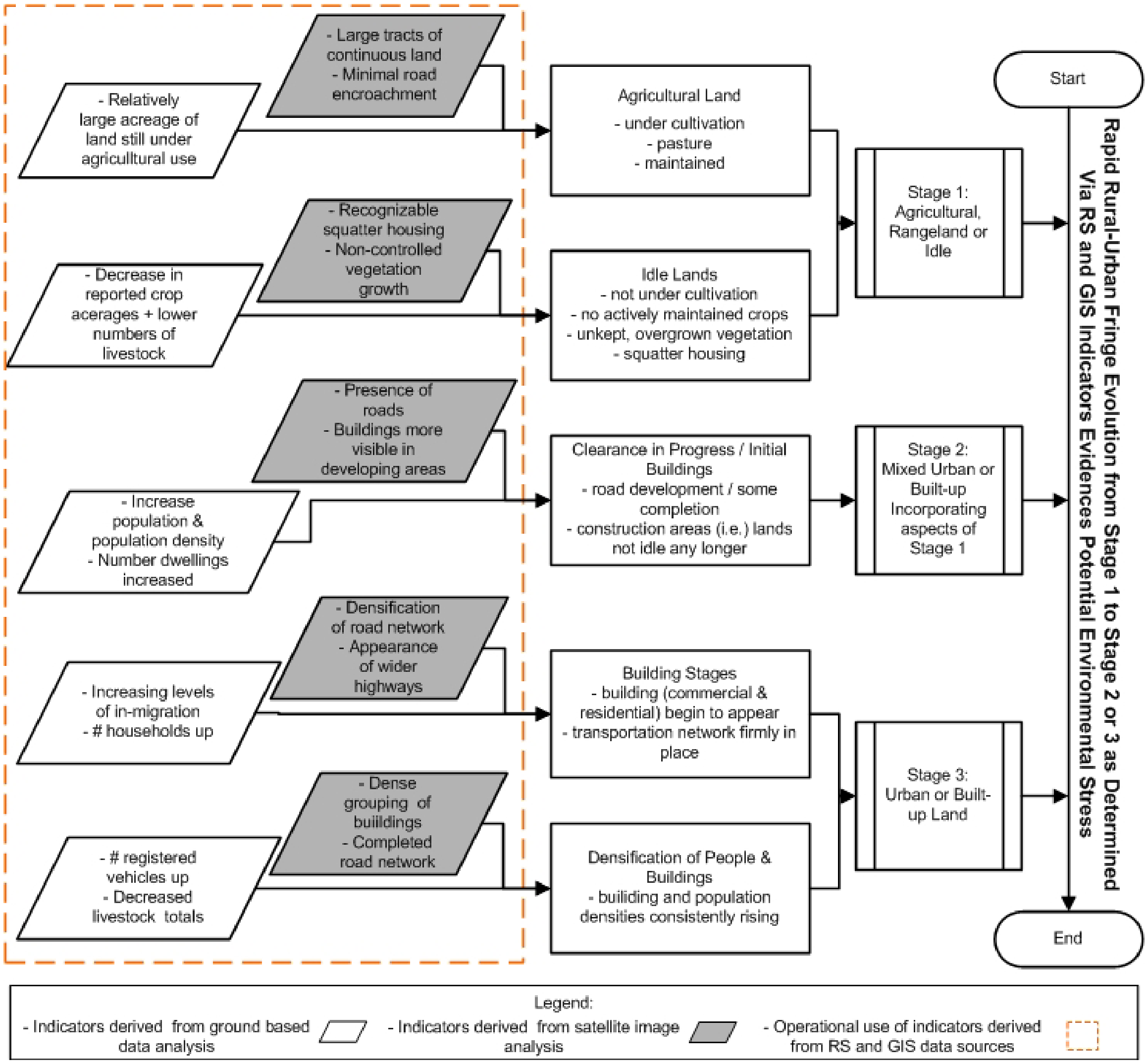


Figure 2-4: Operationalizing Figure 2-3 for Urban Fringe Land Use Classification

The model outlines the progression from agricultural land use to intense urban use and the varying stages of progression in-between. To identify what stage of change or existing state the rural-urban fringe is in, the model uses specific indicators of development. These indicators, beginning with roads, are all derivable from either RS or ground-based GIS data, or in some cases, from both. However, not only do the indicators seek to point to land use change, they are also designated for their potential to allow planners to identify, over time, areas of impending land use stress at the fringe. The specific RS and GIS methods of analysis applied to these indicators are discussed in Chapter 3.

As noted above, Figure 2-4 combines characteristics from both RS imagery and ground-based GIS data to detect sites of potential environmental stress by detecting and locating areas of rapid urban development. The indicators on the left hand side (inside the gold dotted box) include land cover / land use, transportation and building infrastructure, population and population density, acreages of land use, number of livestock, numbers of registered vehicles and number of dwellings. Collectively, these represent 'triggers' of potential environmental stress that are identifiable depending on the spatial resolution of satellite imagery and the quality and quantity of ground-based information available.

Within the operational use of SIT for urban fringe land use classification, the indictors derived from RS and GIS data sources (shown on the left hand side of Figure 2-4) can be categorized into five relatively specific and three broader land use classifications. The first two specific classes, reading from the top of Figure 2-4, are agricultural land and idle land. These two are combined into the broader Stage 1 category. The stage is generally representative of either purely agricultural or idle land or unkempt, sparsely settled land use.

The middle class, which equates to Stage 2 in the broader classes, is representative of mixed urban or built-up land uses that incorporates some aspects of Stage 1. Other characteristics of this stage include road network development and new construction of buildings and other urban infrastructure. The final two specific classes include the building stage and the densification of people and buildings. These two classes are included in the broader Stage 3, the urban or built-up land use stage. The characteristics of this final stage include continued and expanded building of commercial and residential buildings, a firmly established transportation network and the further densification of buildings and people consistently rising.

Moving from Stage 1 through to Stage 3, on the right hand side of Figure 2-4, rural-urban fringe change is occurring. The indicators are used to point to areas of potential environmental stress that may be appearing as land use changes from Stage 1 to Stage 2 and from Stage 2 to Stage 3. These indicators, as well as their representative stages, are addressed in detail below.

2.6.1 Indicators Derived from RS

From space, it is possible to see and study the earth as a complete organism, whose health depends on the health of all its elements (WCED, 1987). The main indicators of potential environmental stress that can be extracted from remotely sensed imagery, as included in the operational portion on the left hand side of Figure 2-4, include land use / land cover, transportation networks and building infrastructure.

These three indicators are selected for use in determining the location of urban growth over time and, subsequently, their potential use in detecting environmental stresses. Based on these indictors, it is possible to classify land use at the urban fringe in terms of the stages of development shown in Figure 2-4. The areas that pass rapidly from stage one to two or three can then be targeted for improved planning practice and SUEM policy development. Also, based on the integrated framework outlined in this chapter, these indicators play a key role in the RS change detection process used to localize areas of potential environmental stress.

In general, the loss of prime agricultural land in the course of urbanization greatly impacts the likelihood and possibilities of SD in a region (Yeh and Li, 2001). In terms of SUEM, a decrease in the amount of land at the urban periphery under agricultural production is likely to point to urban growth, or alternatively land that has moved from agricultural production to idle, speculative land uses in anticipation of growth in the future demand for the land. This process is clearly demonstrated from left to right and top to bottom in Figure 2-4. If it can be determined that a rapid shift from rural to urban land use is occurring in a particular area, then this location can be further monitored to evaluate its sustainability.

If a rapid shift such as this goes unidentified, the probability of environmentally sound development occurring is unlikely. The conversion of agricultural land into urban land uses has become, and will continue to be, a serious issue for sustainable growth in developing countries (Li and Yeh, 2000). Specifically, inefficient or isolated urban sprawl makes ineffective use of land and energy resources, by leaving large transportation and communication gaps between areas of development, and forces large-scale intrusion onto surrounding agricultural lands. In particular, fragmented conversion of agricultural land to urban uses can be harmful to biological conservation by inhibiting diversity of natural biological and wildlife habitats (Yeh and Li, 2001). At the rural-urban fringe in Stage 1 of Figure 2-4, much of the land use is likely to be range or idle land, as intense agricultural use has been abandoned due to land speculation. Indicators such as large tracts of continuous homogenous land cover and relatively large acreages still under agricultural land use are used to determine whether or not land at the urban fringe belongs in Stage 1. As the land use at the fringe changes from agricultural and idle uses into urban land uses, such as road development and initial building stages, a shift from Stage 1 to Stage 2 is generated (Figure 2-4). In general, the more rapid the shift is from Stage 1 to Stage 2, the more likely the potential for environmental stress to occur as there has not likely been sufficient time for proper SUEM polices to have been implemented by planners.

As noted earlier, transportation infrastructure is regarded as the most important trigger of change that is detectable and extractable from RS in term of SUEM. Hence, this aspect of the urban landscape needs to be monitored for planning purposes, updating cartography, and as landmarks for automated navigation (Karimi *et al.*, 1999). New paths or roadways appearing at the rural-urban fringe of a city can potentially be considered the first sign of human settlement in these sectors. This can be regarded as a move from Stage 1 to Stage 2 in the operational classification of urban fringe land use change (Figure 2-4). By facilitating early identification of this movement and subsequent settlement, an early evaluation of urban transportation can be completed for this sector. With this information, prevention of environmental deterioration can be facilitated through improved and more targeted planning policy related to development at the fringe. Furthermore, as road networks become denser over time, the conversion of adjacent land uses can be identified and analysed with satellite imagery in a timely and efficient manner.

Extracting building infrastructure from satellite imagery is dependent on image resolution. However, what can be extracted is useful in terms of indicating where development is occurring and, in particular, identifying the density of this development. Most urban objects, including buildings, are complex with respect to both their spectral and spatial characteristics, making them somewhat difficult to detect and classify (Zhang, 1999). Since buildings are one of the most important classes in urban land use, their identification and classification is important in terms of SUEM. As the densification of buildings occurs, in terms of urban fringe land use classification, a movement from Stage 2 to Stage 3 is likely occurring (Figure 2-4). Through the determination of building location and density, the enhanced conservation and protection of urban natural and cultural environments can occur and the provision of required urban infrastructure can be achieved. Depending on the rate of densification of buildings, there exists an increasing potential for environmental stress as buildings are erected relatively quickly and without adherence to proper zoning by-laws and construction quality guidelines.

2.6.2 Ground-based GIS Indicators

The ground-based GIS indicators used in this thesis, shown to the right in Figure 2-4, are all derivable from census-based socio-economic data typically collected by local and national governments. As such, these data are available to planners in developing countries. However, without a properly designed and implemented framework to analyse the data, their potential is unexploited. The main indicators in this research that can help to identify locations of potential environmental stress, and that are derived from ground-based GIS data, include:

1) acreage of land use / land cover under rural vs. urban use;
2) numbers of livestock in selected regions;
3) population, population density and internal migration levels;
4) numbers of dwellings; and
5) numbers of registered vehicles per province.

These indicators are not used independent of one another. Their individual and combined impacts point to potential environmental stresses that may be occurring at the rural urban fringe as urban growth occurs. Furthermore, these ground-based GIS indicators are analysed via an integrated process with indicators derived from RS imagery. The integration of indicators derived from RS imagery and ground-based census data within a GIS provide further spatial analysis capabilities beyond what either can reveal alone. Each of these ground-based indicators is now discussed in greater detail.

First, acreage of land use by land use class provides the same type of information as the satellite imagery analysis and can be used as collaborative data to validate the imagery, assuming a similar time frame. Similar to the RS derived land use indicators discussed in the previous section, in terms of the operational classification of urban fringe land use, the greater the acreage of land still under agricultural use, the more likely that this land would fall into Stage 1 (Figure 2-4). As this value decreases, the classification moves from Stage 1 to Stage 2 and perhaps as far as Stage 3, depending on the amount of land use change. As noted earlier, it is the rate of change that determines the relative potential for environmental stress evidenced by the amount of change in the indicator under examination.

Second, related to rural land use, is the numbers of livestock in a particular region. A rapid reduction in the numbers of livestock in a region over time can imply a possible change in land use from rural to other uses. If change such as this is occurring too rapidly, for example, a movement from Stage 1 to Stage 3 of Figure 2-4, it is unlikely that enough time was given to plan this change properly. This situation will likely not lead to SUEM without substantial increases in government spending on improving planning practises. This type of scattered development, often referred to as "leapfrog development" because of the dispersed and random growth, has been criticized for its inefficient use of land resources and energy (Yeh and Li, 2001).

Population, population density, numbers of dwellings and migration levels are all indicators of growth and sprawl. The difficulty with these indicators is that ground-based population measurements and estimates are not always very accurate (Cowen and Jensen, 1998). Census taking in developing countries is, in most cases, sporadic at best, and not even as frequent as the typical ten year census carried out in most developed nations. Even when a census has been completed, the results often take a long time to process and publish, and the quality and validity of the data are questionable. However, with these constraints noted, the data that are collected and reported can be used to assist in the management of the urban living and working environment. With this information, SUEM can be better facilitated because without such data, there is little indication of where growth may occur and how quickly the landscape is likely to change from rural to urban uses.

Further, density and numbers of dwellings can also be used as indicators of quality of living. Population density is an important parameter in determining the location of rapid urban growth as it can be inferred that areas at the fringe with higher population densities are more likely to be potential low-income locations. While this may not always be the case, higher densities are more likely to be characteristic of lower income neighborhoods with less individual space per unit area (Hall *et al*, 2001). In particular, this is more likely to be the case if the growth is occurring without proper planning input, such as within a squatter settlement. This type of rapid settlement and population growth in a localized area is likely to be representative of a movement from Stage 1 to Stage 2, or perhaps even Stage 3 of Figure 2-4. The operational use of indicators derived from GIS-based data analysis to classify urban fringe land use can, in this context, be successful in terms of identifying the location of this land use change by accurately identifying potential stress areas.

Finally, the number of vehicles registered is a surrogate measure for transportation infrastructure. In Bangkok in 1980 there were less than half a million private vehicles (cars and motorcycles registered); by 1990 there were 1.3 million registered private vehicles (Punpuing and Ross, 2001). For SUEM to occur, urban transportation must be observable and quantified in terms of growth and density of road network patterns. Just as the extraction of roads from satellite imagery can be used as the skeleton around which development occurs, the number of vehicles registered can be used as supplementary data to help confirm the findings from the satellite images. In Stage 1 of Figure 2-4, minimal road development is evidenced. However, as land use evolves into Stage 2, a detectable characteristic is the development of the road network. This is further exemplified in the move to Stage 3, where road development may be complete, and intensification is occurring rapidly adjacent to these roads. The ability to identify roads in contrast to other forms of urban growth is uniquely important in terms of urban fringe classification and in the context of this thesis. Specifically, roads must be identifiable as they form the main trigger of development that can be used to force a movement from a Stage 1 land use classification to either a Stage 2 or Stage 3. Once roads begin to appear and the land use classification evolves from Stage 1 to Stage 2 and beyond, the relative rate of this evolution can be used to determine the potential development of environmental stress occurrence.

The indicators outlined above that are derived from RS imagery and GIS-based ground data analysis can be methodically combined to classify land use at the urban fringe. The operational use of SIT based on these indicators (Figure 2-4) is integral to the staging of development occurring at the urban fringe in terms of accurately identifying areas of rapid land use change and subsequent potential environmental stress. This classification and identification process is fundamental to the goals of SUEM in terms of their successful application to planning guidelines and policy creation in cities in developing countries.

2.7 Summary

This chapter has summarized the current situation in developing countries in terms of the application of the concepts of SD and UEM. Combined, these define the concept of SUEM, which is the desire for sustainable urban growth and management in conjunction with social and economic development. SUEM was then placed in the context of using SIT to achieve SUEM in developing countries. Specifically, the discussion focused on the concept of urban environmental stress and the use of SIT to detect and analyze potential stress triggers. Throughout the discussion it was noted that without access to spatial information, it is difficult to develop and implement growth management strategies, especially at the fringes of rapidly expanding large and middle-sized urban areas. To this end, an integrated framework model was presented that linked the concepts of SD, UEM and SUEM with the use of SIT to facilitate potential stress detection analysis.

The current state of research on the integration of RS and GIS for the detection of environmental stresses was also reviewed. In particular, the discussion focussed on the detection and extraction of features that are possible indicators of environmental stress from satellite imagery, their union with ground-based indicators, and their subsequent integration to facilitate SUEM. To achieve this detection, a model was presented to operationalize the integrated framework model in order to facilitate urban fringe land use classification. In the context of this thesis, the city of Bangkok, Thailand, is the case study for the operational implementation of the integrated framework outlined in this chapter. As such, Bangkok's past and current planning practices are discussed further in the following chapter along with a detailed review of the research design implemented in this thesis.

CHAPTER 3

RESEARCH DESIGN

This chapter discusses the methods and operational design of the research undertaken in this thesis. To set the stage for the study area discussion, the past and current economic and planning frameworks of cites in Southeast Asia, and specifically those of Bangkok, Thailand, are discussed. Next, the process of selecting the study area, field research experiences, the specific research methodologies used, data collection, data processing and analysis methods are all discussed in sequence. Each aspect of the research design relates directly to the components of the integrated framework presented and discussed in Chapter 2.

3.1 Study Area

> I wonder where Bangkok is. Shouldn't it be here by now? Shouldn't the city lumber out of the rice fields soon? Bangkok always comes to you slowly, languidly, but its sprawling outskirts gradually transform into a taloned, grinning creature with an appetite for money and human time. … The pace of the city always surprises me. Slums trip into office buildings, apologizing with flimsy fences; markets wander into streets, shopping centers into dirty sky. Concrete edges elbow ancient temples, nudge palaces for room to grow, expand, swallow up the old to spit out the new. …
>
> (Connelly, 1992)

Connelly's first impressions of Bangkok, Thailand from her trip there in 1986 are still fundamentally accurate fifteen years later. The city 'lumbers' out of the rice fields with its sprawling outskirts more aggressively than ever before as it envelopes surrounding unpaved ground. The city's ability to capture an entire spectrum of human living environments in a single residential block is part of the reason Bangkok was selected as the study area for this thesis. With a population of over 60 million, Thailand has experienced an average annual population growth rate of 1.05 percent over the last ten years (National Statistics Office, 2000). In addition to this, it had the distinction of being the world's fastest growing economy between 1984 and 1994 (Johnson, 2000). Bangkok has grown to well over 9 million inhabitants and has experienced only a slightly lower rate of growth than the entire country in the same time period (0.72%) (National Statistics Office, 2000).

The population growth rate has two primary spatial manifestations, one internal and the other at the urban periphery. The former has the effect of increasing already high population densities in specific inner city areas. Poor housing and indigent rural migrants, many of whom find work in the informal sector, typically characterize these areas. The latter dimension of growth has had the effect of pushing development out into hinterland areas of productive agriculture or idle land use. This growth has implications for loss of agricultural productivity and extending urban services further from traditional service hubs; often to the point where new, dispersed service hubs have evolved. The current economic boom after the Southeast Asian economic crisis of the late 1990's resulted in additional uncontrolled urban growth. Because of this rapid and continued growth, the need to provide proper urban infrastructure has occurred at the same rate. However, the provision of this infrastructure, which is necessary to sustain a reasonable quality of life, has not been provided at a rate equal to its demand. This problem has had a tendency to lead to environmental damage, as people have turned to alternative means of compensation for the lack of infrastructure, which in turn further lowers the quality of life for persons living in the fringe regions.

Despite the need for improved infrastructure and better growth management, inadequacies in local planning processes have put unprecedented pressure on surrounding urban fringe locations, endangering not only long term environmental sustainability but also the quality of life of residents in these areas. In this context, Bangkok is fundamentally similar to many other cities in Southeast Asia. Prior to discussing planning within the Bangkok Metropolitan Area, recent urban growth and economic trends in the region are reviewed.

3.1.1 Recent Growth & Economic Trends in of Southeast Asian Cities

The population boom following World War II foreshadowed a serious concern in cities in Asia and Southeast (SE) Asia regarding urban expansion and its potentially negative impact on development (Laquian, 2000). To help combat the high rate of natural increase, in the 1970's countries such as Thailand initiated the provision of family planning services (Tirasawat, 1985). At this time, as rural-urban rates of migration were on the rise, the dominant view in many countries in SE Asia was that in the absence of improvements in living conditions and poverty alleviation for rural residents, there would be continued rural out-migration to urban areas where families would join the growing ranks of the urban poor (Laquian, 2000). Working with this same belief, the government of The Philippines, instituted a twin development policy based on Rice and Roads. Laquian (2000) notes that once the government had instituted this policy of improving rice production and building better roads to market to sell the harvest, rather than curbing rural-urban migration, more farmers took their sudden rice profits and travelled the now good roads to become squatters in the cities. Policies of this type were used often in attempts to curb rates of rural-urban migration, however they have met with little success and rural-urban migration continues unabated.

Recent patterns of internal migration in SE Asia have been triggered primarily by income related factors (Ogawa, 1985). Shifts in population distribution in these countries continues to cause many unwanted side effects, including high rates of unemployment, housing shortages, and the propagation of squatter settlements. Present directions of urbanization and internal migration do not bode well for improvement of these problems. Ogawa (1985) pointed out six sources of uncertainty surrounding migration and urban growth in 1985 including:

1) the international economic environment is likely to be considerably different from what has been experienced before;
2) the scope of regional development plans for ASEAN countries are unknown
3) patterns of urban development are clearly distinct from urban growth patterns in industrialized countries;
4) the disappearance of the agricultural frontier, which will effect the pattern of population movements;
5) the potential development of improved communication and transportation networks; and
6) the unknown demographic mechanism of urban growth.

(Ogawa, 1985)

Fifteen years later, these uncertainties still plague virtually all cities in SE Asia. Hence, the tasks of facilitating proper urban planning practices and, in particular, achieving SUEM are very difficult.

Growth in Asian economies was favourable from the mid-1980s through to the mid-1990s. Foreign investment and strong export-based economies led to predictions of unlimited economic growth and development potential for the region. However, the financial crisis of 1997 raised fundamental questions about the future state of SE Asian countries (Zha, 2000). This crisis prompted a re-evaluation of Asia's future, both financially and politically, and has subsequently raised new questions about globalization in SE Asia in terms of ideological/political clashes between those who desire greater Western liberalism/capitalism versus those who prefer to continue the 'Asian Way' of life in the future (Zha, 2000). The economic crises left many countries and cities in SE Asia with much to consider in terms of growth and prosperity. Bangkok, located on the central plain in Thailand, was certainly no exception.

The City of Bangkok, and its surrounding *changwats* (provinces) (Figure 3-1) represent the most rapidly urbanizing region in Thailand (Greenburg, 1994). Collectively, they (Bangkok Metropolis, Samut Prakarn, Pathum Thani, Nakhon Pathom, Samut Sakhon and Nonthaburi) combine to form the Bangkok Metropolitan Region (BMR). Many problems have long been identified in terms of urban growth and development within the BMR, including:

1. a haphazard, poorly coordinated pattern of development,
2. imbalances and conflicts in land utilization,
3. a poorly developed communications network,
4. a mal-distribution of living and working places,
5. large tracts of idle and under-utilized lands, and
6. an absence of basic necessities for the urban poor.

(Edwards, 1983)

Collectively, this list represents not only many inconveniences for people living and working in the BMR, but the problems also serve as warning signs of potential environmental stress due to inadequate urban planning and improper development patterns.

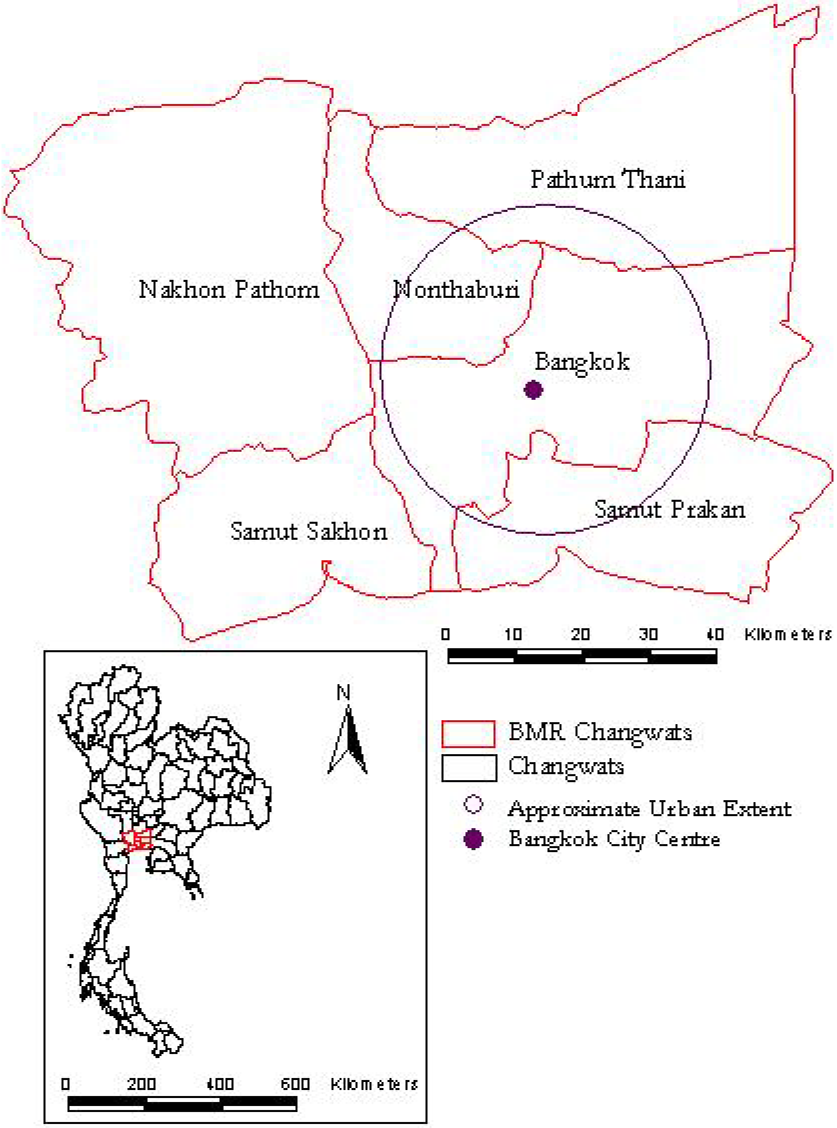


Figure 3-1: Location of Bangkok City Centre and Bangkok Metropolitan Region (BMR) *Changwats* within Thailand

3.1.2 Urban Planning in the Bangkok Metropolitan Region (BMR)

Suburban development, at the expense of lost rice fields and gardens converted into middle class and wealthy bungalow settlements, figured prominently in Bangkok's post-war development (McGee, 1994). From 1947 to 1956, the built-up area in and around the city expanded from about 67 square kilometers to 90 square kilometers and by 1980 it had reached over 239 square kilometers (Askew, 1994). The majority of rural-urban migration flow in Thailand consists of Bangkok-bound movers (Ogawa, 1985). Because of this in-migration, settlement in Bangkok now extends over 40 km from its historic core, with no discernable structure or organized pattern. The leapfrog development, which comprises pockets of unconnected development, has led to a fragmented metropolitan area and a progressive loss of some of the best agricultural lands at the edge of the expanding metropolitan area (Hack *et al.*, 1994). However, even though this is a well-known and well-documented phenomenon, little has been done successfully in terms of planning and policy development in Bangkok to halt this pattern of development. This can, in part, be attributed to the lack of experience in planning and implementing large-scale development processes in Thailand (Hack *et al.*, 1994). Additional factors pertaining to past planning initiatives, including politics and government corruption, and the urban morphology and structure of a city like Bangkok must also be taken into consideration.

Foreign and local urban planners have long been attempting to bring some form of management to the sprawling urban development (Greenburg, 1994). However, this has been only met with limited success. Almost 20 years ago, Edwards (1983) noted that there had been growing and widespread agreement for over a decade that measures to control the growth of Bangkok were urgently needed. At that time, it was already recognized that the capacity of the land to absorb the needs of the expanding city was diminishing and the growth of Bangkok, unlike the rest of the country, was occurring at a dramatic rate relative to the rate of total growth.

The processes of transformation on the urban fringe areas of Bangkok have brought changes in settlement patterns, land uses and social relations. To study these processes, it is necessary to gain a greater understanding of the underlying socio-spatial and ecological changes. Askew (1996) notes that the key to this understanding lies in placing the emphasis of study on the re-shaping of urban fringe regions at two separate, but equally important levels, namely the societal/state/economic level and the local level. Integrated within the former is the process of structural change, including transportation systems. In this thesis, the examination of structural change is regarded as a key element in the determination of land use change and the detection of potential environmental stress. By identifying transportation system change and expansion as one of the primary catalysts of other changes at the urban fringe, Askew (1994) lends support to the thesis and the importance that the transportation network plays in urban fringe development.

The development plans for the BMR over the last two decades have been based on the Bangkok Metropolitan Area Plan, which is summarized by Edwards (1983). The concepts described are based on several official documents from various government departments and may be listed as:

1) The containment and ordering of development particularly within the area of Bangkok's outer suburbs.
2) The division of development to, and the accelerated growth of, a selected number of satellite towns and communities.
3) The establishment of a system of major transport corridors in the context of an effective, developed transportation hierarchy.
4) The retention and consolidation of an economically viable, convenient and socially vital Central Area.
5) The concentration of commercial development (other than in the central area) into a number of selected suburban sub-centers and satellite towns.
6) The consolidation of existing industrial locations.
7) The establishment of a comprehensive metropolitan open space system.

This list is not exhaustive in terms of the items incorporated into the Metropolitan Area Plan. However, it does represent the main conceptual base of the plan. What is important to note about this is that while representing some obvious development planning principles for any city, the items do not represent the current state of development within the BMR. The study of any given cross-section throughout the BMR yields evidence to the fact that the growth of Bangkok has not been adequately contained or properly ordered using sound planning practice. The establishment of major transport corridors may have been completed to a certain extent. However, these have contributed to exacerbating problems of congestion and air pollution throughout the city and the entire BMR. Finally, the concentration of commercial and industrial development has not occurred, as these land uses are dispersed throughout the urban area. Because these plans have been less than successful in many respects, several more recent policy improvement plans have come into effect.

Specifically, more recent policy development has sought to address environmental impacts of urban expansion and industrial development. In an interim report created by an M.I.T. Consultant Team (Hack *et al.,* 1994) on strategic planning for the BMR, seven objectives on the development of the urban fringe area were proposed. These objectives were:

1) to promote a jobs-housing balance in suburban sectors;
2) to promote the use of transit in suburban areas, and for commuting;
3) to encourage compatible mixed use development;
4) to improve amenities in suburban centers;
5) to allow for the decentralization of government employment;
6) to assure the installation of infrastructure in advance of development; and
7) to mobilize private expertise and capital in the creation of metropolitan centers.

With these objectives in mind, Hack *et al.* (1994) note that several major planning initiatives were attempted in the BMR in the decade prior to 1994. In particular, the decentralization of development within the BMR to create a "Chao Phraya Multipolis" that would see the creation of three major sectors in each region. However, this would require costly transportation infrastructure and would not aid in rectifying the problem of continuous urban sprawl in the short term. Second, there were planning initiatives undertaken to rationalize the systems of mass transit in the BMR. Despite these initiatives, it is evident to anyone attempting to use the transit system in the BMR today that there is nothing rational about the system. Buses continue to run on an incomprehensible time schedule and on continually revised routes. Finally, major studies of urban development have been completed for the entire eastern side of the BMR in anticipation of the Second Bangkok International Airport development. This airport is expected to begin operation in late 2004.

Even though many studies have been completed, the list of Bangkok's problems outlined by Edwards (1983) in terms of undesirable urban growth and development, are still as prominent today as they were almost 20 years ago. It is argued in this thesis that the use of spatial information technologies will be able to facilitate improved planning practices such that this list of problems can be more effectively dealt with than in the past. However, Durongdej (1995) notes that there are several shortcomings in the current Thai provincial development planning process that must be overcome. In particular, she lists the following shortcomings:

1) centralization of decision-making and budget control;
2) a lack of cooperation among the government agencies;
3) duplication of data sources and data quality;
4) lack of public participation in planning;
5) the time constraint; and
6) plans do not respond to the real needs of the local people.

Given these shortcomings, Durongdej noted that while planning in Thailand improved systematically since the fifth plan (1982-1986), new planning frameworks and access to data were needed to facilitate a decision making process able to overcome the many existing problems with the Thai planning process. Having noted this necessity for improved planning frameworks and data, the future directions of planning practice in Bangkok need to be further explored.

The future of planning practice in Bangkok can take many forms. However, several improvements in the facilitation of this practice are necessary before effective planning can take place. Because of past failures to achieve coordination between private development and investment in infrastructure, Onchan (1997) pointed to the need to adopt a form of comprehensive land use planning that combined land use control with free market incentives. Increases in land use efficiency could be achieved through property and land taxes, which would simultaneously decrease land speculation, and environmental impact fees could help to ensure sustainable and environmental correct growth and ultimately SUEM. Also, Onchan (1997) stated that while a number of policies, plans and initiatives were in place to improve environmental conditions, some of which are discussed in this section, they were still not effective. He attributed their ineffectiveness to inadequate organizational capacity and a complete lack of institutional and governmental mechanisms to respond to the pervasive environmental impacts of the expanding economy and current patterns of social change (Onchan, 1997). Furthermore, he noted that in the short term, the Thai government was unlikely to be able to meet the objectives of sustainable development and effective environmental management.

Because of these problems, and because it is impractical to assume that Bangkok will stop growing and expanding anytime in the near future, it is necessary to determine a means to monitor and assist with the sustainable management of this growth. A means of carefully planned and controlled development is possible and spatial information technologies can assist in achieving this type of planning. The results presented in the following chapter show that urban growth can be effectively monitored and analyzed to identify the location of potential environmental stresses at the urban fringe.

3.2 Criteria for Selecting Specific Study Area

The study area selected for analysis lies at the northern edge of Bangkok. This area is the gateway to the BMR from the north and is an area of rapid urban development and land use change. The study area centres around the point where the recently completed *Don Muang* Elevated toll way comes to an end near Future Park, Rangsit, the new, mega-shopping complex built in 1997. The elevated toll way runs above the Phaholyothin Highway, the main roadway to the North and Northeast of the country. This site was selected because of the rapid urban development occurring in the area and the high likelihood of identifying stress points.

The land use in this area is characterized by various urban activities including roads and buildings (businesses and dwellings) mixed with idle lands, cultivated lands for agricultural use, and swamp lands. The idle lands (shown on the left side of Figure 3-2) are typically left unused for crop or tree planting, as rising land prices brought on by urban growth has led to land speculation and the diversion of these lands from agriculture to an "unused state" in anticipation of increased value (Weimin, 1995). Because of the activities of real estate speculators, industrialists, tourism growth and golf course development, an irreversible trend of agricultural demise in the region is occurring (Greenberg, 1994). Sinclair (1982) further noted that due to the concentration of industrial and commercial activity in the BMR, there existed a highly skewed distribution of activity here, which is still typical of Thailand. In general, much of the development noted by Sinclair has evolved in classical ribbon patterns along the main roads and minor roads or laneways (*soi*) have sprouted from these arterials (Figure 3-3), providing the basic spatial skeleton for an emerging sprawl of multi-use areas (McGee, 1994).

The 'Northern Corridor' area, shown with the broader study area in Figure 3-4, was formally recognized during the Fifth Economic and Development Plan (1982-1986), when policy makers identified a potential zone of decentralized growth around and along the Phaholyothin Highway (Greenberg, 1994). Along the highway, the standard characteristics of Bangkok's classic ribbon development pattern are still clear, with shop-house businesses lining the edges of the road (Askew, 1996). Administratively, the Northern Corridor area is bordered to the north by the *changwat* of Ayutthaya and to the south by Bangkok *changwat*.

Most of the area is flat and low-lying with the topographical characteristics belonging to a low basin sitting about 2-3 metres above mean sea level.

Figure 3-2: Idle Lands in Study Area Adjacent to Urban Growth Pocket (January, 2001)

Figure 3-3: Ribbon Development along Phaholyothin Highway (January, 2001)

The population in the Northern Corridor was enumerated as 80 684 in 1985 and was projected to be 162 400 in 2001, representing a 100% increase in 16 years (current year census information is not yet available)(Greenberg, 1994). Housing settlement within this area varies greatly and includes apartments, townhouses and many worker dormitories. One striking development of note is the large number of informal slums or settlements that have appeared with increasing population and industrial development (Greenberg, 1994).

The two provinces to the north and northwest adjacent to Bangkok that are targeted in this research are Pathum Thani and Nonthaburi (refer to Figure 3-1 for location). In particular, the Northern Corridor area shown in Figure 3-4 falls within Pathum Thani. However, Nonthaburi has also faced the impact of unstoppable urban sprawl over the last few decades and therefore also figures prominently in the research.

3.2.1 Pathum Thani Province

Pathum Thani (Figure 3-5) is a neighbouring province of Bangkok, located approximately 30 km directly north of the downtown Bangkok city centre. It is located in the 'rice bowl' of the Central Plain, which is the most productive rice growing area between Ayutthaya to the north and Nonthaburi to the southwest, along the Chao Phraya River (Huan, 1995). The total area of the province is 1528 square kilometres and it is bisected by an artificial, systematic and dense canal network used for irrigation, drainage and transportation (Huan, 1995). However, road transport is one of the most important characteristics of the province as the main north/south highway into and out of Bangkok bisects it.

The land use in the province is a confused mix of ribbon pattern rural and urban uses, mostly built-up along the main highway. As mentioned before, a large amount of urban clustering occurs in the province along roads and canals. Huan (1995) noted that in the early 1990's there was a striking amount of land lying idle due to a lack of access or more commonly for speculative purposes. Also there was, and continues to be, a noticeable difference in the density of urban land use along the major highways and the largely empty lands that flank this ribbon development. Greenburg (1994) noted that much of the land within two kilometres of the Phaholyothin Highway was lying idle, presumably under speculation, with exorbitant land prices of Baht 2-3 million per rai (CDN $175000-265000 per acre) in the early 1990's. With continued pressure exerted on land available for development during the past decade this value will have significantly increased on equivalent parcels.

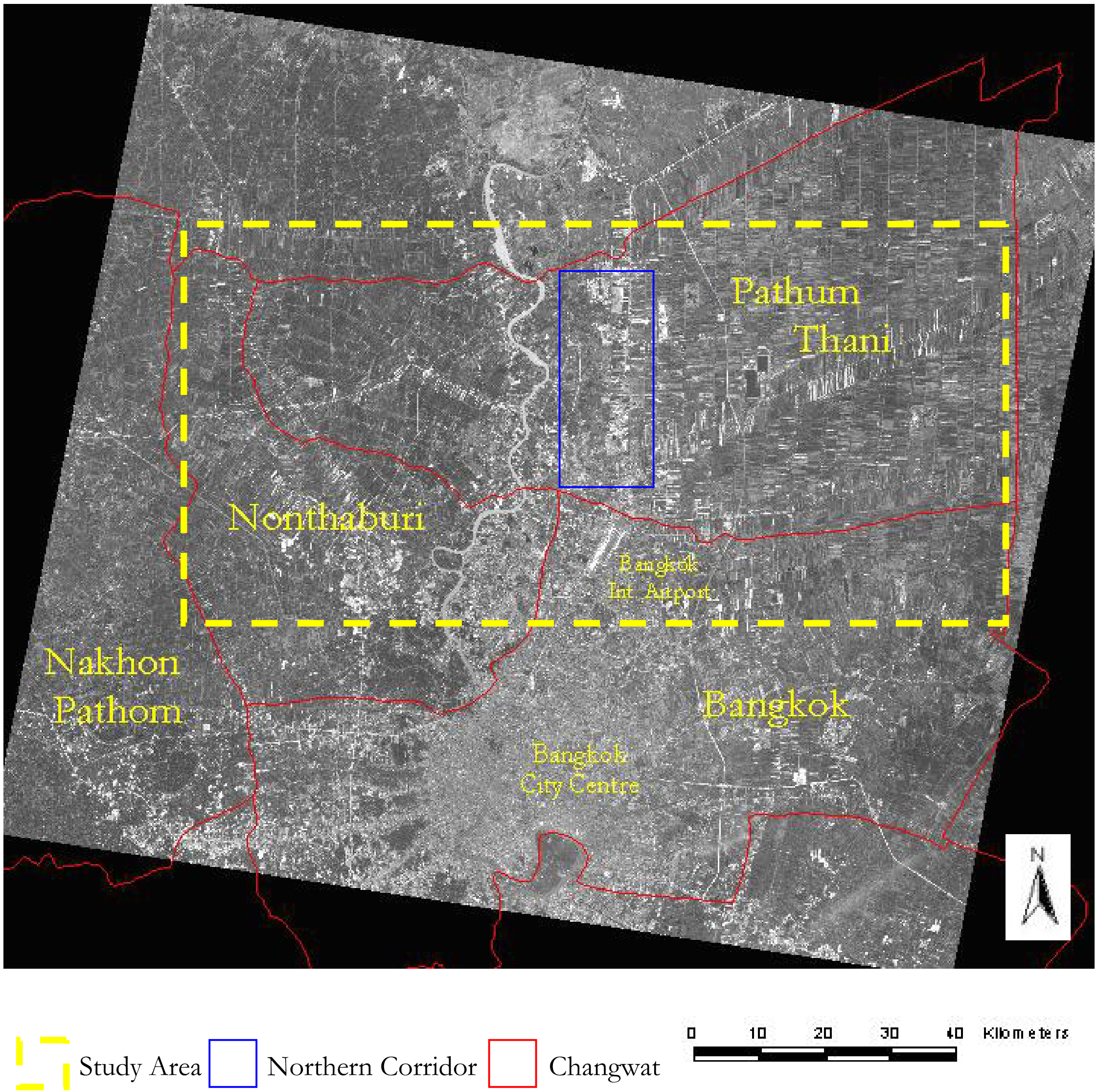


Figure 3-4: Study area denoted on an Advanced Earth Observing Satellite (ADEOS) Panchromatic Image overlaid by BMR *Changwats.*

In terms of urban growth, *amphoe* (district) Khlong Luang, within Pathum Thani province, saw its population more than double between 1970 and 1990 and during the same time period, its agricultural labour level fell fourfold (Greenberg, 1994). Hence, Pathum Thani, like its southwesterly neighbour, Nonthaburi, has experienced much of the brunt of Bangkok's expanding outer boundaries.

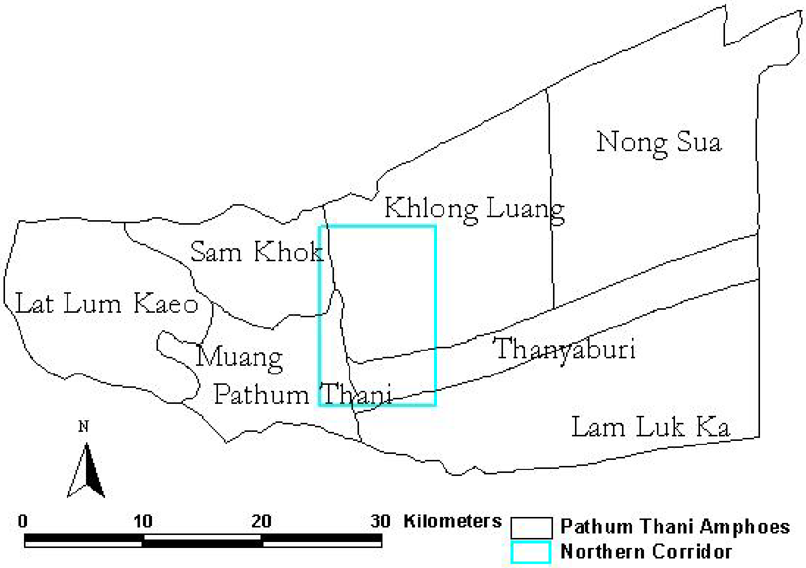


Figure 3-5: *Amphoes* in the *Changwat* of Pathum Thani

3.2.2 Nonthaburi Province

Located to the northwest of Bangkok Province, the Province of Nonthaburi (Figure 3-6) was approximately 48.1% farmland in 1991 (Askew, 1996). The traditional agricultural land use in the Province has steadily declined throughout the 1990s to the present in the face of urban expansion. The *amphoes* located closest to Bangkok have experienced the greatest amount of change in terms of land use transformation as commercial, industrial and residential uses have all moved into these areas over the last 20 years (Askew, 1996). Now, the southern and eastern portions of the Province are built-up and western Nonthaburi is targeted for future housing estate expansion.

Aside from these patterns, elongated settlement has often also occurred along the banks of the *klongs*. Traditionally, this form of development facilitated easy access to water-borne transportation. However, over time this has become less important with the proliferation of the road network. Over the past decade, Nonthaburi has been regarded as the dormitory residence area in the BMR. Because of this, its viability as an agricultural province has slipped greatly in favour of the economic and social pressure associated with urban growth. With a population of approximately 570000 in 1990, the projected population of Nonthaburi by 2015 will be 1.24 million (Hack *et al.,* 1994).

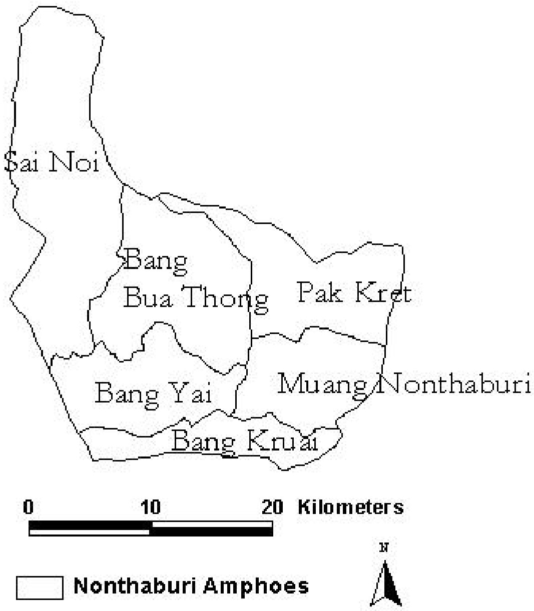


Figure 3-6: *Amphoes* in the *Changwat* of Nonthaburi

Because of Nonthaburi's proximity to Bangkok Province, the population growth and urban sprawl into this Province is inevitable and virtually unstoppable. The only course of action is to devise and implement a form of development that is consistent with the goals of SUEM as presented in this thesis.

3.3 Field Research

The field research for the thesis was undertaken from the end of September 2000 through to the end of January 2001. Research, data collection, and preliminary data analysis were completed with the assistance of faculty in the School of Environment, Resources and Development and the School of Advanced Technologies at the Asian Institute of Technology (AIT), located forty-two kilometers north of central Bangkok. In particular, the Asian Centre for Research on Remote Sensing (ACRoRS), provided assistance, data and a work area.

3.3.1 RS Data Collection

Several data sources were utilized in order to gather as much RS imagery and ground-based GIS data as possible during the fieldwork period. Imagery available at ACRoRS and the School of Advanced Technologies at the AIT was used (Table 3-1). An

Advanced Earth Observing Satellite (ADEOS) image of Bangkok from January 18th 1997 was examined first. The ADEOS satellite was launched August 17th, 1996, supplying 16 metre resolution data on the earth's environment for about ten months until it went out of orbit in June of 1997. As it orbited the earth in a sun synchronous orbit at an altitude of 800 km, ADEOS had a revisit period of 41 days. More than 250 scenes in both multi-spectral and panchromatic sensor modes were acquired over Thailand during its operational time. Two images of Bangkok, one multi-spectral and one panchromatic, are used in this thesis. The multi-spectral image contains four channels, three in the visible and one in the near-infrared portion of the electromagnetic spectrum, each with a spatial resolution of 16 meters. The panchromatic band (visible) has a spatial resolution of 8 meters.

To allow for the temporal analysis of land cover change that is essential to the integrated framework presented in Chapter 2, other imagery had to be incorporated with the ADEOS panchromatic and multi-spectral images, as they were both captured in 1997. In this case, a Landsat TM image from May 21st, 1995 was used. The Landsat program is the longest running project for the acquisition of imagery of the earth from space. The first Landsat satellite was launched in 1972 and the most recent was launched in April 1999. Over the past three decades, Landsat satellites have captured millions of images from around the world for research and applications in agriculture, geology, forestry, and regional planning. The Landsat imagery used here has an across-track swath of 185 km at 30-metre ground resolution cell size (except for the thermal band, which has 120 metre resolution). The Landsat TM sensor collects seven bands of data ranging from a wavelength sequence of 0.45 micrometers in the visible blue through 2.35 micrometers in the mid-infrared portion of the electromagnetic spectrum.

To enhance the temporal analysis, an Indian Resource Satellite (IRS) image from January 18th, 1998 is also included in the analysis. The IRS-1C Satellite was launched on December 28th, 1995 using a Soviet launch vehicle. Its orbiting altitude is 817 km and it has a 24-day repeat cycle. There are three sensors onboard including a Panchromatic Camera (PAN), a multi-spectral LISS-III Sensor, and a Wide Field Sensor (WiFS). An image captured with the LISS-III sensor is used in this thesis. This sensor captures four bands ranging from 0.52 micrometers in the green portion of the visible spectrum to 0.7

micrometers in the near infrared portion of the electromagnetic spectrum with a spatial resolution of 23.5 metres.

Satellite	Sensor	Orbit	Acquisition Date	Channels / Wavelength (um)	Resolution (m)
IRS-LISS-III	Multi-spectral	24 days / 817 km	Jan. 18, 1998	1. 0.52 – 0.59 2. 0.62 – 0.68 3. 0.77 – 0.86 4. 1.55 – 1.7	23.5 23.5 23.5 23.5
ADEOS	(a) Panchromatic (b) Multi-spectral	41 days / 800 km	Jan. 18, 1997	(a) 0.52 – 0.69 (b) 1. 0.42 – 0. 5 2. 0.52 – 0.6 3. 0.61 – 0.69 4. 0.76 – 0.89	(a) 8 (b) 16
Landsat	Thematic Mapper	16 days / 705 km	May 21, 1995	1. 0.45 – 0.52 2. 0.52 – 0.6 3. 0.63 – 0.69 4. 0.76 – 0.90 5. 1.55 – 1.75 6. 10.4 – 12.5 7. 2.08 – 2.35	30 30 30 30 30 120 30

Table 3-1: RS Image Data Utilized

3.3.2 Global Positioning System (GPS) Image Ground Truthing

To assist in ensuring the positional accuracy of the RS imagery, several days of *in-situ* ground truthing were undertaken. An Eagle Magellan GPS unit was used for data collection at various positions throughout the study area. The GPS uses a precision achievable with 12 parallel channel receptions to track multiple satellites simultaneously and to provide reliable and accurate navigational data. Prior to May 2000, a system of selective availability was held in place by the United States government that reduced the civilian GPS accuracy levels to within 100 meters or less, 95% of the time. However, since this date, selective availability has been eliminated and current positional accuracy with this unit is to within plus or minus 10-20 metres. More than 20 Ground Control Points (GCPs) - a point on the surface of the earth where both image coordinates (measured in rows and columns) and map coordinates (measured in degrees of latitude and longitude, feet, or meters) can be identified (Jensen, 1996) - were collected throughout the study area (Figure 3-7).

While collecting the GCPs, detailed road characteristics were also identified at each location. Attributes such as road width, number of lanes (if applicable), type of road surface, and adjacent features were all collected at each GPS waypoint. Both the attribute data and study area photographs were used to assist with image analysis and interpretation. Also, change detection analysis, discussed below, was better facilitated with this information by helping to improve image interpretation and to assist in the identification of certain image features.

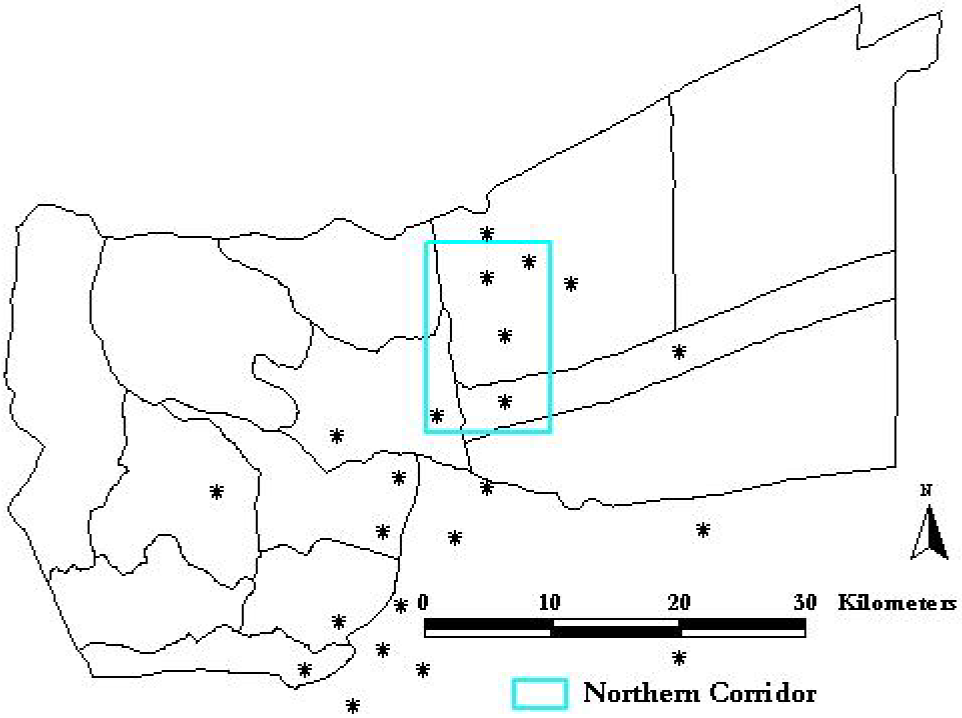


Figure 3-7: Geographic Location of Select GCPs Collected with GPS Unit

3.3.3 Ground-based GIS Data Collection

The collection of ground-based GIS data proved difficult and required a great deal of travel around the BMR. Ultimately, data were secured from several sources, including the Bangkok Metropolitan Authority, the National Statistics Office, the Royal Thai Survey Office, the Tourism Authority of Thailand and The Information Processing Institute for Education and Development at Thammasat University. The tabular census data collected from these sources are listed in Table 3-2.

Source	Tabular Data Description
National Statistics Office	• Pathum Thani, Nonthaburi, & Bangkok ▪ Statistical Report of Changwat 2000 ▪ Statistical Report of Changwat 1996 ▪ Agricultural Census 1993 ▪ Population and Housing Census 1990
Information Processing Institute for Education and Development	• Village level socio-economic database from 1994 and 1999

Table 3-2: Collected Tabular Data and Sources

Also, various digital map layers were collected from several sources to facilitate the research. Unfortunately, most of the data collected were poor in quality and no metadata were included to provide information pertaining to data quality, validity, and creation date. These data layers are summarized in Table 3-3 along with their known errors and measures undertaken to render them useful to this thesis.

Digital Layer	Data Source	Error Source	Applied Error Correction
Administrative Boundaries • Provincial • District	Internet	• Incomplete data • Minimal Metadata • No coordinate system	• Geo-registered to UTM coordinate system • Digitized/edited district boundaries where necessary to complete topological analysis
Roads	1. Internet 2. ACRoRS	1. Same as above 2. Incomplete data, no metadata and unknown accuracy	1. Geo-registered to UTM coordinate system

Table 3-3: Digital Data Layers Utilized

3.3.4 Field Study Limitations

Several limitations were encountered during the field study period and data (digital and hard-copy) collection process. These include:

1) The paper base maps generated by the Royal Thai Survey collected for this study were, in most cases, not up-to-date, nor were they in a usable digital format. In general, there is a complete lack of available digital map resources for Bangkok at both government offices and educational institutions that were adequate in terms of accurateness and

completeness. Part of the problem in terms of data availability is the fact that quite often there are many data sources in the city. However, the bureaucracy is such that the different agencies and departments are unable to share their data resources. Subsequently, there may in fact be a lot of data, but many persons and organizations are still information poor (Nghi and Kammeier, 2001).

2) The RS and GIS data collection process was difficult and often hampered by language barriers and problems caused by midday traffic difficulties in downtown Bangkok. These constraints limited timely and efficient movement between geographically dispersed offices. On several occasions, it was only possible to make a visit to one government office per day.

3.4 RS Data Processing and Analysis

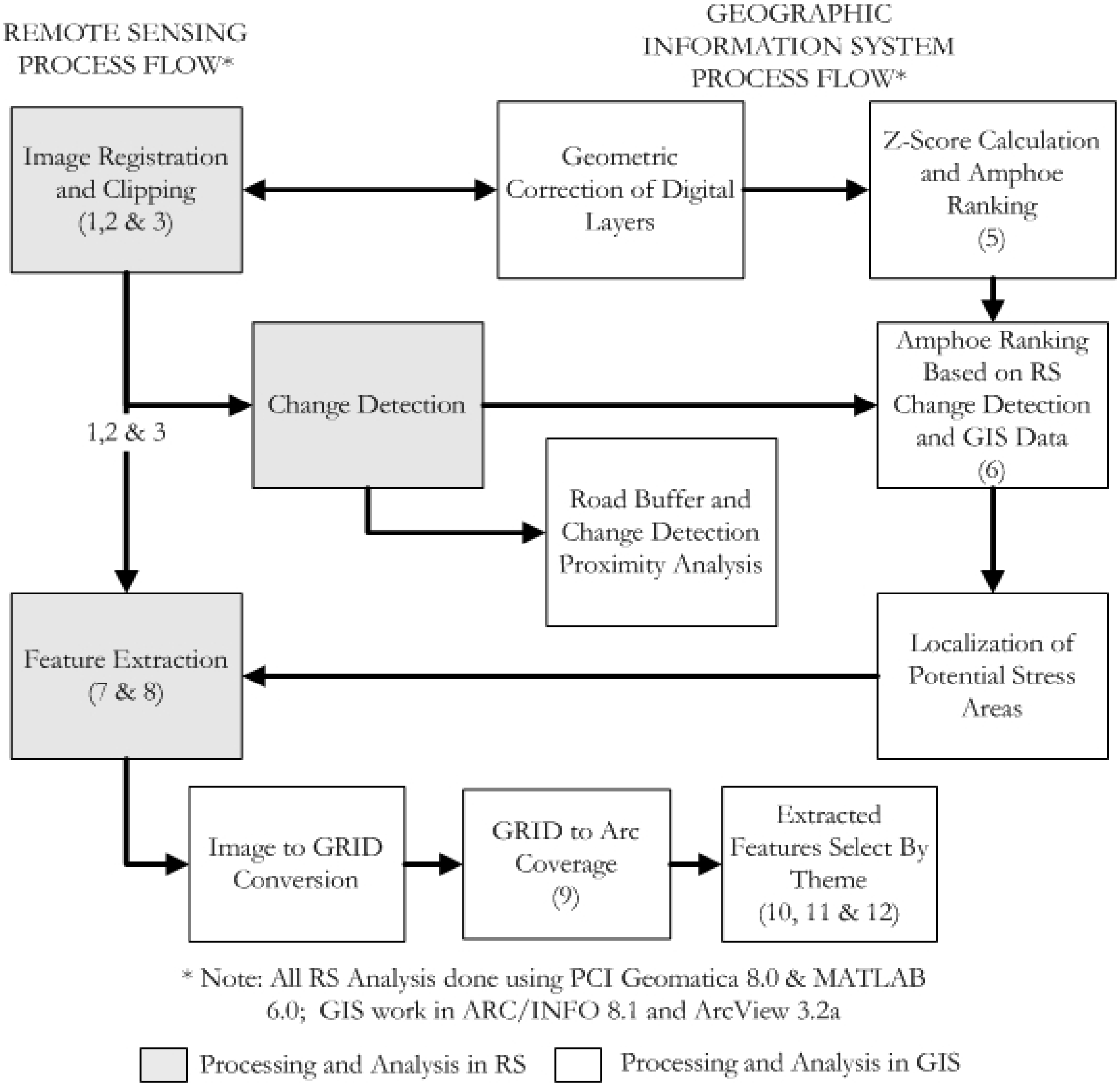
This section outlines the methods of RS data processing undertaken. The methods of analysis used in this thesis are listed in Figure 3-8. Specifically, this diagram is a direct subset of the integrated framework presented and discussed in Chapter 2 (Figure 2-3), and further outlined in the operational model, also presented and discussed in Chapter 2 (Figure 2-4). In several places the datasets (both RS and GIS) are numbered, for example (1), in the diagram to assist in the understanding of their methodological flows. These numbers are referred to throughout the discussion below and are specifically derived from the detailed version of Figure 3-8, which is presented in Appendix I.

Throughout the RS and GIS data processing analysis, several software packages were utilized. Table 3-4 identifies the specific software and the specific analytic components used. Where possible, software neutral terminology is used throughout the remainder of the thesis.

An important process related to the integration of RS and GIS technologies concerns spatial data creation. In most cases, the mapping phase, which can be achieved either through automated feature extraction processes or via manual digitization, of converting satellite image information into GIS data is the most time consuming and expensive component of building a multi-source GIS database. To achieve this, several analytic steps were undertaken with the temporal images to study land use change over time as well as to explore street feature identification and extraction (as outlined in Figure 3-8). These analysis steps included:

1. Geometric Corrections
2. Change Detection
    - Binary-classification
    - Results Exportation
3. Temporal Linear Feature Extraction
    - Results Exportation

The geometric correction and change detection steps are now discussed in detail. Following the GIS analysis, the RS linear feature extraction is discussed (Section 3.8).



* Note: All RS Analysis done using PCI Geomatica 8.0 & MATLAB 6.0; GIS work in ARC/INFO 8.1 and ArcView 3.2a

Figure 3-8: RS and GIS Processing and Analysis Methods

Software	Analytic Component
PCI Geomatica 8.0	• Image Geometric Correction • Image filtering (edge sharpening) • Change Detection • Binary-classification
MATLAB 6.0	• Linear Feature Extraction
ESRI ArcInfo 8.1	• Digital Layer Geometric Correction • Z-score calculation and Amphoe Ranking • Image to GRID Conversions • GRID to Arc Conversion
ESRI ArcView 3.2a	• Road Network Buffers and Change Detection Proximity Analysis • Select By Theme New Roads • Localization of Potential Stress Areas

Table 3-4: Software Packages and Analytic Components

3.4.1 Geometric Corrections

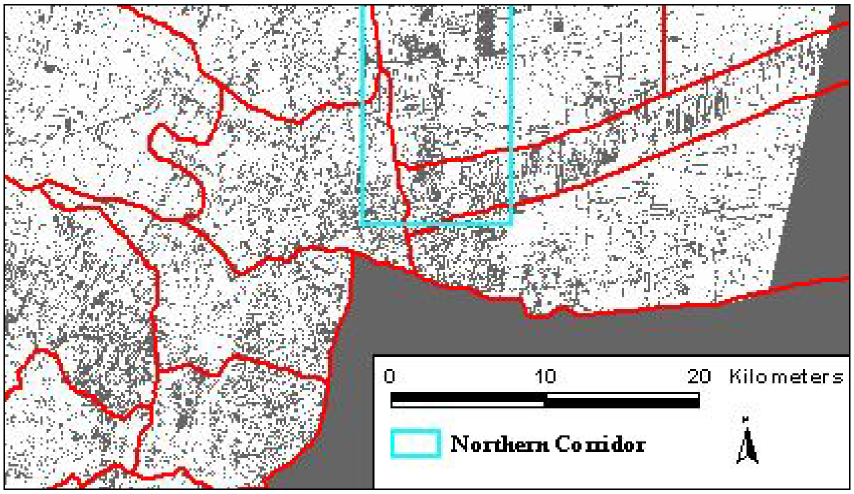
Merging multi-sensor image data is a commonly used procedure in the study of land use and land cover change detection (Shaban and Dikshit, 2002). Thus, the first step in the analysis is the geometric correction of the Landsat (1), ADEOS (2) and IRS (3) images. Existing, albeit inadequate, street and administrative boundary digital GIS layers were used to provide partial ground control points for the geo-referencing process. Also, coordinates collected with the GPS receiver were used to provide additional positional accuracy. The images were corrected to the Universal Transverse Mercator (UTM) grid coordinate system, Zone 47, with the World Geodetic System 1984, (WGS 84) Ellipsoid projection. It was important that the images were geo-registered to the coverages in order to achieve successful future integration and analyses with ancillary ground-based GIS data. The images were geo-referenced to the BMR road and administrative boundary digital map layers, which were in Arc/Info GIS coverage format. Once the first image was geo-referenced, all subsequent images were geo-referenced to this. The 3rd order Root Mean Square (RMS) Error for these image to image registrations were 0.78 and 0.68, 2.25 and 1.49 and 0.67 and 0.55 for the ADEOS, Landsat TM and the IRS images respectively.

The RMS is a measure of GCP distortion as it computes the square root of the squared deviations to represent a measure of which GCP exhibit the greatest error while the model order determines the order of polynomial used to perform the registration warping (Jensen, 1996). In general, the higher the order of polynomial transformation, the greater the number of GCPs required for registration and the more complex the warping that can be achieved. Following registration, all of the images were clipped to the political boundary of the combined area of Pathum Thani and Nonthaburi Provinces.

3.4.2 Change Detection

Several approaches were investigated for image analysis. First, change detection analysis was completed for both the Landsat (1) and the IRS (3) RS images. The ADEOS image from 1997 was not used in this analysis as the Landsat image acquired in 1995 and the IRS acquired in 1998 provided the maximum temporal range for land use change detection. These approaches, including image overlay, image arithmetic (image differencing) and Principal Component Analysis (PCA), provided a good account of variability between different surface reflectances and thus successfully distinguished areas of change, particularly at the urban fringe. Of these methods, the image arithmetic method was determined to be the most effective in terms of visually highlighting areas of change at the fringe and was therefore carried forward in the analysis.

In image arithmetic, or raw image differencing, co-registered images from two dates are subtracted pixel by pixel (Yuan *et al.*, 1998). The resulting digital image represents the change between the two images with the same number of bands as the input images. This process results in positive and negative values in areas of radiance change and values of zero in the areas of no change in a new image (Jensen, 1996). In this thesis, the Landsat image (1) was subtracted from the IRS image (3) for arithmetic change detection (4). A portion of the result of this image arithmetic is shown in Figure 3-9. Subtractions utilizing bands 1, 2, and 3 of the IRS and bands 2, 3, and 4 of the Landsat image were analyzed respectively. The best combination of bands, based on visual interpretation, was selected for further inclusion in the analysis.



White = No Change Grey = Change / No Data (outside denoted *amphoe* boundaries)

Figure 3-9: Change Detection Image Differencing Result (IRS Band 3 - Landsat Band 4)

Interpretation of images can be generally achieved by visual inspection as gray tones represent areas of little or no change and areas of very bright or very dark, white and black respectively, as areas of temporal differences. However, some of these differences in the rural areas of the study site can be attributed to differences in crops, time of year (seasonal variation) and crop rotation practices.

A binary-classification was performed on the subtracted image (4). This method was used to identify homogeneous areas of change thereby separating a region of change from a region of unchanged land cover. This supervised classification, with training areas based on the arithmetic change detection results, produced a binary (change/no change) image of the study area based on the results of the change detection process.

3.5 GIS Data Processing and Analysis

In conjunction with the satellite image analysis, other methods were used to identify environmental stresses on the urban fringe of the study area. Specifically, the analysis of district level census data for the provinces of Nonthaburi, and Pathum Thani was undertaken. The initial steps undertaken in the GIS data processing included:

1) Geometric Correction of Digital Layers
2) Data Input
3) Data Conversion

4) Z-score Calculation and Amphoe Ranking
5) Data Relates

The following sections outline the steps undertaken to input, correct, and analyze the census socio-economic tabular data.

3.5.1 Geometric Correction of Digital Layers

The first step in the GIS process flow in Figure 3-8, was to geo-register the digital data layers to the corrected digital roads layer. This was achieved by defining the data projection and subsequently transforming the administrative boundary layer as necessary to facilitate future integration and overlay analysis. The UTM, Zone 47, WGS 84 coordinate system, the same as that applied to the RS images, was applied to the GIS data layers.

3.5.2 Data Input and DBASE Conversion

This section outlines the analysis of indicators at the *amphoe* level in Pathum Thani and Nonthaburi to detect and locate areas of potential environmental stress. The incorporation of socio-economic data is an important step in locating and analyzing trigger points at the rural-urban fringe. Seven census-derived parameters were considered in this thesis: population growth, population density, net migration change, acreage of land use / land cover under rural use, number of livestock, number of dwellings and number of registered vehicles. All of these indictors were discussed in Chapter 2 (Figure 2-4).

Population growth, population density, agricultural land use area, number of livestock and number of houses were all input and analyzed at the *amphoe* level of aggregation. The information pertaining to net migration and number of vehicles was only available at the Provincial level for one of the time periods under examination. Therefore, for these two indicators the Provincial totals were allocated to *amphoes* relative to population aged 20-65 for number of vehicles allowing these areas to be ranked in terms of their z-score calculation. This step is discussed further below.

Census data were entered from printed tables and a locational relation was created from the Provincial and District codes to facilitate their integration in subsequent stages of the analysis process. The finished spreadsheets of data were converted to DBASE format to allow import of the tables into the GIS software.

3.5.3 Census Data Utilization, Z-Score Calculation and Amphoe Ranking

To show proportional magnitudes for each indicator, z-scores were calculated. The z-score for a variable is used to indicate how far and in what direction the variable deviates from a population mean of zero, with a standard deviation of one (standard normal distribution). Once transformed to z-score values, each indicator has a mean of zero and a standard deviation of one. The z-score is calculated as follows:

$$z_i = \frac{x_i - \mu}{\sigma} \qquad 3.1$$

where:

z_i is the z-score, or standard unit of area i,
x_i is the raw value for absolute x and area i,
μ is the population mean of the set of data and
σ is the population standard deviation of the set of data.

Basically, the z-score represents the conversion of the absolute values of the variable under consideration into standard units. Therefore, as the value of z increases, the variable moves further from the mean of the distribution. A portion of the resulting table is shown in Table 3-5 pertaining to the changes in numbers of livestock in particular districts of Nonthaburi and Pathum Thani.

Based on the z-score, each *amphoe* was ranked according to its environmental stress potential. Each of the seven indicators was separately ranked from highest to lowest based on their z-scores in each *amphoe.* The rankings were then summed for each *amphoe* over all indicators with the lowest sum representing the *amphoe* with the highest potential of environmental stress based on the seven combined indicators. This process of *amphoe* ranking was completed to provide an assessment of temporal change within each *amphoe* relative to the surrounding *amphoes.* This ranking was based on land use change as described by the seven indicators such that the *amphoes* were ordered from highest to lowest in terms of their potential contribution to environmental stresses. The results of this summation are presented and discussed in the following chapter.

To facilitate spatial analysis of the indictors, their z-scores and their potential environmental stress ranks were appended to the administrative boundary digital layer. This was completed by relating the database containing the z-scores and rankings to polygons attributes (5) using the GIS software.

District Index #	Number Livestock 95	Number Livestock 99	Difference in Livestock 1995 and 1999	z-score
2401	58798	31883	26915	-0.25
2402	277521	405918	-128397	-0.56
2403	18360	1150	17210	-0.27
2404	315497	355206	-39709	-0.38
2405	119980	38186	81794	-0.14
2406	42838	121114	-78276	-0.46
2801	146483	330548	-184065	-0.67
2802	275758	98512	177246	0.05
2803	264328	682524	-418196	-1.13
2804	774825	272886	501939	0.70
2805	1872505	215250	1657255	2.99
2806	382950	247981	134969	-0.03
2807	689939	466088	223851	0.14

Table 3-5: Portion of Database Containing Number of Livestock Information

3.6 RS and GIS Integration and Analysis

This section outlines the process of integration of the satellite imagery with the ancillary ground-based data within the GIS to detect and localize areas of potential environmental stress along the urban fringe.

These analysis steps included:

1. Image to Arc/Info GRID Conversion (4)
2. Road Buffer and RS Change Detection Proximity Analysis
3. Amphoe Ranking Based on RS Change Detection
4. Temporal Land Use Change and Census Data Join (6)
5. Localization of Stress Areas and Definition of Growth Management Policy

Each of these stages of analysis is outlined in further detail below.

3.6.1 Image to GRID Conversion and Vectorization

The first step in the conversion from RS processes to the multi-source GIS database was to export the RS image files into GIS-ready format. The derived areas of land use change (4) were exported to Geo-TIFF files. The TIFF format was selected for reasons outlined by Malcolm (1999) including:

1) supported by GIS software
2) may contain geo-referencing information in header tags
3) supports black-and-white, grayscale, pseudocolour and true colour images.

The Geo-TIFF image (4) containing the binary-classification of the change detection results was then converted to Arc/Info raster GRID format. The image was converted to a GRID as an interim process as raster images can be more easily integrated in a multi-source GIS database. Subsequent to GRID conversion, the original image file was converted in Arc/Info to a vector polygon coverage based on the change and no change classes. This was achieved with the Arc/Info 'gridpoly' function in order to facilitate the integration of the land use change data derived from the RS imagery with the ground-based census data through a tabular join.

3.6.2 Road Buffer and RS Change Detection Proximity Analysis

To link further the results of the land use RS change detection analysis with the major transportation infrastructure at the urban fringe, a process of proximity analysis was undertaken at the provincial level. Using the existing major road network digital layer, last updated in 1991, major roads in the provinces of Pathum Thani and Nonthaburi were buffered to distances of 100, 200 and 500 metres (Figure 3-10). These buffered areas were then overlain with the binary classification of the RS change detection analysis (4) to determine the proximity of detected change to the existing road network circa 1991. The analysis was completed at the province level to demonstrate the overall correlation between detected change between 1995 and 1998 and existing arterial roads.

3.6.3 Amphoe Ranking Based on RS Change Detection

To show the amount of actual change that had occurred in each of the *amphoes* based on the results of the RS change detection analysis, the actual total area of change for each *amphoe* was analyzed. First, the total area of change in each *amphoe* was calculated. Then, using the known total *amphoe* areas, percentages of change were calculated for each *amphoe* by dividing the area of change, less any areas of no data, by the total area of the *amphoe*. Based on these percentages, the *amphoes* were ranked from highest to lowest change values.

Figure 3-10: Major Roads with 100 metre Buffer

3.6.4 Temporal Land use Change and Census Coverage Data Joining

With the temporal land use change layer converted to a polygon coverage and the census data attached to the administrative boundary polygon coverage, a tabular data join between the two polygon digital layers was completed (4 and 5). The join allowed for a combined spatial analysis of the features of the two input layers (6). Specifically, the combined rankings from the seven census indicators and the change detection area rankings were combined to facilitate a ranking of the *amphoes* based on these two datasets.

3.7 Localization of Stress Areas & Growth Management Policy

The methods identified above were used to detect potential areas of environmental stress in the study area. To this end, the results were used to determine the areas in the two provinces that had experienced the fastest and largest rates of urban growth and therefore with the highest potential for environmental stress. Once the localization of potential stress areas was complete, these areas were reviewed for use in the temporal linear feature extraction analysis based on their ranking. Ultimately, one area was selected for continued analysis due to its high overall ranking indicating a strong potential for environmental stress.

Based on the results, attempts could be made to define new growth management policy. Policy development, in a wider sense, includes both strategic policy and operational budget development (McGill, 2001). At the centre of the emergent growth management policy is the fact that identified areas of potential stress allow planning practice to work toward achieving SUEM.

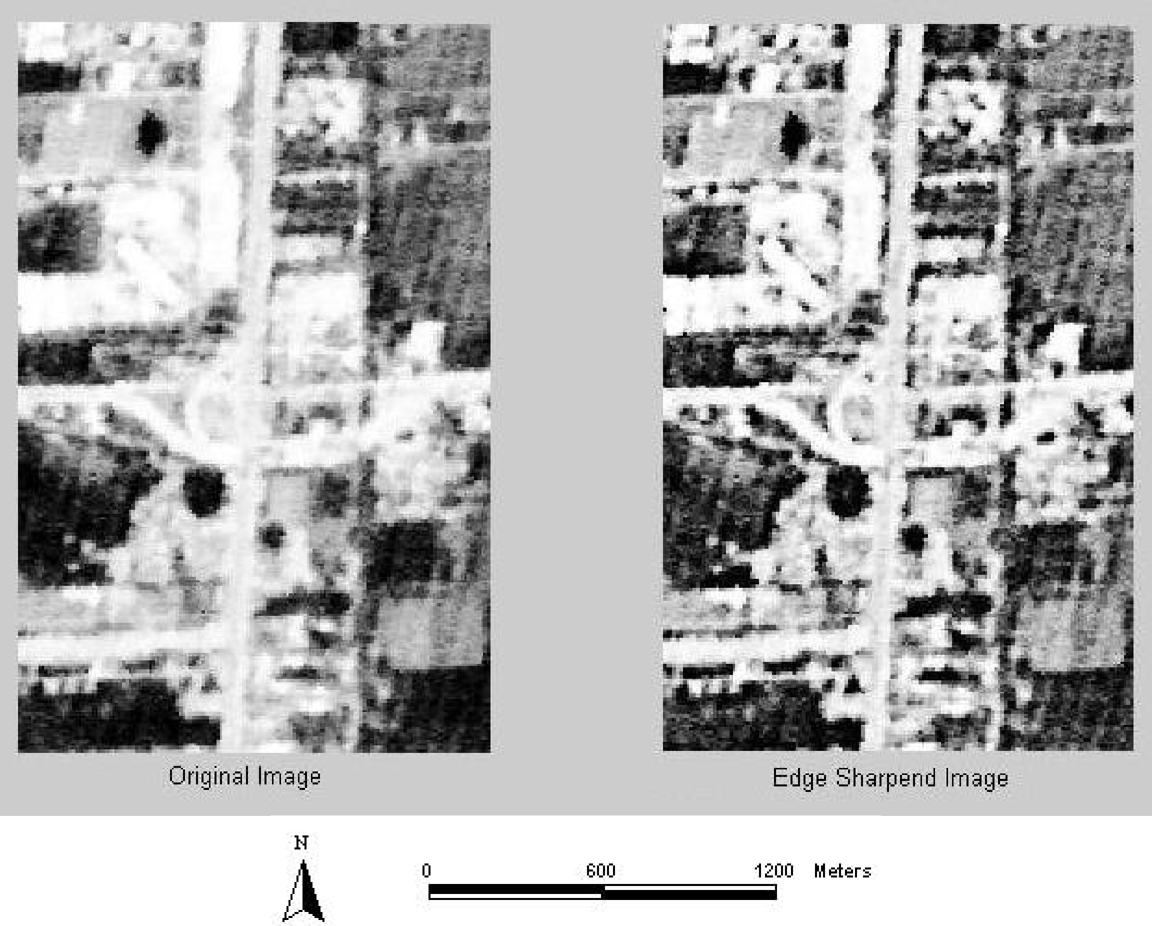
Using the methods outlined in this Chapter, it is expected that at least one of Durongdej's (1995) points on her list of shortcomings in the current Thai provincial development policy, outlined earlier, can be alleviated. Specifically, problems associated with duplication of data sources and, in particular, data quality can be improved through the integration of RS and GIS source data to facilitate environmental stress indicator analysis. With timely and accurate information about the changing morphology at the rural-urban fringe of Bangkok, the difficult process of planning for current and future growth and subsequent land use change will hopefully be mitigated.

3.8 Temporal Linear Feature Extraction

Edge detection is the principal means of detecting from imagery roadways and other linear features that have definite boundary edges, as discussed in Chapter 2. If homogeneity can be found within a certain region bounded by a sharp, contrasting periphery, this represents the edge of this particular feature. In this case, specific edge detection algorithms included in the Image Processing Toolbox of the MATLAB software package were utilized to attempt to isolate the road network from the satellite imagery.

In this portion of the analysis, only the area termed as the Northern Corridor was analysed. This limited geographical focus was used because if roads could be isolated within this area, then they could also be isolated in the broader study area. Because the Northern Corridor is the fastest growing area within the Provinces of Pathum Thani and Nonthaburi with the most rapid growth over the last decade, it was deemed the best location to test the accuracy and effectiveness of the linear feature extraction process outlined below.

To enhance the edge detection capabilities of the algorithms, an edge sharpening filter was applied to the images prior to edge detection and extraction. This procedure was implemented to assist in the efficient processing of images to detect linear features and to ensure enhancement in areas where low-contrast existed between road features and adjacent man-made and natural features. A sample of the edge sharpening is shown in Figure 3-11.


Original Image

Edge Sharpend Image

Figure 3-11: Results of Edge Sharpening Filter (7 x 7) With ADEOS Image

The edge-sharpening filter uses a subtractive smoothing method to sharpen an image by first averaging the image and subsequently attenuating the high frequency features such as edges and lines. Following this, the averaged image is subtracted from the original image and the remaining features of the resulting difference will be primarily the high frequency edges and lines. Finally, the original image is added back to the edge enhanced image creating the final image to reveal greatly enhanced high frequency detail. The filter smoothes the image while at the same time sharpening edges within the image, which is desirable in this methodology.

The edge-sharpening filter navigates through the image using an *n* x *n* window. For this thesis, windows of size 3 x 3 through 11 x 11 were tested in an iterative process. The results of these tests are discussed in more detail in the next chapter. Following the filtering process, the images were exported to TIFF format.

To enhance the imagery further prior to applying the edge detection algorithms, histogram equalizations were applied. Histogram equalization enhances the contrast in an image by transforming its intensity values so that the output image matches a specified histogram. If no output histogram is specified, a flat histogram of the image is generated. Similar to the edge sharpening filter, 3 x 3 through 11 x 11 histogram equalization windows were applied to the images in an iterative testing process. This process was utilized to enhance optimally the contrasting edges between linear features in the image and any adjacent non-linear features. The results of the histogram equalization are shown in Figure 3-12 with the IRS image prior to enhancement on the left and the histogram-equalized image on the right.

The methods of feature extraction used were developed through an iterative process of edge detection algorithm examination. Several edge detection algorithms are available including the Sobel, the Laplacian of Gaussian, and the Canny algorithms. Figure 3-13 compares the use of each algorithm on the Landsat image. The Sobel algorithm performs a spatial gradient measurement of an image using a pair of 3 x 3 convolution kernels to emphasize regions of high spatial frequency, which are equivalent to edges (Fisher *et al.* 2000). Convolution can be defined as means of multiplying two arrays of numbers of different sizes to produce a third array of numbers. For example, a small matrix, as shown in Table 3-6, also known as a kernel, could be multiplied together to produce a third matrix of numbers in a convolution. Similarly, the Laplacian algorithm is used to highlight regions of rapid intensity change using a convolution filter (Fisher *et al.*, 2000).

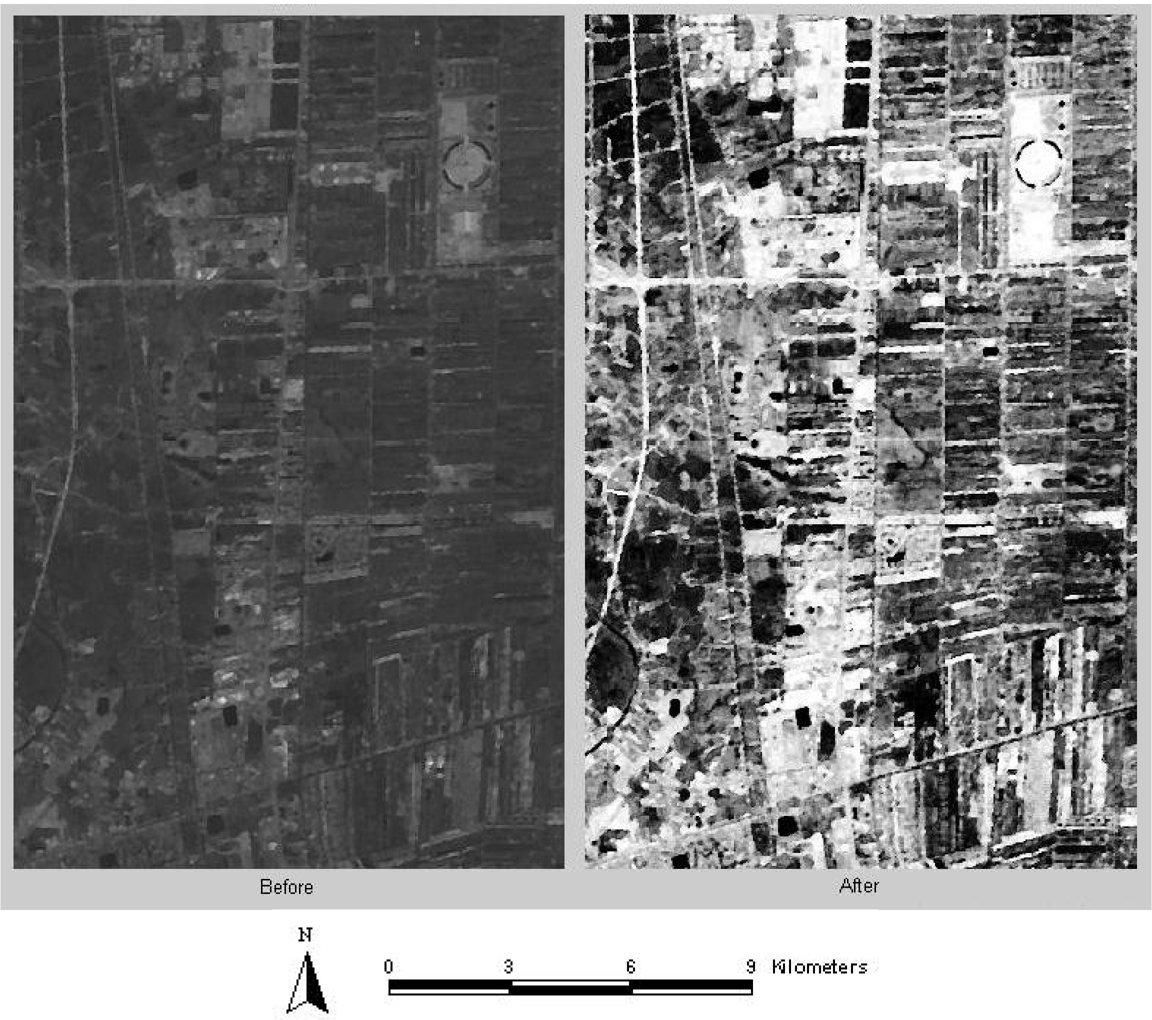


Figure 3-12: Histogram Equalization Comparison of IRS Image of Northern Corridor

The Canny edge detector algorithm was designed to be an optimal edge detector that works on a multi-stage process (Fisher *et al,* 2000). First, the image is smoothed using a Gaussian convolution. This step is used to blur the image to remove unnecessary noise. Subsequently, an operation is applied to the image to highlight regions of the image with high contrast. These contrasts are representative of edges, as they often correspond to high magnitude gradients in the image. Finally, the algorithm maps the gradients along these ridges to produce the linear edge outputs.

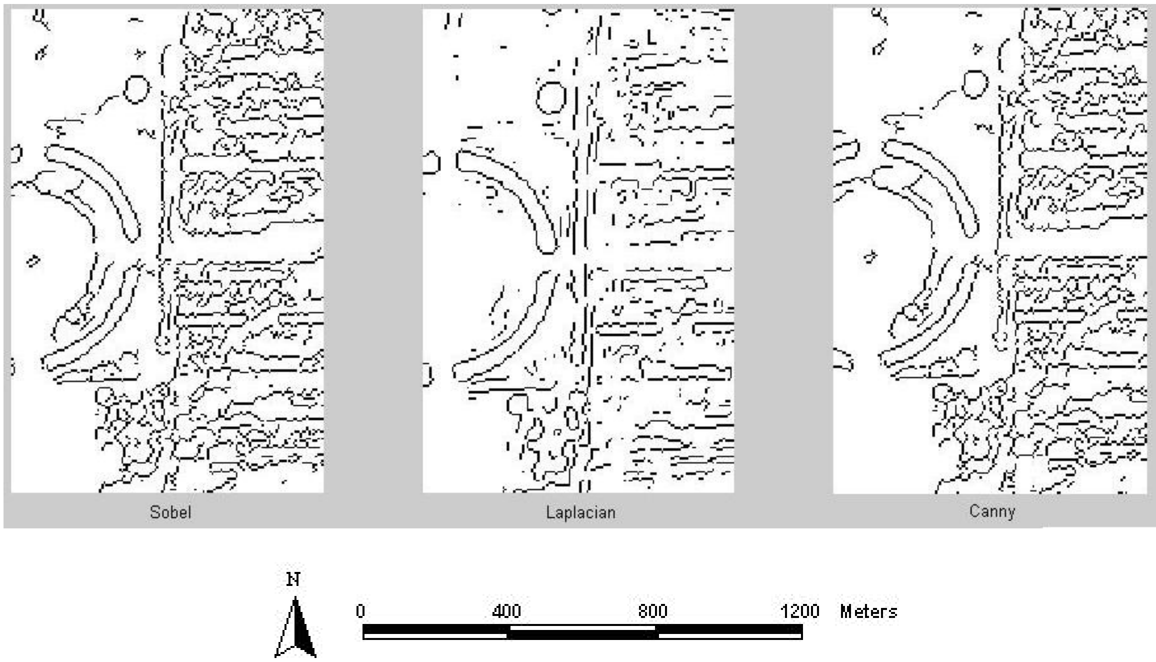


Figure 3-13: Edge Detection Comparisons with Landsat Image

-1	0	+1
-2	0	+2
-1	0	+1

+1	+2	+1
0	0	0
-1	-2	-1

Table 3-6: Sobel Convolution Kernals

Each of the Sobel, Laplacian, and Canny methods were sequentially applied to all three images, which had been clipped to the Northern Corridor boundary (1,2,3 from Figure 3-8). The results of each analysis were visually inspected for the clarity of the extracted road features from the different types of imagery under examination. The results were evaluated and accordingly accepted or rejected. If accepted, the extracted road segments were kept and advanced to the next stage in the overall methodology (2=7, 3=8 from Figure 3-8). If rejected, alternative algorithms were iteratively tested until the best extraction results were achieved. Figure 3-14 presents the results of the edge detection a portion of the ADEOS Panchromatic image from 1997 within the Northern Corridor using the Canny algorithm set to the lowest edge detection threshold (0.1). At this point, only the ADEOS and IRS images (7 and 8) were carried forward in the analysis. The reasons for this are outlined in the following chapter when the results of the procedure are presented and discussed.

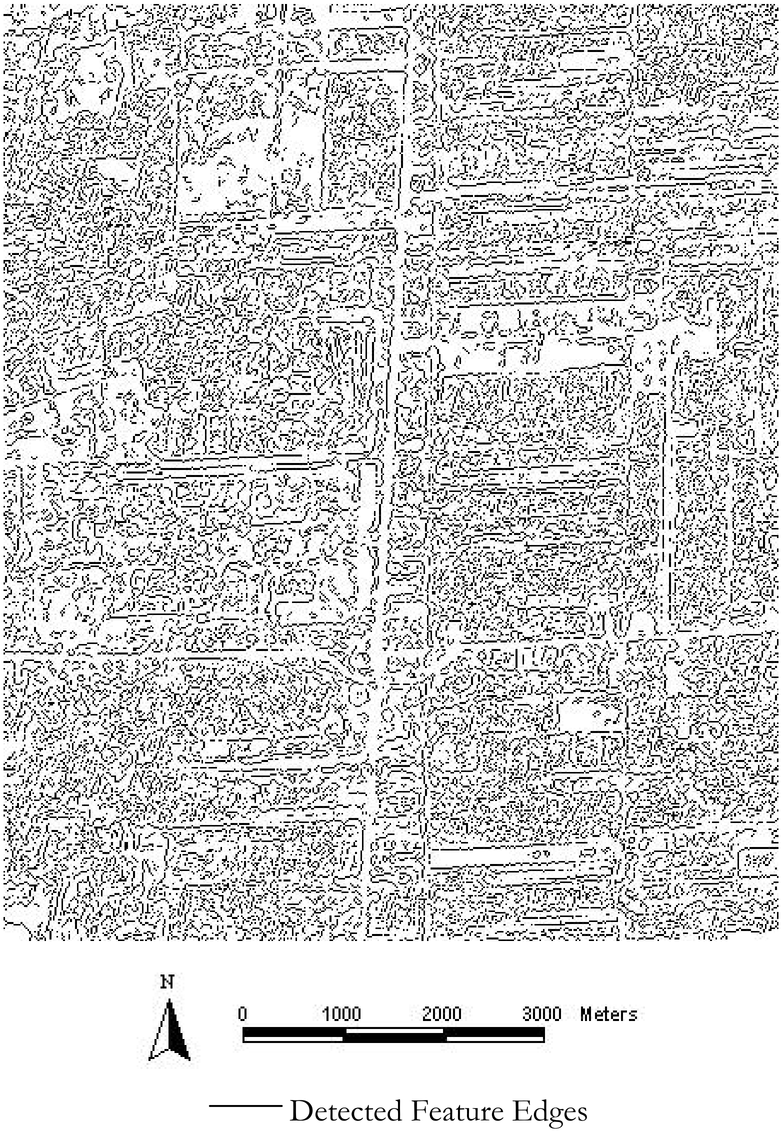


Figure 3-14: Canny Algorithm (0.1) at lowest threshold (ADEOS Image)

3.8.1 Conversion of Temporal Land Use Information and Extracted Linear Features to GIS

The extracted linear features (7,8) were already in TIF format so no export was required. Similar to the process used with the RS change detection Geo-TIFF, the images were converted to the Arc/Info raster GRID format. After being converted to a GRID, the temporal land use change image was automatically converted in Arc/Info to a vector line coverage using the 'gridline' function. By automatically converting to a line coverage, the extracted edges were represented by arcs that could be further analyzed to determine their potential as new road segments. Also, by using the 'gridline' function, all of the edges were automatically processed without any manual intervention at this point. This was desirable because the ability to extract the edges automatically and subsequently generate an arc coverage was one of the objectives of the thesis.

3.8.2 Selecting New Road Segments by Layer

Utilizing the two vectorized segments of extracted linear road features (7 and 8), a process of selecting the features within these vectorized map layers was undertaken to separate the newest road segments from older ones. First, using a 'Select By Layer' function, the extracted features from the 1998 IRS image (8) were selected if they were within a specified distance of the extracted features of the 1997 ADEOS image (7 creating stage 9). Various distances were experimented with, as it was desirable to locate areas of potential environmental stress at a slightly larger search area based on the extracted features. Once selected, the results were inverted such that the selected features of the original IRS image were now the features that were greater than the specified distance from any of the extracted features in the original ADEOS image (10). The selected features were then put into a new ESRI shapefile for further analysis, as they had now been determined to be 'new' sections of the extracted features developed within the study timeframe (11).

Ultimately, an integrated RS/GIS multi-source/multi-temporal database was created from the results of the RS land use change detection, ancillary census data analysis and the RS feature detection and extraction results.

3.9 Summary

This chapter has outlined the methods used to analyze and classify the study area based on its exposure to potential environmental stresses and its current state of development. First, planning practices in Bangkok were discussed to set the stage for the necessity of the integrated framework used in the thesis. Following this, a discussion of the study area was provided including an examination of the morphology of the provinces within which the study area is located.

Finally, the research design was discussed. This methodology was created to make operational the integrated framework presented and discussed in Chapter 2 (Figures 2-1 to 2-3). Several research techniques were used to obtain the necessary RS imagery and ground-based GIS data and an integrated RS and GIS process flow was outlined demonstrating the work undertaken. The next chapter presents the results of the research based on this design.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter extends the discussion in Chapter 3 by presenting and discussing the results derived from the previously outlined methods. The results are presented in several sections. First, the outputs of the RS data processing and analysis are discussed. This includes first the temporal change detection and, following the census data analysis, the linear feature extraction is discussed. The first part of the RS analysis is an important step in determining the overall success of identifying areas of potential environmental stress. The subsequent feature extraction RS analysis was driven by the results of the combined change detection work and the GIS data analyses, which are then presented and discussed. Secondary GIS data results are analyzed and incorporated with the results of the RS change detection analyses based on the stages of the integrated framework outlined in Chapter 2 and the detailed methods explained in Chapter 3.

4.1 RS Change Detection Data Processing and Analysis

This section builds upon the discussion in Chapters 2 and 3 by presenting the results of the RS analysis stages outlined in the integrated model (Figure 2-3) and the research design. The analyses involved the examination of several indicators of environmental stress detectable in the RS imagery. The analysis steps used in the thesis include temporal change detection and linear feature identification and extraction. The results of the first part of the RS analysis are now presented in detail. The latter results pertaining to feature extraction are presented following this discussion and the subsequent census data analysis results.

4.1.1 Change Detection

The change detection analysis of the RS images produced results that were successful in terms of differentiating between pre-existing and new development in the Provinces of Nonthaburi and Pathum Thani during the period of 1995-1998.

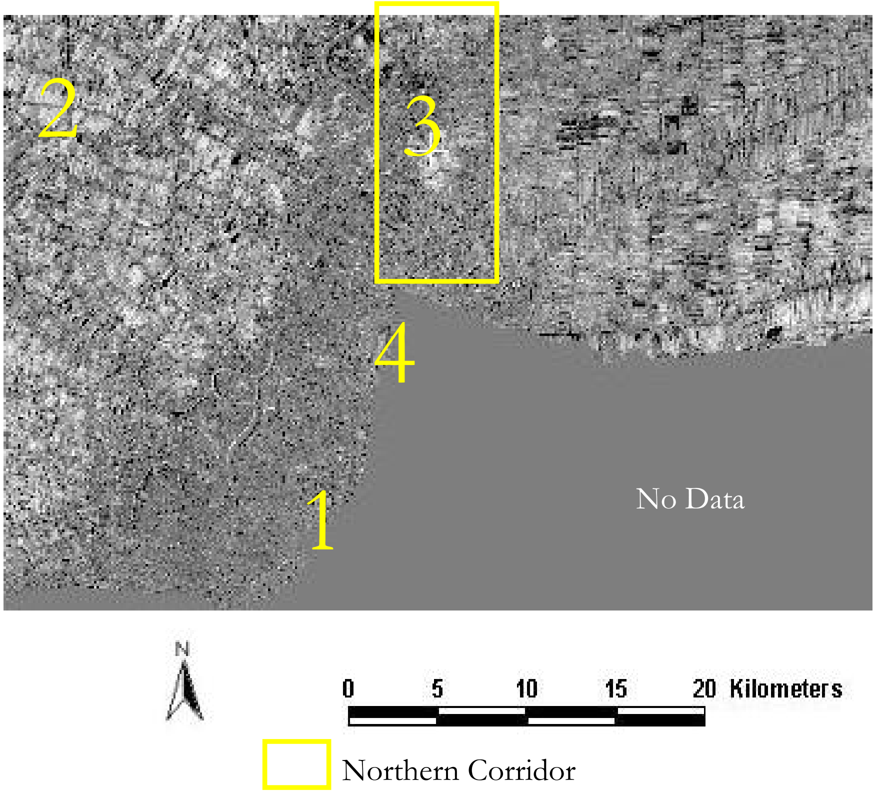
As expected, the identified areas of change within Pathum Thani and Nonthaburi lie mostly at the immediate urban fringe of the greater Bangkok Metropolis. More specifically, change is especially evident within the area termed as the Northern Corridor in Pathum Thani and the districts of Lam Luk Ka, Thanyaburi, Khlong Luang and Muang Pathum Thani (Figure 3-5). This area is delineated in yellow on the image in Figure 4-1. Interpretation of the change detection image provided the following results:

1) minimal to no change is noticeable throughout most of the urban areas, as illustrated by the medium grey tone in the image (not including 'no data' area to southeast of Pathum Thani and Nonthaburi);
2) some of the notable differences, visually the significantly darker and brighter tones, in the predominately rural areas are attributable to differences in crops and time of year (January 1998 versus May 1995);
3) some of the very bright areas throughout the image may be characteristic of land currently under development (from bare soil to developed land use);
4) the brighter and darker areas at the urban fringe and along the Northern Corridor represent the areas of greatest change between 1995 and 1998 in terms of urban land use development.

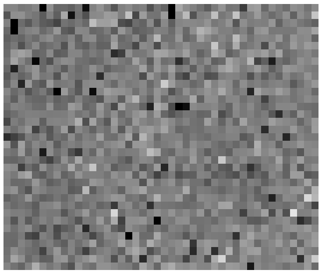
Examples of the locations that typify these general observations are numerically denoted (yellow numbering) and are shown in separate close-up images in Figure 4-1.

Based on these general observations, more detailed conclusions can be stated in terms of the temporal changes at the urban fringe during the time frame under investigation. First, and of greatest significance, the area in Pathum Thani along the Northern Corridor is particularly prominent in terms of definite detectable urban development between 1995 and 1998. This assists in affirming the expectation that this area is, in fact, one of the most rapidly growing areas at the urban fringe of the Bangkok Metropolis is likely to be one of the areas most susceptible to potential environmental stresses. This indication of rapid growth is further confirmed with the ground-based census data analysis discussed later in this chapter.

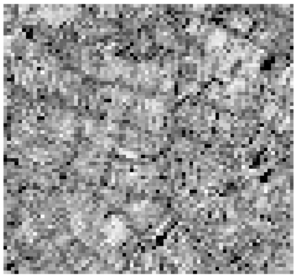
Second, it is visually evident from the change detection image that the areas of change form a band along the known edge of the Bangkok Metropolis. In particular, within this band, areas of change are most evident along major roadways and waterways. This pattern is consistent with the expected forms of ribbon development predicted in the thesis. Total areas and locations of change are further discussed in the following two sections.



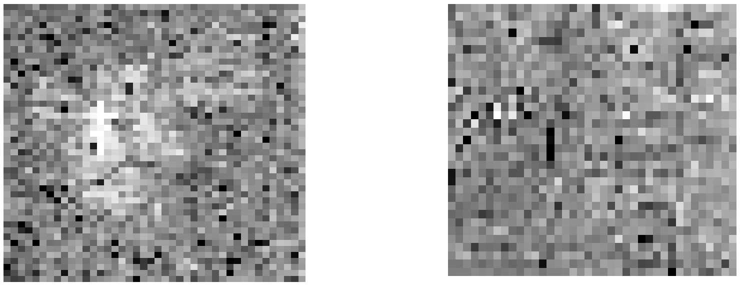
Medium Gray = No Change   Darker and Brighter Tones = Change



Area 1 – Medium gray tone denotes no change in urban regions.



Area 2 – Some change, brighter areas, in rural regions may be due to crop rotation.



Area 3 – Some very bright tones may be attributable to land currently under development.

Area 4 – Pockets of generally darker and brighter areas denote change.

Figure 4-1: Areas of Noted Change Detection Between 1995 and 1998 in Pathum Thani and Nonthaburi

4.1.2 Change Detection Binary-classification

A binary classification (Figure 4-2) was applied to the change detection results to provide a homogeneous representation of the regions of change within the study area.

The production of the change detection results in this format allowed them to be integrated with GIS analysis. The total calculated area of change, excluding the areas of no data (no concurrent satellite coverage), was 266.7 square kilometres (26,676 hectares) while the total area of no change was 1058 square kilometres (105,805 hectares). The total area of both provinces, less the areas of no data, is 1324 square kilometres (132,482 hectares). This represents a percentage change of 20.1%.

4.1.3 Change Detection by *Amphoe* in a GIS

Utilizing the results of the change detection and binary-classification, the image was subdivided to determine the total amount of change in each *amphoe*. Once divided, the total area of change per *amphoe* was calculated and then ranked in order from greatest to least (Table 4-1). The ranking was based on the percent of change of the total area of the *amphoe*, less any areas of no data. The *amphoe* with the most change at 29.37 percent was Thanyaburi, in Pathum Thani Province. This represented a total area of change of 55.41 square kilometres (55,41 hectares) out of 124.3 square kilometres (12,430 hectares). Not surprisingly, three of the top five ranked *amphoes* are directly adjacent to Bangkok Province and the other two, Thanyaburi and Bang Bua Thong, are next in terms of concentric outward growth amongst the provinces. The total area of change for the top eight provinces, those directly adjacent to Bangkok province as well as Thanyaburi and Bang Bua Thong, was 514.7 square kilometers (51,470 hectares) out of a total area of 1286 square kilometres (128,600 hectares). This represents a significant amount of detected land use change in these provinces. Table 4-1 presents the results in total areas and percentages of land use change for all the *amphoes* and Figure 4-3 displays the change detection a*mphoe* rankings based on percentage change for the Provinces adjacent to Bangkok Province.

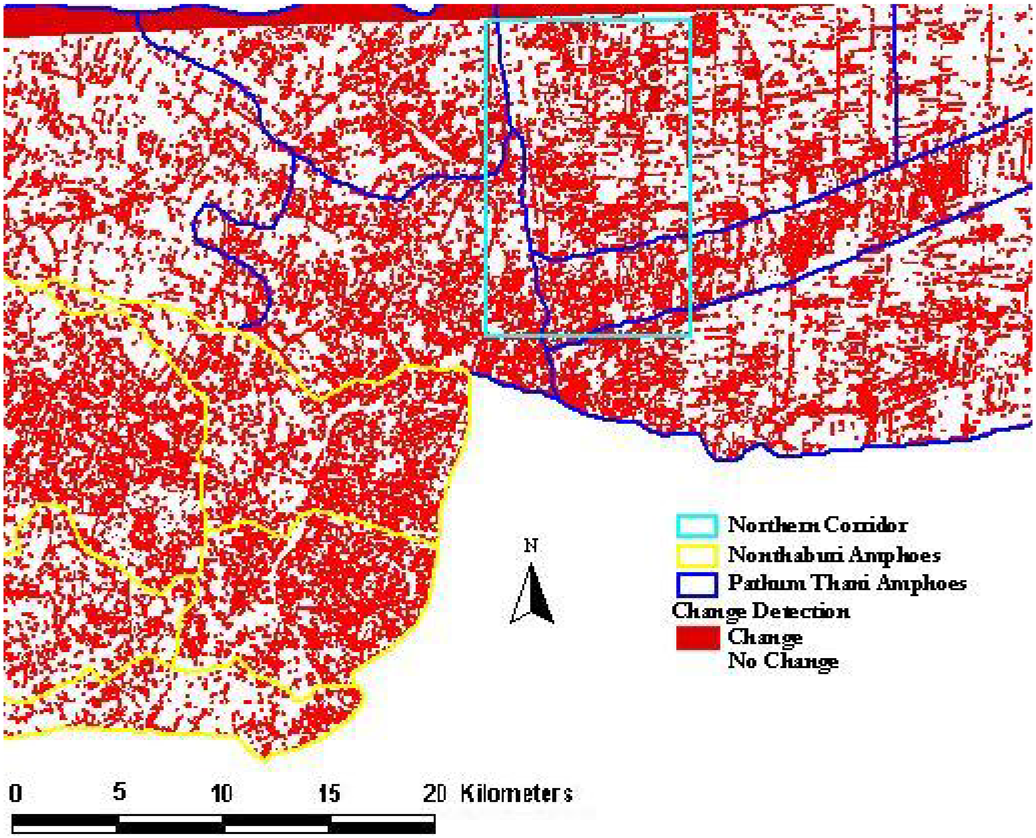


Figure 4-2: Binary-classification of Image Arithmetic Change Detection Results

As anticipated, the provinces that contain the Northern Corridor are all within the top seven of the thirteen *amphoes*, and represent three of the top four from Pathum Thani - Lam Luk Ka, Thanyaburi, and Khlong Luang. These results are supportive of the overall conjecture of this thesis, namely that a great amount of land use change is occurring along the urban fringe of Bangkok, and in particular, along the Northern Corridor. Based on these results, and the census indicator analysis, the Northern Corridor is confirmed as an appropriate location for linear feature detection and extraction.

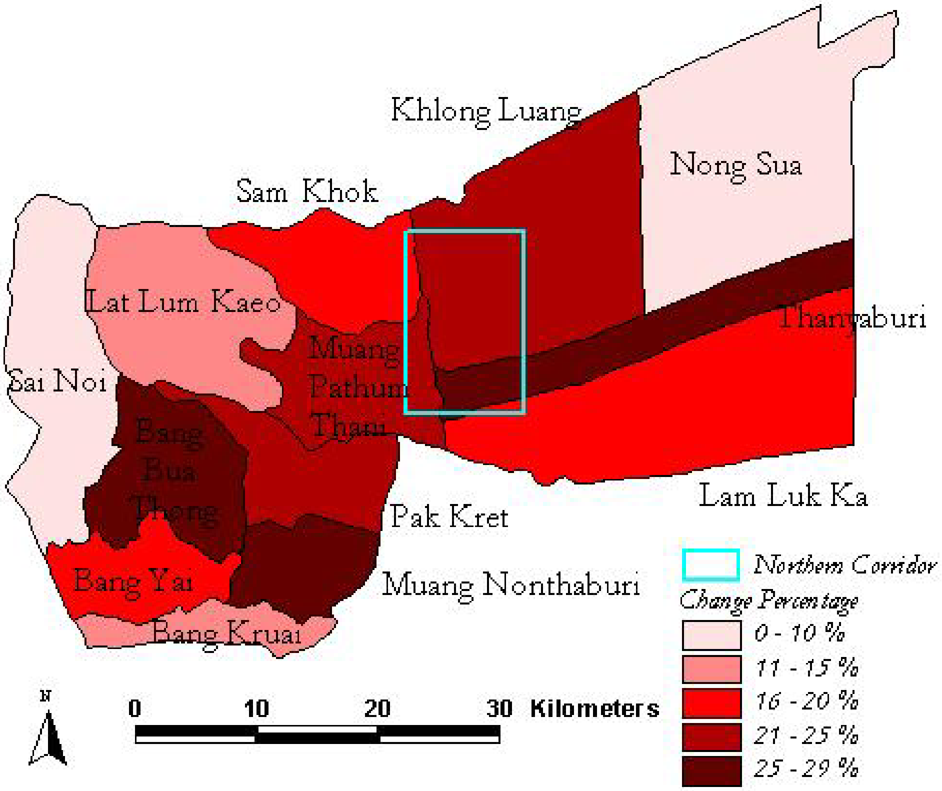


Figure 4-3: Change Detection *Amphoe* Rankings

Notable in Figure 4-3 is the high percentage change detected in Muang Nonthaburi, Pak Kret, Muang Pathum Thani, Lam Luk Ka and Thanyaburi, with change detection rankings of 3, 5, 4, 7 and 1, respectively.

Amphoe	Province	District	Area of Change (*)	Total Area (*)	No Data (*)	Percent Change (%)	Rank Based on Amount Change
2803	Pathum Thani	Thanyaburi	55.41	124.30	27.20	29.37	1
2404	Nonthaburi	Bang Bua Thong	46.78	131.56	11.76	29.26	2
2401	Nonthaburi	Muang Nonthaburi	19.52	76.66	0.00	25.74	3
2801	Pathum Thani	Muang Pathum Thani	29.21	127.87	0.00	22.89	4
2406	Nonthaburi	Pak Kret	22.38	103.59	0.00	22.01	5
2802	Pathum Thani	Khlong Luang	156.5	299.89	117.42	21.23	6
2805	Pathum Thani	Lam Luk Ka	149.6	311.08	113.56	18.29	7
2806	Pathum Thani	Sam Khok	34.69	111.94	19.52	16.30	8
2405	Nonthaburi	Bang Yai	38.07	89.18	28.76	15.79	9
2403	Nonthaburi	Bang Kruai	13.66	55.53	6.28	14.08	10
2804	Pathum Thani	Lat Lum Kaeo	55.59	189.40	36.58	12.41	11
2807	Pathum Thani	Nong Sua	283.8	342.01	277.52	9.31	12
2402	Nonthaburi	Sai Noi	190.00	191.32	190.90	4.28	13

* square kilometres

Table 4-1: *Amphoe* Environmental Stress Potential Rankings Based on RS Change Detection

In general, these results can be applied to the stages of development outlined in Chapter 2 (Figure 2-4). Specifically, the *amphoes* that have experienced the largest percentage of detected change have the greatest potential for environmental stress as they are evolving quickly from Stage 1 to Stage 2 or 3 or from Stage 2 to Stage 3. If this movement is occurring too quickly, these areas are decidedly suspect in terms of localized rapid land use evolution and potential for consequent environmental stress. Supportive evidence that this is occurring are the relatively short time frame being investigated, 1995-1998, and the large percentage of detected change, up to 29% in some of the *amphoes*.

4.1.4 Road Buffer and RS Change Detection Proximity Analysis

The analysis of the road buffer and the RS change detection proximities in the provinces of Pathum Thani and Nonthaburi revealed some important correlations in terms of substantiating one of the conjectures of this thesis. By applying a 100 metre buffer to the existing road network (from 1991) and selecting areas of noted change within this buffer, a total area of change of 25.87 square kilometres (2586.96 hectares) was detected within 100 metres of existing roads. This represents approximately 10% of all change noted within the combined provinces of Pathum Thani and Nonthaburi. Increasing the buffer to 200 metres raised the total detected change to 65.33 square kilometres (6532.97 hectares), or approximately 25% of the total detected change, as shown in Figure 4-4. This total represents a significant proportion of the change within a narrow buffer adjacent to existing roads.

Finally, by increasing the road network buffer further to 500 metres, the total detected change within this buffer is 154.98 square kilometres (15498.17 hectares). This represents 59% of the total detected change of both provinces combined. These results are notable in terms of providing a conclusive link between the results of the RS change detection and existing transportation infrastructure. They also serve to confirm further that a significant portion of new urban growth is occurring in close proximity to roadways.

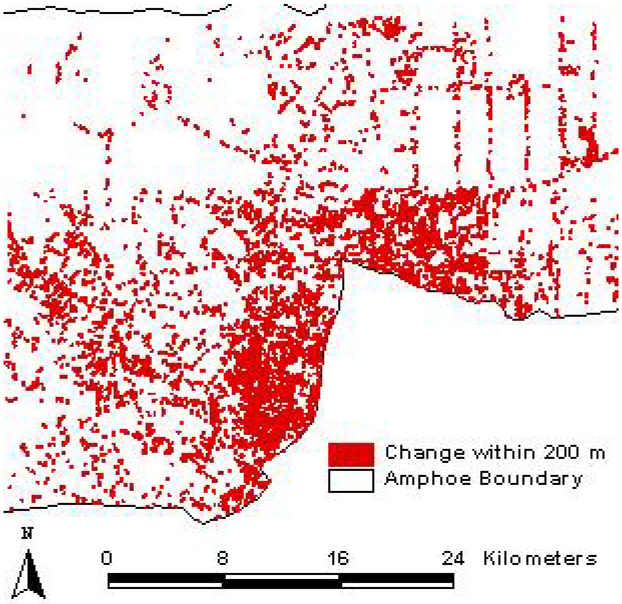


Figure 4-4: Detected Change Within 200 metres of Existing Roads

With the change detection analysis complete, the census data in the Provinces of Nonthaburi and Pathum Thani are discussed.

4.2 GIS Data Analysis and Processing

Prior to discussing the integration of RS and GIS data, the results of the census GIS data are presented.

4.2.1 Temporal Land Use Change and Census Coverage Intersection

The analysis of the seven indictors of potential environmental stress in the provinces of Pathum Thani and Nonthaburi produced interesting, yet expected results. Table 4-2 displays the overall *amphoe* rankings for the two Provinces. *Amphoe* Lam Luk Ka in Pathum Thani province had the lowest summation of individual district rankings signifying that it is the district with the highest potential for environmental stress based on the seven indicators examined (Figure 4-5). Lam Luk Ka had the highest ranking of all districts in terms of rate of population growth, decrease in observed agricultural land and decline in the total number of livestock between 1995 and 1998. Second and third to Lam Luk Ka comes *amphoes* Muang Pathum Thani and Khlong Luang, both located in Pathum Thani Province. It is not surprising that these three districts are at the top of this order because the Northern

Corridor and Phaholyothin Highway directly bisects both Lam Luk Ka and Khlong Luang, and it is partially located within Muang Pathum Thani. This result is consistent with the general expectation that locations adjacent to recent road and highway development show the greatest propensity for rapid land use change and hence potential stress on the preexisting and predominately rural environments. However, slightly contrary to expectations, Thanyaburi, the *amphoe* in-between Lam Luk Ka and Khlong Luang is ranked tied for sixth (out of 13) with *amphoe* Muang Nonthaburi. One factor that might explain the relatively low score for Thanyaburi is that it has an elongated shape from east to west and it is narrow from north to south. Since Phaholyothin Highway runs north to south through these three *amphoes,* its growth inducing effects are likely to have been less substantial in Thanyaburi than in either Lam Luk Ka or Khlong Luang.

The *amphoe* in the fourth position is the top ranked *amphoe* in Nonthaburi. Bang Bua Thong is located centrally in Nonthaburi and is therefore somewhat of a surprise in terms of its ranking based on the growth indicators. However, it is not surprising that Bang Bua Thong is followed by the two *amphoes* in Nonthaburi that are located in the southeast portion of the province, Bang Yai and Muang Nonthaburi. Given the known existing growth patterns in the Bangkok Metropolis discussed earlier, the results for these *amphoe* rankings are as expected. Also, tied for sixth in the ranking is Thanyaburi, as noted above. Finally, it is also of note that the two *amphoes* that are last in the ranking are Nong Sua and Lat Lum Kaeo, both in Pathum Thani and both located at the northern most corners of the province, farthest geographically from Bangkok Province and from the Northern Corridor region.

Amphoe	Province	District	Population Density	Popu-lation	Agri-culture	Livestock	Number Houses	Net Migration	Number Vehicles	Rank Sum	Final Rank
2805	Pathum Thani	Lam Luk Ka	7	1	1	1	11	2	4	27	1
2801	Pathum Thani	Muang Pathum Thani	3	3	7	12	1	1	3	30	2
2802	Pathum Thani	Khlong Luang	9	7	2	4	2	4	7	35	3
2404	Nonthaburi	Bang Bua Thong	1	2	10	9	3	10	2	37	4
2405	Nonthaburi	Bang Yai	6	8	3	6	6	8	9	46	5
2401	Nonthaburi	Muang Nonthaburi	2	5	9	7	13	13	1	50	6
2803	Pathum Thani	Thanyaburi	4	4	11	13	10	3	5	50	6
2406	Nonthaburi	Pak Kret	5	6	8	10	7	12	6	54	8
2806	Pathum Thani	Sam Khok	10	12	5	5	8	6	10	56	9
2402	Nonthaburi	Sai Noi	11	9	4	11	4	9	13	61	10
2403	Nonthaburi	Bang Kruai	8	10	12	8	5	11	8	62	11
2804	Pathum Thani	Lat Lum Kaeo	12	11	13	2	9	5	11	63	12
2807	Pathum Thani	Nong Sua	13	13	6	3	12	7	12	66	13

Table 4-2: *Amphoe* Environmental Stress Potential Rankings Based on Census GIS Indicators

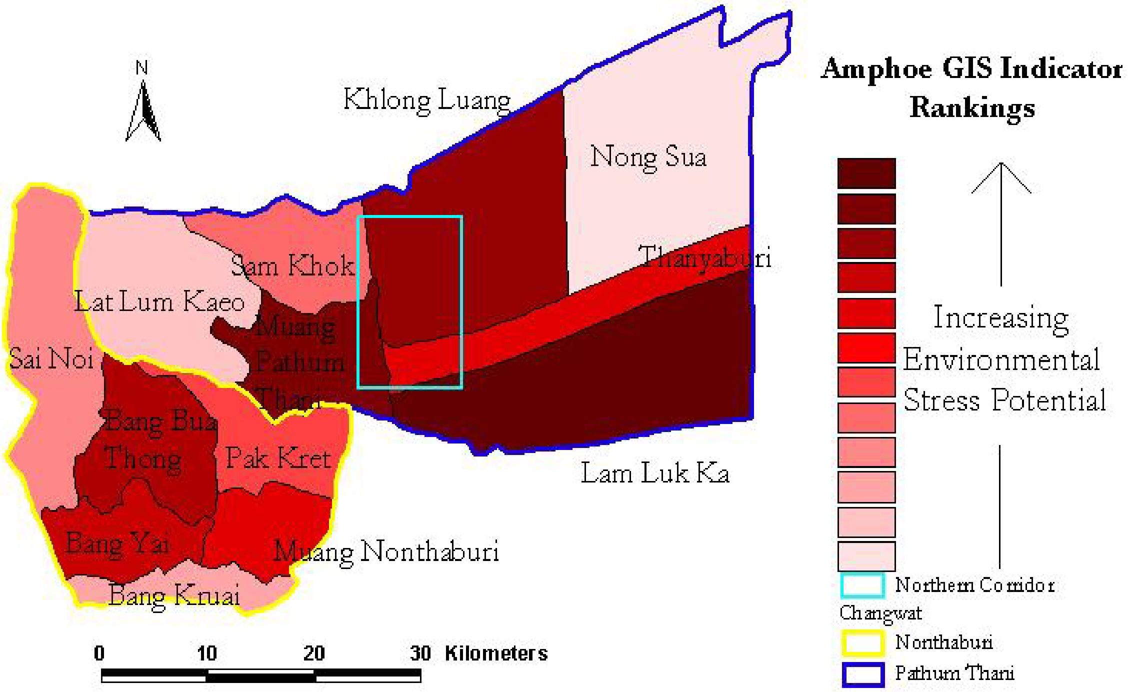


Figure 4-5: Potential Environmental Stress *Amphoe* Rankings Based on Census GIS Indicators

4.2.2 RS Change Detection and GIS Census Data Integration

The separate examination of the results of the change detection and the census indicator analyses, outlined individually above, generally indicate similar results in terms of areas of change and thus areas of potential environmental stresses. However, alone, neither is as persuasive as when the two methods are combined for environmental stress detection at the *amphoe* level. The change detection results, ranked based on total area of detected change, were added to the overall rank sum of the seven census GIS-based indicators. This provided a new overall rank summation. Table 4-3 presents the *amphoe* ranking results based on the combination of the change detection analysis integrated with the results of the census indicators analysis.

The results of the rankings are illustrated in Figure 4-6. Based on the results presented in Table 4-3 and displayed in the figure, some minor, yet notable adjustments to the previous *amphoe* rankings are apparent. In general, the overall *amphoe* rankings changed little and in fact, the addition of the RS change detection rankings served to confirm further the results of the GIS-based indictor analysis. The final two columns in Table 4-3 display

Amphoe	Province/ District (see legend)	Popu-lation Density	Popu-lation	Agricul-ture	Livestock	Number Houses	Net Migration	Number Vehicles	RS Change Detection	Rank Sum	Final *Amphoe* Rank	Rank Prior to Change Detec-tion
2801	P1	3	3	7	12	1	1	3	4	34	1	2
2805	P2	7	1	1	1	11	2	4	7	34	1	1
2404	N1	1	2	10	9	3	10	2	2	39	3	4
2802	P3	9	7	2	4	2	4	7	6	41	4	3
2803	P4	4	4	11	13	10	3	5	1	51	5	6
2401	N2	2	5	9	7	13	13	1	3	53	6	6
2405	N3	6	8	3	6	6	8	9	9	55	7	5
2406	N4	5	6	8	10	7	12	6	5	59	8	8
2806	P5	10	12	5	5	8	6	10	8	64	9	9
2403	N5	8	10	12	8	5	11	8	10	72	10	11
2402	N6	11	9	4	11	4	9	13	13	74	11	10
2804	P6	12	11	13	2	9	5	11	11	74	11	12
2807	P7	13	13	6	3	12	7	12	12	78	13	13

Table 4-3: *Amphoe* Environmental Stress Potential Rankings Based on Combined RS Change Detection and Ground-based GIS Indicators

Legend:

Pathum Thani	Muang Pathum Thani	P1	Nonthaburi	Bang Bua Thong	N1
	Lam Luk Ka	P2		Muang Nonthaburi	N2
	Khlong Luang	P3		Bang Yai	N3
	Thanyaburi	P4		Pak Kret	N4
	Sam Khok	P5		Bang Kruai	N5
	Lat Lum Kaeo	P6		Sai Noi	N6
	Nong Sua	P7			

the current *amphoe* rankings and the previous *amphoe* rankings prior to the addition of the RS change detection analysis results. Lam Luk Ka and Muang Pathum Thani are ranked equally at the top and Khlong Luang is ranked fourth, instead of third, flipping spots with Bang Bua Thong. Aside from the upward movement of Bang Bua Thong, the ordering of the other three *amphoes* is directly in line with the suggestion that the areas of potential environmental stress are located in the *amphoes* that contain the Northern Corridor. Also, it should be noted that while Bang Bua Thong may seem an anomaly being ranked above Khlong Luang, this *amphoe* is in the centre of Nonthaburi, a province that has seen unprecedented growth and urban development over the past decade. While it is not directly adjacent to Bangkok Province, it is within the range of Bangkok's known prior sprawl patterns and has thus been affected by a significant amount of leapfrog growth.

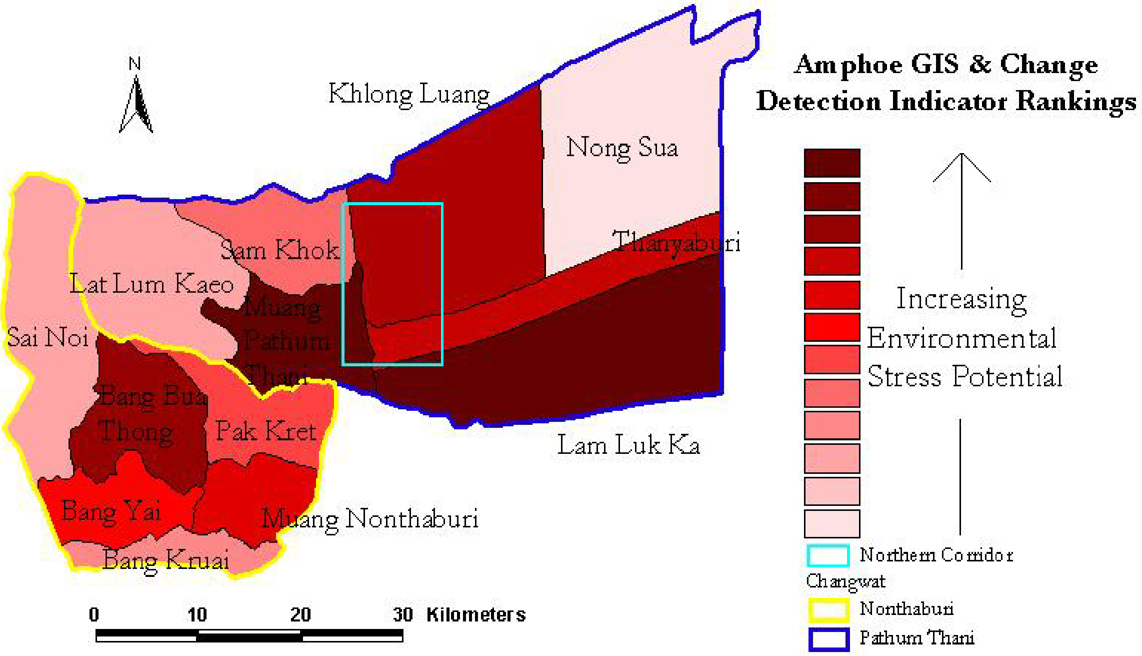


Figure 4-6: Potential Environmental Stress *Amphoe* Rankings Based on Integrated RS Change Detection and GIS Indicators

Also of note is that Thanyaburi has moved up one position in the rankings with the integrated RS and GIS results, from sixth to fifth, out of the thirteen *amphoes*. Having moved into only the top third in terms of *amphoes* that exhibit the greatest potential for environmental stress, it is evident that the shape of Thanyaburi continues to contribute significantly to its position in the rankings. However, because the addition of the RS change detection results moves Thanyaburi into fifth position, it is a strong indication that at least the western portion of this district is experiencing rapid land use change and urban development.

4.2.3 Land Use Classification and Localization of Detected Stress Areas

Based on these integrated ranking results, it is evident that the Northern Corridor represents an unmistakable region of significant urban growth and thus has increased potential for environmental stresses above and beyond other regions within Pathum Thani and Nonthaburi.

In general, the results of the integration of data derived from both the RS and GIS analyses, has, at the district level, divided the provinces of Pathum Thani and Nonthaburi into areas of varied susceptibility to environmental stresses. This classification system can be extrapolated into the stages of development outlined in Chapter 2 (Figure 2-4). Specifically, the zones of greatest potential for environmental stress based on these ranking are most likely to be located in Stage 2 or Stage 3 in terms of built-up land. These districts are likely to be characteristic of these stages of development in terms of the seven indicators of development derived from the census data and in terms of the RS change detection analysis. Further, the *amphoes* with the lowest potential for environmental stress based on the overall rankings are more likely to be located in Stage 1 or the early part of Stage 2. This type of generalized stage classification is possible because the seven census indicators and the RS change detection were selectively included in this analysis given their expected potential to indicate change from rural to urban land use at the *amphoe* level.

4.3 Linear Feature Extraction

The next step in the overall operational framework focuses on the detection and extraction of linear features from temporal imagery in an attempt to locate new road development as potential indicators of urban growth and of higher potential environmental stress. Because the Northern Corridor was revealed, through earlier analysis, to be the area in either Pathum Thani or Nonthaburi that has experienced some of the largest actual and implied urban growth, this sub-region was targeted for feature extraction analysis. The results of this process are now presented.

Based on preliminary results, it was evident that the Canny algorithm produced the best results in terms of quality of linear edge detection and number of edges located. Further, because the Canny algorithm was specifically designed as an edge detector and has been described as the 'most powerful' edge detection method available (The MathWorks Inc., 2000), it was deemed the best option for continued analysis in terms of linear feature detection and extraction.

The threshold value used with the Canny algorithm produced varying ranges of extracted edges. Ultimately, a threshold of 0.2 was used for the ADEOS image and a threshold of 0.1 was used for the lower resolution IRS and Landsat images to ensure the capture of all desirable edges and in particular, any known or potential road segments.

4.3.1 Edge Detection with 1995 Landsat TM Imagery

The Landsat TM from 1995 performed, in general, inadequately in terms of its use for effective linear feature extraction. Figure 4-7 depicts the results of the extraction process with the original image (post pre-edge extraction sharpening) in the background. A visual inspection of the results quickly reveals that the low spatial resolution of the image did not allow for an effective detection and extraction of many discernable features, including roads. Even though several pre-detection image enhancements had been performed, as discussed in Chapter 3, the results for the Landsat image in this scene were inferior when compared to results achieved with other higher resolution imagery.

Due to the unsatisfactory results produced with the Landsat image, it was removed from further examination in terms of attempting to detect the development of new roads in the Northern Corridor. Unfortunately, this left only a one-year time frame for investigation since the remaining available images were captured in 1997 and 1998 respectively. Nevertheless, given that one of the objectives of this thesis is to capture newly developed roads at the rapidly expanding rural-urban fringe, it is possible that new roads were developed in a time period of less than a one year. This rate of development is not uncommon in both the developing and the developed world as new roads, and often complete subdivisions, appear in North American cities at rates faster than one year from groundbreaking to completion.

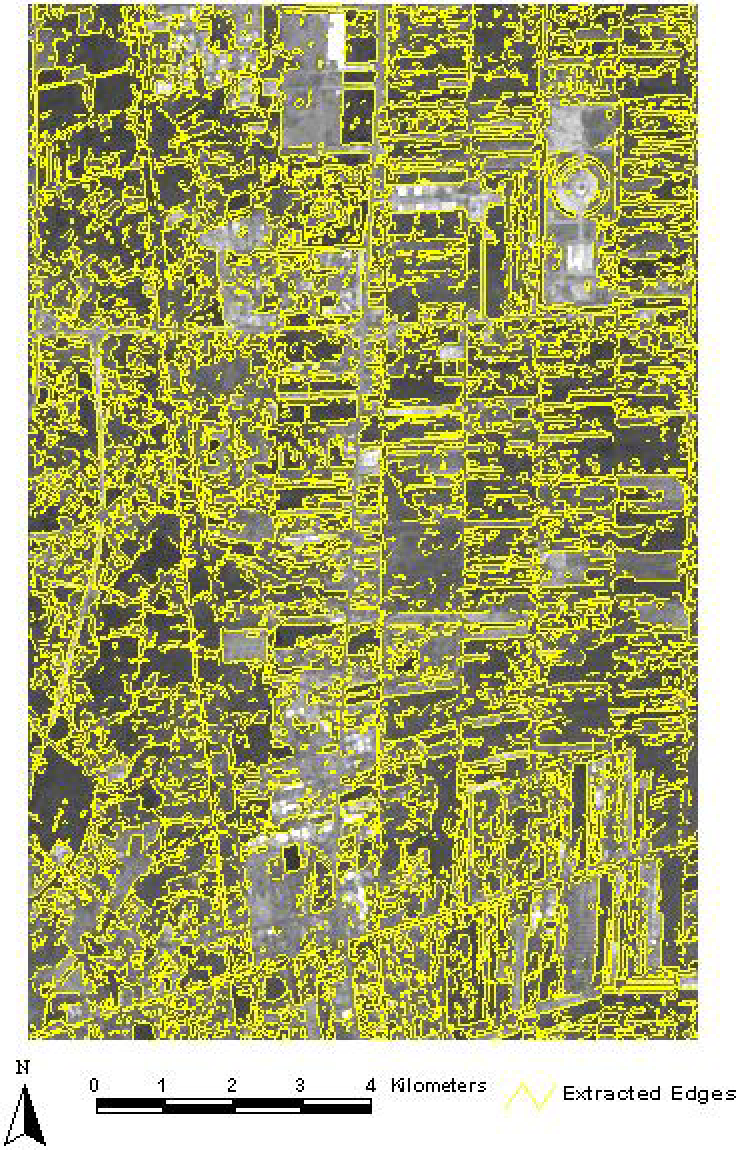
Background Image
Landsat TM

Band 4 = Red
Band 3 = Green
Band 2 = Blue

Figure 4-7: Extracted Edges in the Northern Corridor Using the 1995 Landsat TM Image

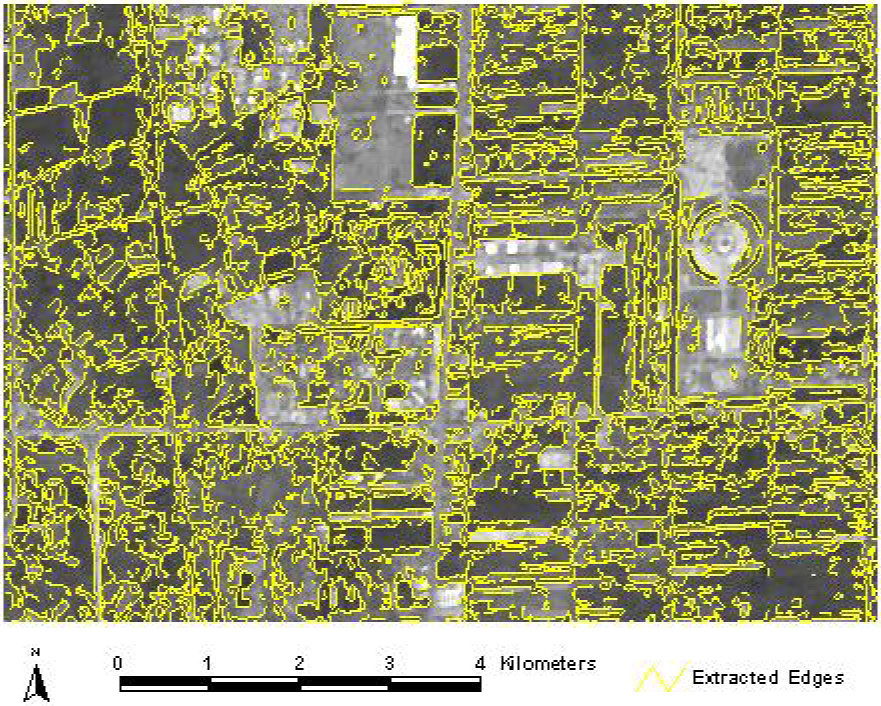
4.3.2 Edge Detection with 1997 ADEOS Panchromatic Imagery

The ADEOS Panchromatic image from 1997 produced the best relative results in terms of edge detection and linear feature extraction (Figures 4-8 and 4-9). With the highest spatial resolution of the three images (8 metres) the ADEOS image detection results are visually superior. Nonetheless, similar problems were experienced to those of the Landsat image, such as the detection of non-linear and non-road features. However, these were not as problematic as with the Landsat image. Also, many known features, including roads, were also apparent as successfully extracted items. Relative to the other two images, the ADEOS Panchromatic image produced the most extracted features, also due to its higher spatial resolution.



Background Image
ADEOS Panchromatic Band 1

Figure 4-8: Extracted Edges in the Northern Corridor Using 1997 ADEOS Panchromatic Image



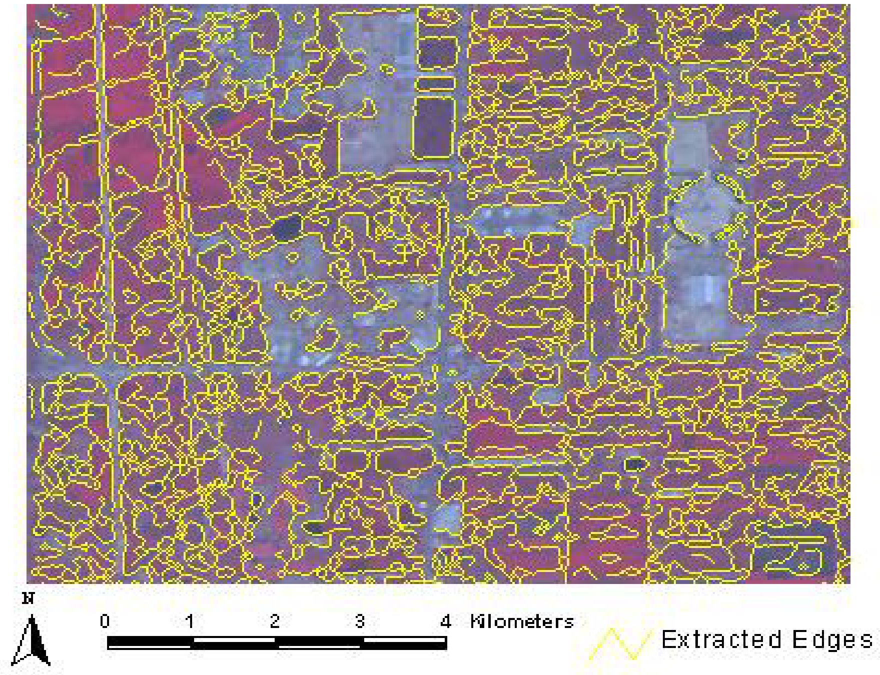
Background Image
ADEOS Panchromatic Band 1

Figure 4-9: Central Portion of the Northern Corridor Extracted Edges ADEOS Image

4.3.3 Edge Detection with 1998 IRS Multi-Spectral Imagery

The results for the IRS image feature extraction can be placed in-between those of the relatively successful ADEOS image and the unsuccessful TM image (Figure 4-10). This can once again be attributed to the spatial resolution, as the IRS image has a slightly higher resolution than the TM image at 24 meters, but still lower than the ADEOS image.

It is clear from the image segment that the edge detector, when utilized with the lowest threshold, has the ability to detect every edge in the image notwithstanding varying image intensities. In terms of the linear features, given the relatively low spatial resolution of the images under investigation, the algorithm was most effective at detecting larger highways and roadways within the study area. This is evident in Figure 4-10. While detectable, secondary roads were visually difficult to distinguish from other types of edges detected within the imagery.



Background Image IRS

Band 3 = Red
Band 2 = Green
Band 1 = Blue

Figure 4-10: Northern Portion of the Northern Corridor Extracted Edges Using 1998 IRS Image

4.3.4 Combined Edge Detection Results

Common amongst all of the imagery examined is the fact that the number of edges detected and extracted is more prolific in the urban areas of the Northern Corridor as compared to the relatively more rural areas. This phenomenon is particularly prominent along the major arterial roads and is evident immediately adjacent to Phaholyothin Highway, which bisects the Northern Corridor. Moving from south to north along the highway, a pattern of dense development is apparent adjacent to the highway relative to more outlying locations (Figure 4-11).

Aside from these edges, it is also evident in Figure 4-11, and the previous four figures (4-7 through 4-10) that many non-linear and non-road man-made and natural features have also been detected and extracted by the Canny algorithm. This pattern of extraction supports one of the conjectures of this thesis in that the ability to extract linear features from satellite imagery is greatly affected by the location of the study area. Specifically, an urban study area tends to produce extraction results that are more disorderly and less successful relative to a rural study area. This is due to the density of features, man-made and natural, in an urban area with spectrally unique image values. This proliferation of unique values in close proximity forces the detection and extraction of many edges in the urban scene. Unfortunately, current extraction algorithms are not able to distinguish successfully between these urban features automatically and to generate such an algorithm is beyond the scope of this thesis.

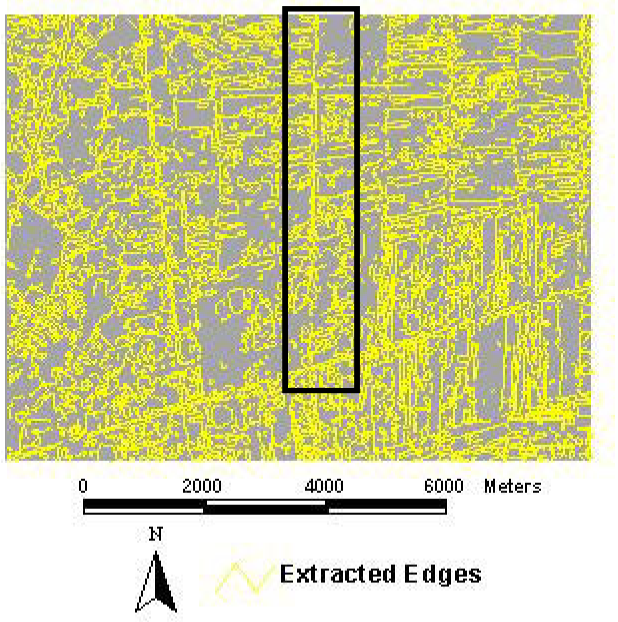


Figure 4-11: Phaholyothin Highway (inside box) and adjacent detected features

Following the extraction of the edges, the IRS and ADEOS images were written to TIF image format and then imported into Arc/Info as GRIDS. Using the 'gridline' command, they were then automatically converted to ARC coverages.

4.4 Further Integrative RS and GIS Analysis of the Northern Corridor

This section provides an examination of the integration between the features extracted from the RS imagery and the further temporal analysis of these features in a multi-source GIS.

The results of the conversion from GRIDs to ARC coverages further reveals the over abundance of edges that were detected and extracted. In particular, the ADEOS image is inundated with edges that are clearly not representative of roadways in many cases. To improve these conditions, some manual editing of both ARC coverages was necessary to remove some of the more obvious non-road features. However, limited manual removal of lines was performed to ensure that potential minor road segments were not mistakenly deleted.

Also, manual checking was completed to verify that any discrepancies between the extracted lines from the two images were minimal and that the extracted lines were coincidental to allow for the ensuing overlay process. Discrepancies were potentially caused by several possibilities including geo-referencing inconsistencies, edge extraction variability and raster to vector conversion divergences. In general, minimal, and largely insignificant inconsistencies were visible between the two images.

One other source of extracted feature discrepancy represented the largest source of inconsistency between the extracted lines. This divergence was a result of the difference in image spatial resolution. Some of the extracted features are misaligned in the two time periods by up to a maximum of approximately 50 metres. This number is consistent with the differences between the two spatial resolutions, eight for the ADEOS versus 24 for the IRS, and the range of variation potential that was possible for the same features in each image. This range is evident in Figure 4-12 where the red (ADEOS) extracted arcs do not match up exactly with the blue (IRS) extracted arcs. To account for this variability in spatial resolutions and subsequent positional accuracy dissimilarities in the feature selection by theme stage, the next and final step of this thesis uses a wide selection distance to ensure only potential new line segments are selected.

4.4.1 New Feature Segment Selection by Layer

Utilizing the results of the 'gridline' conversion along with some subsequent manual coverage editing, a selection of temporally extracted features was undertaken. Using a 'Select By Layer' procedure, features from the 1998 IRS image were selected that were within a certain distance of features extracted from the 1997 ADEOS image. Distances ranging from 5 to 50 metres were input in an iterative process of determining the most successful at returning the highest number of potential new features. Ultimately, it was determined that a median distance of 25 metres was most efficient at capturing more established new features and eliminating minor edge variances that were being captured at a shorter buffer distance

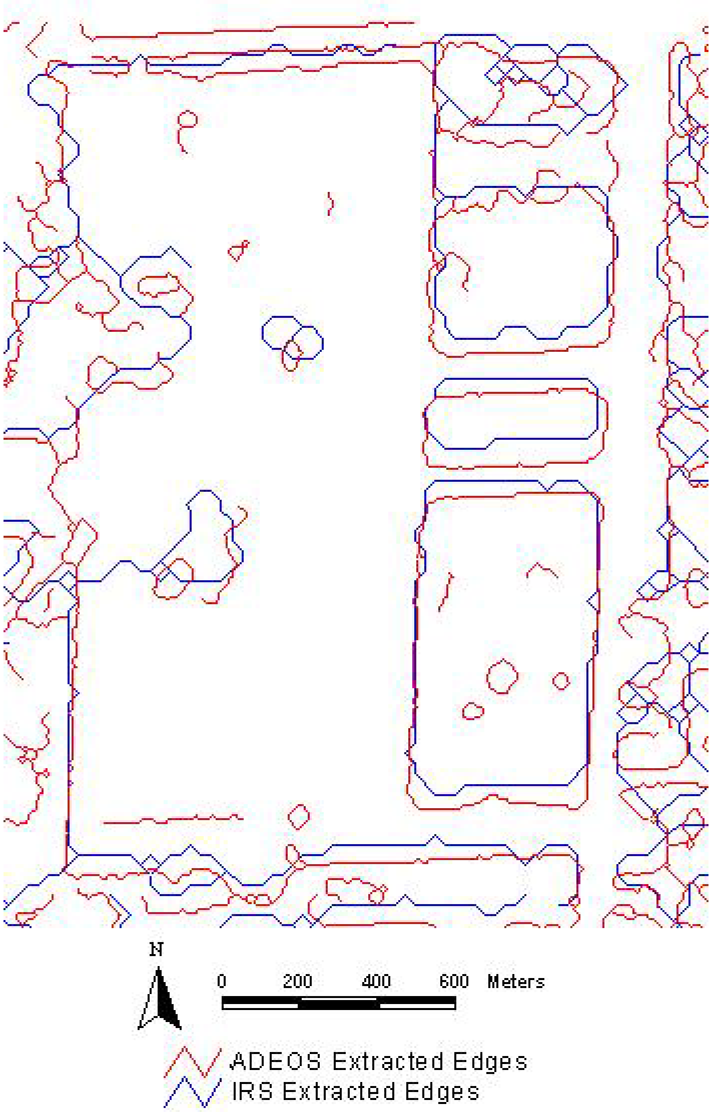


Figure 4-12: Overlaid Detected and Extracted Features from ADEOS (red) and IRS (blue) Images

Once the selection by digital layer was completed, the resulting selection was inverted such that the selected items were now the features located at the specified minimum distance from any feature extracted from the 1997 image (Figure 4-13).

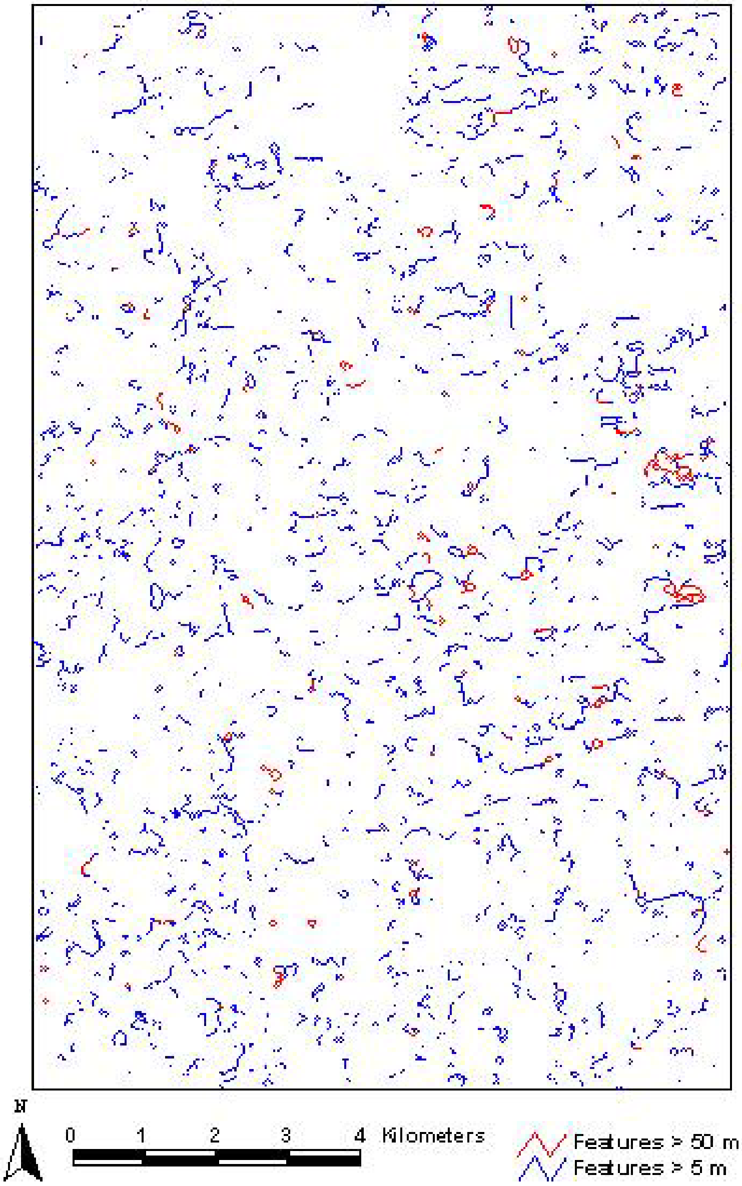
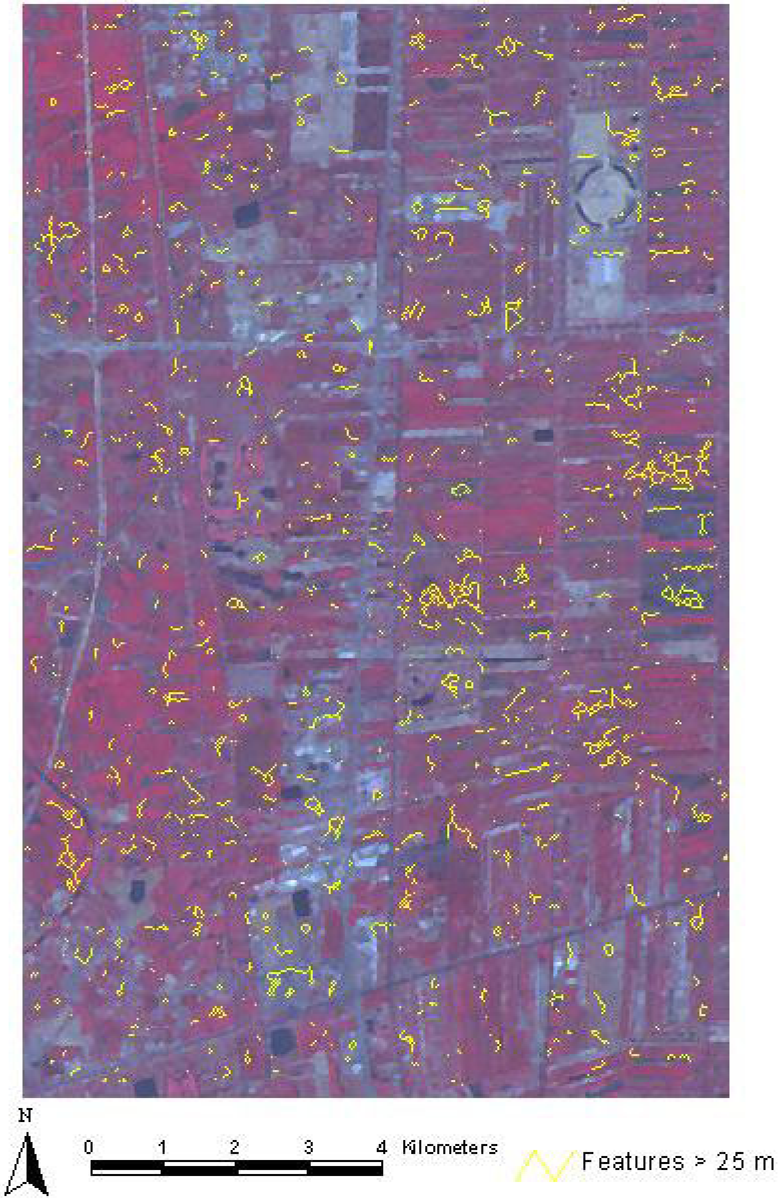


Figure 4-13: Extracted IRS Features At Greater Than 5 (blue) and 50 (red) Metres From Extracted ADEOS Features

While it is quickly apparent that many of these selected features are not roads, the possibility that some of them are new roads is high given that many of the arcs are located in-between major arterial roads throughout the Northern Corridor. This would suggest that some of these new lines might be roads that would have been recently constructed to link major arterial roads. Alternatively, these new lines may simply be new extensions to existing roadways as growth occurs outwards into new areas of development. The only method of determining whether or not these new lines are actually roadways was through manual visual inspection of each arc overlaid with the IRS and ADEOS imagery to determine actual feature status. Figure 4-14 depicts the 1998 IRS image overlain by the extracted features selected as being at a distance greater than 25 metres from any extracted feature from the 1997 ADEOS image.



Background Image IRS

Band 3 = Red
Band 2 = Green
Band 1 = Blue

Figure 4-14: Extracted IRS Features Greater Than 25 Metres Overlaying IRS Image

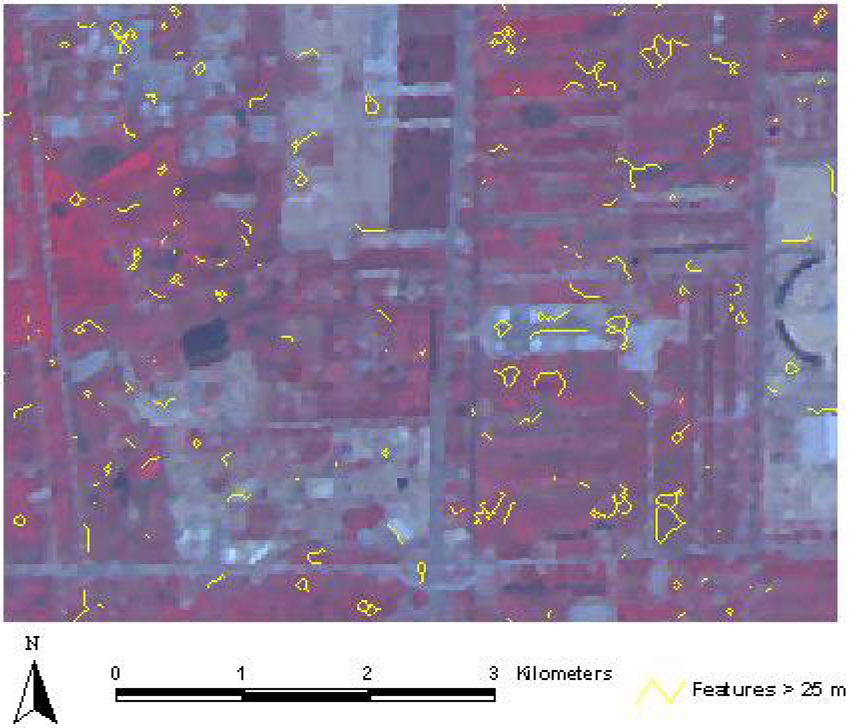
4.4.2 New Road Determination Results

Manual examination of these new lines reveals the potential for some preliminary conclusions in terms of whether extracted features are actually representative of new road development or not. However, given the inability to state with a high degree of certainty whether these features are road segments, conclusions are speculative at best. For example, some segments branching out along Phaholyothin Highway may indeed be new roads supporting the rapid urban sprawl occurring along the highway (Figure 4-15). Unfortunately, given the generally low spatial resolution of all of the imagery under examination, it is impossible to conclude that any of these segments are indeed new roads.

Therefore, in terms of the results presented above, while the outcome in this context is less than conclusive, it can be stated that the operational process outlined here could potentially be utilized in other more conducive situations and alternative study sites to detect and effectively extract features from satellite imagery. Specifically, an entirely rural study area would be more likely to allow for the generation of improved results when utilizing this operational process, as the number of extracted image features would be greatly reduced, as would be the intensity and number of edges.

4.5 Process Simplification with AML Generation

Due to the wide range of steps and software packages utilized in this thesis, the creation of one application to enhance and simplify the utilization of this process was not possible. Analyses in PCI Geomatica, MATLAB and Arc/Info has complicated this process, however each was necessary to produce the best possible results based on the available data. Nevertheless, since the majority of the steps following the edge detection in MATLAB were completed using Arc/Info, it was deemed appropriate to develop these into an Arc Macro Language (AML) program that allows interactive input, analysis and output for several stages of the overall operational framework. In general, this AML takes the output edges from MATLAB in TIF format, converts them to a GRID, performs a GRIDLINE operation to generate an ARC coverage and finally, outputs the ARC coverage for subsequent selection of new features by theme. The program code is included in Appendix II.



Background Image IRS
Band 3 = Red
Band 2 = Green
Band 1 = Blue

Figure 4-15: Potential New Road Segments Along Phaholyothin Highway

4.6 Summary

This chapter has described the results derived from the implementation of the integrated framework outlined in Chapter 2 and further discussed in the context of an operational methodology in Chapter 3. Starting with the RS change detection analysis, the results of each stage of the methodology were presented and reviewed. This was extended to include the change detection and road proximity analysis, the census-based GIS indicator analysis, the integrated *amphoe* rankings, the localization of areas of potential environmental stress and the linear feature detection and extraction. The final product was a multi-source and multi-temporal GIS database that had the capability to locate areas of environmental stress in the rural-urban fringe of Bangkok.

Based on these results, Chapter 5 presents the conclusions of the thesis. Also, a review of the overall effectiveness of the process is discussed along with some recommendations for further research.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This chapter provides a synopsis of the central arguments presented in this thesis and outlines the conclusions derived from the results obtained. Also, suggestions for growth management policies with respect to improved policy formation and planning practice are presented. Finally, some recommendations for future research are discussed as well as practical applications and implications for the use of RS and GIS to achieve sustainable urban environmental management (SUEM) in developing countries.

5.1 A Synopsis of the Argument

The main objectives of this thesis were: (i) to develop to an integrated framework based on the concepts of SD and UEM for the achievement of SUEM in cities in developing countries and (ii) to detect land use change and indictors of potential environmental stresses at the urban fringe of Bangkok. The need for a methodology to evaluate land use conversion at the urban fringe is apparent from the current planning and urban growth management systems in place in the Bangkok Metropolitan Region (BMR). Typically, planning decisions are *ad hoc* and reactive in the absence of up-to-date information on population growth and urban sprawl. Even with past attempts at long-term planning, the provision of necessary urban infrastructure has dragged well behind urban growth rates.

Population growth and urban sprawl are placing immeasurable amounts of stress on natural systems in and around the BMR. To address theses stresses, improved sustainable urban environmental management is necessary. To this end, the integrated framework that is presented and analyzed in this thesis seeks to address some basic needs of SUEM through the use of spatial information technologies. Through this integrated and structured framework, areas of potential environmental stress at the rural-urban fringe are identified and classified so that they can be targeted for proper sustainable growth management.

The need for this integrated approach was made apparent in Chapter 2 where sustainable development and urban environmental management were first discussed in the context of cities in developing countries. Next the use of SIT, including remote sensing and GIS, were discussed in terms of their uses for improved planning practice in developing countries. An integrated framework was then introduced uniting the concepts of SD and UEM to form SUEM, with the operational processes created through the use of SIT.

Chapter 3 presented the Research Design developed to achieve the objectives presented in Chapter 1 and discussed in Chapter 2. Also, the planning practices in Bangkok were addressed. The discussion turned to an analysis of the specific study area and its morphology. The design of the methodology, discussed in the last half of Chapter 3, was created to make operational the integrated framework outlined in Chapter 2. The design is comprised of RS imagery analysis, ground-based GIS data analysis and an integrated analysis combining the RS and GIS source data.

Chapter 4 presented and discussed the results derived from the methods outlined in the research design. The discussion in this chapter was structured to illustrate how the integrated framework was made operational through the methods used in the thesis. In particular, this chapter demonstrated how potential indicators of environmental stress that are detectible in RS imagery and derivable from ancillary census data can be combined and analyzed within a multi-source and temporal GIS database to facilitate improved SUEM.

5.2 Thesis Conclusions

Conclusions regarding each portion of the thesis are presented here including the image analysis, linear feature extraction, and the indicators and locations of potential environmental stresses at the urban fringe of Bangkok.

5.2.1 RS Change Detection Analysis Conclusions

Overall, the steps undertaken in the RS imagery analysis produced some interesting and useful results. First, the change detection using image arithmetic produced anticipated results in terms of the determined locations of change. As noted in Chapter 4, the areas of detected change corresponded with the presupposed locations of change in terms of their locations along the urban periphery of Bangkok Province. Some further examination and alternative change detection experimentation, such as principal component analysis or image overlay, could potentially reduce errors in the change detection results and binary classification. However, given that the results were as predicted, it is expected that only slight improvements in accuracy could be achieved for this section of the thesis methods. In part, the low spatial resolution of the imagery assisted in facilitating these results by producing a general smoothing that would have otherwise been cluttered by extensive detail in a higher resolution image. This produced a more homogeneous surface for the change detection process to detect and classify larger adjacent areas of change at the urban periphery. However, a consequence of this was a potential loss of precision in terms of localizing change.

Overall, the outcome of the *amphoe* rankings based on the results of the arithmetic change detection were as expected. These rankings assisted in the identification and confirmation of the areas in the Provinces of Pathum Thani and Nonthaburi that are experiencing rapid urban growth and, by extension, are most susceptible to potential environmental stress.

5.2.2 Census Indicator Analysis in GIS Conclusions

The incorporation of the seven census indicators analyzed in the thesis also provided useful information in terms of the *amphoes* ranking based on their magnitude of change over the time frame examined. The results of this temporal change ranking were generally as expected such that the *amphoes* showing the greatest amount of change based on the combined indicators were very similar to those selected with the RS change detection rankings. These results serve to reaffirm the selection of the Northern Corridor as one of the areas within the two provinces that is rapidly developing along the urban periphery of the BMR.

5.2.3 RS and GIS Integration and Localization of Stress Areas

Throughout the thesis, the benefits of RS and GIS integration were stressed. This integration was proven to provide timely and necessary information about land use change to planners in developing countries. Overall, the integration of the RS change detection and the census indictor results provided increased utility and validity to each other in terms of raising the level of certainty in localizing the regions with the highest potential for environmental stress. Through this combination, the classification of the *amphoes* into the stages of development as outlined in Chapter 2 was more easily and accurately facilitated. This assisted in the localization of areas of stress that ultimately led to the identification of the Northern Corridor as an appropriate area within Pathum Thani and Nonthaburi for more detailed analysis of road feature extraction.

Overall, the framework presented here represents an important contribution to the future prospects of RS and GIS integration in terms of analyzing change at the urban periphery of any city, not only within developing countries. The localization of areas of stress will help to ensure improved urban environmental management through the timely detection of areas requiring protection and improved environmental supervision. Protection could potentially come in the form of an environmentally sensitive area designation while improved supervision may involve increased monitoring of development to ensure adherence to environmental protection guidelines. Once these areas are located, modifications to government policy to include future protection and improved growth management, such as region-wide infrastructure planning or integrated waste management systems, will ultimately assist in the provision of SUEM throughout the urban periphery.

Development of a growth management strategy involves a balanced combination of planned growth, environmental integrity and economic viability. The integrated framework presented in this thesis has the potential to provide for each of these items. First and foremost, planned growth is essential as population grows and the number of households increase at an equal or even greater rate relative to population. As new development occurs, it must eventually be accommodated with improved road, water and wastewater treatment infrastructure. To ensure this, new policies must be implemented in developing countries to ensure planned growth as opposed to existing random development patterns. However, these policies cannot be devised without adequate information related to the location and form of new development, and this is where the integrated framework can make a substantial contribution to planning policy formation.

Environmental integrity can be achieved through an improved planned growth initiative. The need to protect prime agricultural land, woodlands and environmentally sensitive areas is important in terms of the economy of a city or region and also to the quality of life of its residents. Water resource protection and conservation must become a primary objective of cities in developing countries. The integrated framework can also serve to facilitate improved planning practice in terms of early detection of areas of environmental stress that may require an environmentally sensitive area protection policy.

Finally, economic viability is something that all cities, regions, and countries strive to achieve. As noted in Chapter 2, the desire to achieve economic growth and profit has often come at the opportunity cost of negative impacts on the natural environment. It is hoped that the integrated framework presented in this thesis might be able to assist policy formation in regards to improved land use planning through the provision of timely land use change information. This will potentially ensure environmental sustainability and land use compatibility while at the same time not hindering economic prosperity.

5.2.4 Feature Extraction and New Road Determination Conclusions

Russ (1995) points to the following as the two major problems with edge detection:

> 1) it cannot by itself complete the segmentation of the image because it has to be given each new starting point and cannot determine whether there are more outlines to be followed; and
>
> 2) the same edge-defining criteria used for following edges can be applied more easily by processing the entire image and then thresholding … [however] this produces a line of pixels that may be broken and incomplete.

These two points are evident in the results achieved in this thesis. In particular, the automatic processing of the Northern Corridor resulted in broken pixels and incomplete data, not to mention an overabundance of detected and extracted features.

This analysis has provided a general picture of potential new road development in the Northern Corridor. Unfortunately, the results are disorderly and it is difficult to prove with any high level of confidence that the extracted features can be accurately identified as new roads. In order for a more detailed picture to be developed, the extraction process would need to be examined in further detail to determine if a means of more accurate road identification could be realized.

This further examination could potentially involve a three pronged approach including a reevaluation of the commercial software and algorithms used in the thesis; the potential use of a pre-existing or newly developed linear feature extraction stand-alone application to the images under investigation; and the substitution of the current images with new, higher resolution images into the existing integrated framework for renewed analysis.

The use of alternative commercial software with enhanced feature extraction capabilities could provide improved results in terms of the quality and quantity of the extracted features. Within these alternative packages, algorithms other than the Canny algorithm may be available that might be more successful in extracting man-made features such as roads. Related to this, the use of a pre-existing feature extraction application may also improve results. For example, the LSB-Snakes application, designed by Gruen and Li (1997) and discussed in Chapter 2, may be a viable alternative. To date, the use of LSB-Snakes has been successful in rural scenes, but has yet to be fully tested in an urban setting. The substitution of higher resolution images is discussed further below in the recommendations and implementation section (5.5).

Since one of the main objectives of this thesis was to provide a semi-automatic means for the extraction of linear features, the overall results of this portion of the analysis are disappointing. However, due to a general inability of an edge detection algorithm to distinguish successfully between extracted features, little can be done at this point to improve the results. Consequently, based on the available edge detection technology and the complexity of the study area, the results can be generally considered successful as potential new road features were indeed extracted and localized. These new roads segments can further be used to identify specific areas of rapid urban growth and expansion into new, previously undetected, areas of urban land use development.

5.3 Growth Management Policy

The failure to manage the environment and to produce sustainable development is evident in all countries. Because environmental management and development are not separate challenges, environmental stresses and patterns of economic development are closely linked (WCED, 1987). Based on the results of this thesis, it has been demonstrated that there are many facets of urban planning that may be better facilitated through the use of spatial information technologies. Specifically, the localization of areas of potential environmental stress through the integrated RS change detection and GIS census indicators procedure, will allow local planning authorities to target problem areas for improved infrastructure provision and to make possible sustainable environmental management.

In terms of further facilitating growth management policies, the *amphoe* ranking results based on the integrated RS and GIS indicator analyses will provide a particularly effective means to determine the districts of highest and fastest urban growth. Thus, improved, more environmentally sustainable policies can be created and applied to the *amphoes* with the highest rankings. As noted above, these rankings may also be used to direct general growth management policy in terms of applying stages of development to the provinces and districts adjacent to Bangkok Province.

Specific environmentally sustainable policies must include some or all of the following requirements:

1) A region (BMR) wide land use and infrastructure development plan;
2) Protection and environmental enhancement of agricultural and other natural resources;
3) Providing an integrated regional transportation system;
4) Managing water supply and waste management to ensure service and to minimize negative environmental impacts; and
5) Monitoring change to appropriately adjust policies and actions.

(adapted from Regional Municipality of Waterloo, 1998)

The creation and implementation of policies with these requirements in mind will only be possible if a regional approach to planning within the broader BMR is undertaken through partnerships between the provincial and municipal governments. The integrated framework presented in this thesis seeks to assist in the creation and implementation of such policies by providing more timely and accurate information pertaining to the location and morphology of urban growth and change at the district level within the BMR. This information is a fundamental input to the creation of accurate and informed policy to guide growth and provide protection of the rural and natural environments. These data are also fundamental in the monitoring of change to allow for appropriate adjustments to existing policies and for providing a starting point for action in terms of rectifying improper and environmentally unsustainable urban sprawl.

5.4 Thesis Objective Conclusions

Overall, the integrated framework developed in the thesis, based on the concepts of SUEM, has been shown to make operational an effective process of environmental stress detection through the integration of RS and GIS spatial information technologies. Specifically, RS change detection analysis has been shown to allow temporal land use classification in terms of change versus non-change areas in the Provinces of Pathum Thani and Nonthaburi. Additionally, the GIS census indictor analysis has also been shown to classify *amphoes* in these provinces in terms of land use change and potential environmental stress rankings.

The temporal extraction of road features from RS imagery is the only specific objective of this thesis that has not been completely fulfilled. Generally, the process utilized was effective at detecting and extracting features. However, the quality and ability to distinguish between the types of the extracted features was unsatisfactory. Some recommendations on how these results might be improved are discussed below.

5.5 Recommendations and Implementation

The principal recommendation that comes out of this thesis is the need to transfer the methods outlined here to other scales of research. Specially, if data were available at, for example, the property or plan of subdivision levels, the process of analyzing the ground-based indicators could be moved to a larger scale to provide a finer level of detail in terms of accurately detecting areas of potential environmental stress. By acquiring this level of data, detailed population characteristics could be detected and analyzed. Unfortunately, the collection of this level and type of data is currently very problematic, especially in developing countries.

The use of higher resolution satellite imagery would allow for a more discrete analysis of the existing road network. As mentioned in Chapter 2, high-resolution satellites such as IKONOS and QuickBird, whose imagery are becoming readily available to researchers in developed countries, will allow for the detection and analysis of detailed road characteristics. However, as the roads become more distinct in these high-resolution images, other features also become more visually and spectrally unique relative to their adjacent land uses. This means that rooftops, building footprints and other detailed urban features will appear as sharp edges in terms of feature extraction. Hence, the use of these images in an urban setting could become even more problematic than their lower resolution ancestors.

To overcome this problem, the algorithms utilized in the detection and extraction of edges need to be more intelligent than the available automatic and semi-automatic algorithms. As discussed in Chapter 2, several on-going research projects are attempting to automate further the process of linear feature extraction. Many of these projects are operating in exclusively rural areas and only a few have ventured into the urban fringe and/or an entirely urban setting. Until edge detection algorithm technology becomes 'smart' enough to discriminate between adjacent urban land uses that are spectrally different, migrating the processes used in rural scenes will not be possible.

In terms of implementation, given the complexity of the processes utilized in this thesis, some potential requirements are recommended. First, and particularly for implementation in developing countries, a less complex process must be established. Fewer steps would be beneficial in terms of implementation in a developing country by streamlining the process. This could be partially achieved by limiting the number and types of software packages necessary to produce viable results. The use of PCI, MATLAB, and Arc/Info in this thesis was required in an attempt to generate the best possible results in terms of land use change detection and feature extraction. Unfortunately, the result is a complex process that involves a relatively large amount of data conversion across expensive software platforms and different spatial data structures.

The process of methodological consolidation begun in this thesis was facilitated through the creation of an AML program that incorporates the methods of analysis undertaken in Arc/Info. The generation of this AML is the extent of what could be completed towards this goal given the scope and objectives of this thesis. Further development of an application to carry the datasets, both RS and GIS, through the entire process would be desirable in terms of simplifying the entire operational framework.

However, the development of such an application will not be possible unless all analyses done in both PCI and MATLAB are removed from the process. This would result in a large loss of RS imagery analysis and utility and is therefore not a recommended option of simplification if this framework is to be implemented as designed. An alternative option would be to complete all analysis within PCI, removing both Arc/Info and MATLAB from the process resulting in a large loss of GIS specific data analysis ability. While the difficulties of implementation of these methods in a developing country increases with complexity, the framework as presented represents a favourable methodology for integrated RS and GIS analyses to detect areas of potential environmental stress.

Despite the less than satisfactory results of the transportation feature extraction portion of the thesis, other results at the district level provided a substantial contribution through the identification of trigger points of environmental stress and subsequent policy development. An important benefit of implementation can be realized when this integrated framework is used to address policies related to urban growth and provide value for decision-making. By providing utility to the process of detecting and rectifying areas of environmental stress, the framework presented in the thesis has the potential to bring SUEM practice into the planning process within the Bangkok Metropolitan Region.

All good research poses as many questions as it answers. This thesis has done both by answering questions pertaining to the location of areas of environmental stress at the northern fringe of Bangkok, while posing new questions about how to improve the detection and extraction of transportation features from satellite imagery. The answers provided will assist urban planning in Bangkok through the application of spatial information technologies to provide the basis for a better understanding of urban growth and land use change at the rural-urban fringe.

GLOSSARY

ACRoRS	Asian Center for Research on Remote Sensing at the AIT
ADEOS	Advanced Earth Observing Satellite
Amphoe	Thai census/administrative boundary – equivalent to a county
AIT	Asian Institute of Technology
Baht	Thai currency. CDN $1 = approx. 28 Baht (as of September, 2001)
BMR	Bangkok Metropolitan Region – typically designed to include the Bangkok Metropolitan and its immediate surrounding *changwats* including Samut Prakarn, Pathum Thani, Nakhon Pathom, Samut Sakhon, and Nonthaburi.
CELADE	Latin American Demographic Centre
Changwat	Thai census/administrative boundary – equivalent to a province
CIDA	Canadian International Development Agency
CUC-UEM	Canadian Universities Consortium – Urban Environmental Management
DC	Developing Countries
GDRC	The Global Development Research Center
GIS	Geographic Information System
GPS	Global Positioning System
ECLAC	Economic Commission for Latin America and the Caribbean
ESRI	Environmental Systems Research Institute
IT	Information Technology
PCI	PCI Geomatics – Producer of EASI/PACE Imaging Analysis Software
RAI	Thai unit of area. 1 rai = 0.4 acre = 1600 square metres
RS	Remote Sensing (can include satellite remote sensing or RS)
SD	Sustainable Development
SE	Southeast (Asia)

SIT	Spatial Information Technology
SUEM	Sustainable Urban Environmental Management
TM	Thematic Mapper (Landsat TM)
UEM	Urban Environmental Management

REFERENCES

Achermann, Friedrich. (1999). "Airborne Laser Scanning – Present Status and Future Expectations." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 54, pg. 64-67.

Amissah-Arthur, Abigail, Bernard Mougenot, and Maud Loireau. (2000) "Assessing farmland dynamics and land degradation on Sahelian landscapes using remotely sensed and socio-economic data." *International Journal of Geographical Information Science.* Vol. 14, No. 6, pg. 583-599.

Askew, Marc. (1994). " Bangkok: transformation of the Thai City." Marc Askew and William S. Logan (Eds). *Cultural Identity and Urban Change in Southeast Asia. Interpretive Essays.* Victoria, Austrailia: Deakin University Press, pg. 85-116.

Askew, Dr. Marc. (1996). "Landscapes of the Urban Fringe. A Study of Social, Physical, and Economic Changes in Nonthaburi Province at the Regional and Local Levels." *Final Seminar: Methodology for the Implementation of Urban Planning in Thailand.* JICA Joint Research Program, Department of Urban and Regional Planning, Faculty of Architecture, Chulalongkorn University, Bangkok, Thailand, pg. III 2-1 – III 2-45.

Baltsavias, Emmanuel P. (1996). "Digital Ortho-images – a Powerful Tool for the Extraction of Spatial- and Geo-information." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 51, (1996), pg. 63-77.

Barzohar, Meir and David B. Cooper. (1995). "New Geometric Stochastic Technology for Finding and Recognizing Roads and Their Features in Aerial Images." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic Extraction of Man-Made Objects from Aerial and Space Images.* Basel, Switzerland: Birkhauser Verlag.

Benediktsson, J.A. and J.R. Sveinsson. (1997). "Feature Extraction for Multisource Data Classification With Artificial Neural Networks." *International Journal of Remote Sensing.* Vol. 18, No. 4, pg. 727-740.

Bishop, Ian D., Francisco J. Escobar, Sadasivam Karuppannan, Ian P. Williamson, Paul M. Yates, Ksemsan Suwarnarat, and Haider W. Yaqub. (2000). Spatial Data Infrastructures for Cities in Developing Countries. *Cities.* Vol. 17, No. 2, pg. 85-96.

Breheny, Michael and Ralph Rookwood. (1993). "Planning the Sustainable City Region." David Bannister, Kenneth Button, and Peter Nijkamp (Eds.). *Environment, Land Use and Urban Policy.* Cheltenham, United Kingdom: Edward Elgar Publishing Ltd.

Burrough, Peter A. (1992). "Possibilities and Constraints of GIS Applications in Developing Countries." Pieter van Teeffelen, Leo van Grunsven, and Otta Verkoren, (Eds.). *Possibilities and Constraints of GIS Applications in Developing Countries.* Utrecht: Koninklikjk Nederlands Aardrijkskundif Genootschap, pg. 17-25.

Canadian International Development Agency (CIDA). (1998). *An Urbanizing World: Statement on Sustainable Cities.* Hull, Quebec: Minister of Public Works and Government Services Canada Publication.

Canadian International Development Agency (CIDA). (2001). *CIDA's Sustainable Development Strategy 2001-2003.* Hull, Quebec: Minister of Public Works and Government Services Canada Publication.

Canadian International Development Agency (CIDA). (1997). *Our Commitment to Sustainable Development: The Strategy of the Canadian International Development Agency.* Hull, Quebec: Minister of Public Works and Government Services Canada Publication.

Cartwright, T. J. (1992). "Geographic Information Technology as Appropriate Technology for Development." Ian Masser and H. J. Onsrud (Eds.). *Diffusion and Use of Geographic Information Technologies.* Dordecht, The Netherlands: Kluwer Academic Publishers, pg. 261-274.

Castells, Manuel. (1996). *The Rise of the Network Society.* Oxford, United Kingdom: Blackwell Publishers.

CELADE. (1995). *Knowledge and Data for Population in Development.* Paper Presented at the POPIN Advisory Committee Meeting, ESCAP, Bangkok, June 1995.

Connelly, Karen. (1992). *Touch the Dragon, A Thai Journal.* Winnipeg, Manitoba: Turnstone Press.

Couclelis, Helen. (1991). "Requirements for Planning-Relevant GIS: A Spatial Perspective." *Papers in Regional Science: The Journal of the RSAI.* Vol. 70, No. 1, pg. 9-19.

Couclelis, H. (1999). "Spatial Information Technologies and Societal Problems." M. Craglia and H. Onsrud, (Eds.). *Geographic Information Research: Translantic Perspectives.* London: Taylor and Francis, pg. 15-24.

Cowen, David J. and John R. Jensen. (1998). "Extraction and Modeling of Urban Attributes Using Remote Sensing Technology." *People and Pixels: Linking RS and Social Science.* Washington D.C.: National Research Council National Academy Press.

Da Costa, S.M.F. and J.P. Cintra. (1999). "Environmental Analysis of Metropolitan areas in Brazil." *ISPRS Journal of Photogrammetry & Remote Sensing..* Vol. 54 (1999), pg. 41-49.

Darrow K. and R. Pam. (1978). *Appropriate Technology Source Book.* Washington D.C.: Vita.

Debavalya, Nibhon. (1982). "Urbanization and Regional Policies in Thailand." Victor Sit Fung-shuen and Koichi Mera (Eds.). *Urbanization and National Development in Asia: A Comparative Study.* Conference held at the University of Tsukuba, Tsukuba, Japan, 10-12 August 1981, pg. 69-79.

de Man, W.H. Erik. (2000). "Towards Sustainable Geographic Information Technology: Its Institutionalization." Pip Forer, Anthony G.O. Yeh, Jianbang He (Eds.). *Proceedings 9th International Symposium on Spatial Data Handling.* (pg. 6b 22-30). Beijing, People's Republic of China, 10-12 August 2000.

De Roo, G., and D. Miller. (2001). "Introduction – Compact Cities and Sustainable Development." Gert de Roo and Donald Miller (Eds.). *Compact Cities and Sustainable Urban Development.* Hampshire, England: Ashgate Publishing Ltd., pg. 1-16.

Durongdej, Sripen. (1995). *Participatory Planning In Rural Development: A Case Study in Nam Lang Watershed, Northern Thailand.* Waterloo, Ontario: PhD Thesis, School of Planning, University of Waterloo.

Dutra, L.V. and R. Huber. (1999). "Feature Extraction and Selection for ERS-1/2 InSAR Classification." *International Journal of Remote Sensing.* Vol. 20, No. 5, pg. 993-1016.

Economic Commission for Latin America and The Caribbean (ECLAC). (1992). *Social Equity and Changing Production Patterns: an Integrated Approach.* Santiago, Chile: United Nations.

Edwards, Geoffrey. (1991). "Remote Sensing Image Analysis and Geographic Information Systems: Laying the Groundwork for Total Integration." *Proceedings: The Integration of Remote Sensing and Geographic Information Systems.* Proceedings of a Special Session held at the Baltimore 1991 ACSM-ASPRS Annual Convention.

Edwards, Tony. (1983). *The Bangkok Metropolitan Area. An Appraisal of Planning and Development Issues, Policies, and Mechanisms.* London, England: Roger, Tym & Partners.

Elkington, John and Jonathan Shopley. (1988). *The Shrinking Planet: U.S. Information Technology and Sustainable Development.* Pennsylvania, U.S.A.: World Resources Institute.

Entwisle, Barbara, Stephen J. Walsh, Ronald R. Rindfuss, and Aphichat Chamratrithirong. (1998). "Land-Use/Land-Cover and Population Dynamics, Nang Rong, Thailand." *People and Pixels: Linking RS and Social Science.* Washington D.C.: National Research Council National Academy Press.

Fiset, Robert, Francois Cavayas, Marie-Catherine Mouchot, Basel Solaiman, and Robert Desjardins. (1998). "Map-image Matching Using a Multi-layer Perception: the Case of the Road Network." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 53, (1998), pg. 76-84.

Fisher, R., S. Perkins, A. Walker, and E. Wolfart. (2000). *Hypermedia Image Processing References (HIPR2).* http://www.dai.ed.ac.uk/HIPR2/. Accessed October, 2001.

Foody, Giles M. (1995). "Land Cover Classification by an Artificial Neural Network with Ancillary Information." *International Journal of Geographical Information Systems.* Vol. 9, No. 5, pg. 527-542.

Foody, Giles M. (1999). "The Significance of Border Training Patterns in Classification by a Feedforward Neural Network Using Back Propagation Learning." *International Journal of Remote Sensing*. Vol. 20, No. 18, pg. 3549-3562.

Freund, John E. and Gary A. Simon. 1992. *Modern Elementary Statistics*. New Jersey: Prentice-Hall Inc.

Gahegan, Mark and Manfred Ehlers. (2000). "A Framework for the Modeling of Uncertainty Between Remote Sensing and Geographic Information Systems." *ISPRS Journal of Photogrammetry & Remote Sensing*. Vol. 55 (2000), pg. 176-188.

Global Development Research Center (GDRC). (2001). Introduction: Urban Environmental Management." *The WWW Virtual Library, Urban Environmental Management*. http://www.gdrc.org/uem/index.html. Accessed October, 2001.

Greenberg, Charles. (1994). *Region Based Urbanization in Bangkok's Extended Periphery*. Doctoral Thesis, University of British Columbia, Vancouver, British Columbia, Canada.

Gruen, Armin and Haihong Li. (1995). "Road Extraction From Aerial and Satellite Image by Dynamic Programming." *ISPRS Journal of Photogrammetry and Remote Sensing*. Vol. 50, No. 4, pg. 11-20.

Gruen, Armin and Haihong Li. (1997). "Semi-Automatic Linear Feature Extraction by Dynamic Programming and LSB-Snakes." *Photogrammetric Engineering and Remote Sensing*. Vol. 63, No. 8, pg. 985-995.

Gruen, Armin, Peggy Agouris, and Haihong Li. (1995). "Linear Feature Extraction with Dynamic Programming and Globally Enforced Least Squares Matching." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic Extraction of Man-Made Objects from Aerial and Space Images*. Basel, Switzerland: Birkhauser Verlag.

Gruen, Armin, Peggy Agouris, Dirk Stallmann, and Haihong Li. (1994). "Algorithms for Automated Extraction of Man-Made Objects from Raster Image Data in a GIS." ." Jurg Nievergelt, Thomas Roos, Hans-Jorg Schek, and Peter Widmayer (Eds.). From IGIS '94: Geographic Information Systems, proceeding from a workshop on Advanced Research in Geographic Information Systems, Monte Verita, Ascona, Switzerland, February/March 1994. *Lecture Notes in Computer Science*. Berlin, Germany: Springer-Verlag, pg. 123-132.

Guindon, B. (2000). "A Framework for the Development and Assessment of Ojbect Recognition Modules from High-Resolution Satellite Images". *Canadian Journal of Remote Sensing*. Vol. 26, No. 4. pg. 334-348.

Haala, Norbert and Claus Brenner. (1999). "Extraction of Buildings and Trees in Urban Environments." *ISPRS Journal of Photogrammetry & Remote Sensing*. Vol. 54 (1999), pg. 130-137.

Hack, Gary, Ranjan Nambiar, Jonathan Tom, Tom Campanella, and Paul Wang. (1994). "The Metropolitan Centers Program." *Interim Report Phase IV. Strategic Planning for Metropolitan Bangkok*. Report submitted to the City Planning Division, Bangkok Metropolitan Adminstration by M.I.T. Consultants Team, pg. 1-11.

Hall, G. Brent. (1993). *GIS Use in Rural Planning and Management in Developing Countries.* Keynote Address at Second Seminar on GIS and Developing Countries (GISDECO): The Practice of GIS Applications: Problems and Challenges. Soustenberg, The Netherlands, June 1993.

Hall, G.B. (1999). "Guest Editorial - GIS Education and Infrastructure Challenges and Problems in Emerging Countries." *Transactions in Geographic Information Systems.* Vol. 3, No. 4, pg. 311-318.

Hall, G. Brent and Arthur Conning. (1992). "Integrating Demographic and Socio-economic Data with PC-Based GIS in Latin America." Pieter van Teeffelen, Leo van Grunsven, and Otta Verkoren, (Eds.). *Possibilities and Constraints of GIS Applications in Developing Countries.* Utrecht: Koninklikjk Nederlands Aardrijkskundif Genootschap, pg. 87-102.

Hall, G.B., F. Wang, and Subaryono. (1992). "Comparison of Boolean and Fuzzy Classification Methods in Land Suitability Analysis by Using Geographical Information Systems." *Environment and Planning A.* Vol. 24, pg. 497-516.

Hall, G.B., N.W. Malcolm, and P.M. Piwowar. (2001). "Integration of Remote Sensing and GIS to Detect Pockets of Urban Poverty: The Case of Rosario, Argentina." *Transactions in GIS*. Vol. 5, No. 3, pg. 235-254.

Hanson, J. and U. Narula. (1990). *New Communication Technologies in Developing Countries.* Hillside, New Jersey: LEA.

Huan, Vu Duc. (1995). *Application of Remote Sensing and Geo-information System for Evaluating Urban Development in the Northern Corridor of Bangkok, Pathumthani province.* Thesis No. NR-95-3. Space Technology Applications and Research Program, Asian Institute of Technology, Bangkok, Thailand.

Huxhold, William E., and Allan G. Levinsohn. (1995). *Managing Geographic Information System Projects.* New York, New York: Oxford University Press, Inc.

Ingle, Vinay K. and John G. Proakis. (2000). *Digital Signal Processing Using MATLAB.* Pacific Grove, California: Brooks/Cole Publishing Company.

International Council for Local Environmental Initiatives (ICLEI) and the International Development Agency (IDRC). (1996). *The Local Agenda 21 Planning Guide: An Introduction to Sustainable Development Planning.* Toronto, Canada: The International Council for Local Environmental Initiatives (ICLEI).

Jedynak, Bruno and Jean-Philippe Roze. (1995). "Tracking Roads in Satellite Images by Playing Twenty Questions." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic*

Extraction of Man-Made Objects from Aerial and Space Images. Basel, Switzerland: Birkhauser Verlag.

Jensen, John R. (1996). *Introductory Digital Image Processing: A Remote Sensing Perspective*. Upper Saddle River, New Jersey: Prentice Hall, Inc.

Jiang, Bin. (2000). "Agent-Based Approach to Modelling Environmental and Urban Systems Within GIS." Pip Forer, Anthony G.O. Yeh, Jianbang He (Eds.). *Proceedings 9th International Symposium on Spatial Data Handling*. (pg. 3b 17-29). Beijing, People's Republic of China, 10-12 August 2000.

Johnson, Craig. (2000). "Common Property, Political Economy, and Local Resource Management." *South East Asia Research*. Vol. 8, No. 1, pg. 31-53.

Kalluri, S.N.V., J. Jaja, D.A. Bader, Z. Zhang, J.R.G. Townshend, and H. Fallah-Adl. (2000). "High Performance Computing Algorithms for Land Cover Dynamics Using Remote Sensing Data." *International Journal of Remote Sensing*. Vol. 21, No. 6 & 7, pg. 1513-1536.

Karimi, Hassan A., Xiaolong Dai, Siamak Khorram, Aemal J. Khattak, and Joseph E. Hummer. (1999). "Techniques for Automated Extraction of Roadway Inventory Features from High-Resolution Satellite Imagery." *Geocarto International*. Vol. 14, No. 2, pg. 5-16.

Kim, Taejung and Jan-Peter Muller. (1995). "Building Extraction and Verification from Spaceborne and Aerial Imagery using Image Understanding Fusion Techniques." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic Extraction of Man-Made Objects from Aerial and Space Images*. Basel, Switzerland: Birkhauser Verlag.

Laquian, Aprodicio A. (2000). *The Planning and Goverence of Mega-urban Regions: What Can We Learn from Asia and the Pacific Rim?* Vancouver, Canada: Centre for Human Settlements, University of British Columbia, Vancouver, B.C. From the ACSP Conference, Atlanta, November 2, 2000. http://www.chs.ubc.ca/publications/Mur/Mega-urban_Regions.html (Accessed March 2001).

Li, Xia and Anthony Gar-On Yeh. (2000). "Modelling Sustainable Urban Development by the Integration of Constrained Cellular Automata and GIS." *International Journal of Geographical Information Science*. Vol. 14, No. 2, pg. 131-152.

Lillesand, T. and R. W. Kiefer. (1994). Remote Sensing and Image Interpretation. New York: John Wiley & Sons, Inc.

Liu, Weiguo, Sucharita Gopal, and Curtis Woodcock. (2000). "An Integrated System of Image Classification Using Artmap Neural Network --- Art-Vip." Pip Forer, Anthony G.O. Yeh, Jianbang He (Eds.). *Proceedings 9th International Symposium on Spatial Data Handling*. (pg. 5b 23-37). Beijing, People's Republic of China, 10-12 August 2000.

Low, Nicholas, Brendan Gleeson, Ingemar Elander and Rolf Lidskog. (2000). Nicholas Low, Brendan Gleeson, Ingemar Elander, and Rolf Lidskog (Eds.). *Consuming Cities: The Urban Environment in the Global Economy after the Rio Declaration.* London, England: Routledge, pg. 281-307.

Makarovic, B. (1995). "Image-based Digital Mapping." *ISPRS Journal of Photogrammetry and Remote Sensing.* Vol. 50, No. 2, pg. 21-29.

Malcolm, Neil W. (1999). *Integrating GIS and RADARSAT Imagery to Identify Pockets of Urban Poverty in Rosario, Argentina.* Unpublished Undergraduate Thesis, Faculty of Environmental Studies, University of Waterloo, Waterloo, Ontario, Canada.

Malcolm, N.W., J.M. Piwowar, G.B. Hall, C. Cotlier, and A. Ravenna. (2001). "An Integration of RADARSAT and Landsat Imagery to Identify Areas of Urban Poverty in Rosario, Argentina." *Canadian Journal of Remote Sensing.* Vol. 27, No. 6, pg.

Mark, David M., Nicholas Chrisman, Andrew U. Frank, Patrick H. McHaffie, and John Pickles. (1997). *The GIS History Project.* http://www.geog.buffalo.edu/ncgia/gishist/bar_harbor.html (Assessed March 2001).

Martinez-Casasnovas, Jose A. (2000). "A Cartographic and Database Approach for Land Cover/Use Mapping and Generalization from Remotely Sensed Data." *International Journal of Remote Sensing.* Vol. 21, No. 9, pg. 1825-1842.

Masser, I. and H. Campbell. (1989). *Conditions for the Effective Utilization of Computers in Urban Planning in Developing Countries.* United Kingdom: University of Sheffield, TRP 88, Department of Town and Country Planning.

The MathWorks. (2000). *MATLAB On-line Help.* MATLAB Version 6.0.0.88 Release 12.

Mayer, Helmut and Carsten Steger. (1998). "Scale-space Events and their Link to Abstraction for Road Extraction." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 53 (1998), pg. 62-75.

McGill, Ron. (2001). "Urban Management Checklist." *Cities.* Vol. 18, No. 5, pg. 347-354.

Menou, Michel J. (1993). *Measuring the Impact of Information on Development.* Ottawa, Canada: International Development Research Council (IDRC).

Molenaar, M. and L.L.F. Janssen. (1991). "Integrated Processing of Remotely Sensed and Geographic Data for Land Inventory Purposes." *Proceedings: The Integration of Remote Sensing and Geographic Information Systems.* Proceedings of a Special Session held at the Baltimore 1991 ACSM-ASPRS Annual Convention.

Morain, S. (1998). "A Brief History of Remote Sensing Applications, with Emphasis on Landsat." David Liverman, Emilio F. Moran, Ronald R. Rindfuss, and Paul C. Stern (Eds.). *People and Pixels: Linking Remote Sensing and Social Science.* Washington D.C.: National Academy Press.

National Statistics Office (NSO), (2000). *Population Growth Rate by Region and Province.* Royal Thai Government, Bangkok, Thailand.

Nedovic-Budic, Zorica. (1997). "GIS Technology and Organizational Context: Interaction and Adaption." M. Craglia and H. Couclelis (Eds.). *Geographic Information Research: bridging the Atlantic.* London, England: Taylor and Francis.

Nghi, D. Q. and H. D. Kammeier. (2001). "Balancing Data Integration Needs in Urban Planning." *Cities.* Vol. 18, No. 2, pg. 61-75.

Ngwainmbi, Emmanuel K. (1999). *Exporting Communication Technology to Developing Countries.* Lanham, Maryland: University Press of America.

Ogawa, Naohiro. (1985). "Urbanization and Internal Migration in Selected ASEAN Countries: Trends and Prospects." Philip M. Hauser, Daniel B. Suits, and Naohiro Ogawa (Eds.). *Urbanization and Migration in Asean Development.* Tokyo, Japan: National Institute for Research Advancement, pg. 83-108.

Onchan, Tongroj. (1997). "Urbanization and Life Environment Protection: The Case of Thailand and Bangkok." *International Symposium on APEC for Sustainable Development.* Tokyo, Japan, 1997. http://www.merimekong.org/documents/doc8c.htm (Accessed September, 2001).

O'Sullivan, David, Alastair Morrison, and John Shearer. (2000). "Using Desktop GIS for the Investigation of Accessibility by Public Transport: an isochrone approach." *International Journal of Geographical Information Science.* Vol. 14, No. 1, pg. 85-104.

Ouma-Onyango, Richard. (1997). *Information Resources and Technology Transfer Management in Developing Countries.* London, England: Routledge.

Pal, S.K., A. Ghosh, and B. Uma Shankar. (2000). "Segmentation of Remotely Sensed Images with Fuzzy Thresholding, and Quantitative Evaluation." *International Journal of Remote Sensing.* Vol. 21, No. 11, pg. 2269-2300.

Pereira, L.M. Gomes and L.L.F. Janssen. (1999). "Suitability of Laser Data for DTM Generation: a Case Study in the Context of Road Planning and Design." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 54 (1999), pg. 244-253.

Petit, C.C. and E.F. Lambin. (2001). "Integration of Multi-source Remote Sensing Data for Land Cover Change Detection." *International Journal of Geographical Information Science.* Vol. 15, No. 8., pg. 785-803.

Portnov, Boris A. and David Pearlmutter. (1999). "Sustainable Urban Growth in Peripheral Areas." *Progress in Planning.* Vol. 52 (1999), pg. 239-308.

Punpuing, Sureeporn and Helen Ross. (2001). "Commuting." *Cities.* Vol. 18, No. 1, pg. 43-50.

Ragia, Lemonia and Stephan Winter. (2000). "Contributions to a Quality Description of Areal Objects in Spatial Data Sets." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 55 (2000), pg. 201-213.

Ramasubramanian, Laxmi. (1999). "GIS Implementation in Developing Countries: Learning from Organizational Theory and Reflective Practice." *Transactions in Geographic Information Systems.* Vol. 3, No. 4, pg. 359-380.

Regional Municipality of Waterloo. (1998). *Regional Official Policies Plan (ROPP).* Waterloo, Ontario: Region of Waterloo, December 1998 Consolidation as approved by the Minister of Municipal Affairs and Housing, December 19, 1995.

Ricotta, C. and G.C. Avena. (1999). "The Influence of Fuzzy Set Theory on the Areal Extent of Thematic Map Classes." *International Journal of Remote Sensing.* Vol. 20, No. 1, pg. 201-205.

Richards, John A. and Xiuping Jia. (1999). *Remote Sensing Digital Image Analysis: An Introduction. Third, Revised and Enlarged Edition.* Berlin, Germany: Springer.

Russ, John C. (1995). *The Image Processing Handbook. 2nd Edition.* Boca Raton, Florida: CRC Press Inc.

Saraf, A.K. (1999). "IRS-1C-LISS-III and PAN Data Fusion: An Approach to Improve Remote Sensing Based Mapping Techniques." *International Journal of Remote Sensing.* Vol. 20, No. 10, pg. 1929-1934.

Satterthwaite, David. (1997). "Sustainable Cities or Cities that Contribute to Sustainable Development." David Bannister, Kenneth Button, and Peter Nijkamp (Eds.). *Environment, Land Use and Urban Policy.* Cheltenham, United Kingdom: Edward Elgar Publishing Ltd.

Shaban, M.A. and O. Dikshit. (2002). "Evaluation of the Merging of SPOT Multispectral and Panchromatic Data for Classification of an Urban Environment." *International Journal of Remote Sensing.* Vol. 23, No. 2, pg. 249-262.

Sheppard, Eric, Helen Couclelis, Stephen Graham, J.W. Harrington, and Harlan Onsrud. (1999). "Geographies of the Information Society." *International Journal of Geographical Information Science.* Vol. 13, No. 8, pg. 797-823.

Shettigara, Vittala K., Siegfried G. Kempinger, and Robert Aitchison. (1995). "Semi-Automatic Detection and Extraction of Man-Made Objects in Multispectral Aerial and Satellite Images." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic Extraction of Man-Made Objects from Aerial and Space Images.* Basel, Switzerland: Birkhauser Verlag.

Sinclair, Stuart. (1982). *The Third World Economic Handbook.* London, England: Euromonitor Publications Ltd.

Sit, Victor F.S. (1982). "Urbanization and Development: An Introduction." Victor Sit Fung-shuen and Koichi Mera (Eds.). *Urbanization and National Development in Asia: A Comparative Study.* Conference held at the University of Tsukuba, Tsukuba, Japan, 10-12 August 1981, pg. 1-6.

Sowmya, Arcot and John Trinder. (2000). "Modeling and Representation Issues in Automated Feature Extraction from Aerial and Satellite Images." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 55 (2000), pg. 34-47.

Srinivas, Hari. (1997). "Information Systems in Urban Environmental Management: Roles for the Internet." Paper presented at the Second International Symposium on Urban Planning and Environment on Strategies and Methods for Improving Environmental Quality in Compact Cities. 11-14 March 1997. Groningen, The Netherlands. http://www.gdrc.org/uem/doc-infoenvi.html (Accesed March, 2002).

Steger, Carsten, Clemens Glock, Wolfgang Eckstein, Helmut Mayer, and Bernd Radig. (1995). "Model-Based Road Extraction from Images." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic Extraction of Man-Made Objects from Aerial and Space Images.* Basel, Switzerland: Birkhauser Verlag.

Stow, Douglas, Sally Westmoreland, David McKinsey, Robert Parrott, Sue Carnevale and Doretta Collins. (1991). "Processing Flows for Correcting and Updating Vector-coded GIS Layers using Remotely Sensed Data." *Proceedings: The Integration of Remote Sensing and Geographic Information Systems.* Proceedings of a Special Session held at the Baltimore 1991 ACSM-ASPRS Annual Convention.

Sui, Daniel Z. (1998). "GIS-based Urban Modelling: Practices, Problems, and Prospects." *International Journal of Geographical Information Science.* Vol. 12, No. 7, pg. 651-671.

Tanaka, Sotaro and Toshiro Sugimura. (2001). "A New Frontier of Remote Sensing from IKONOS Images." ." *International Journal of Remote Sensing.* Vol. 22, No. 1, pg. 1-5.

Taylor, D.R.F. (1991). "GIS and Developing Nations." D.J. Maguire, M.F. Goodchild, and D.W. Rhind (Eds.). *Geographical Information Systems: Principals and Applications Volume 2.* London, England: Longman, pg. 71-84.

Thomson, Curtis N. and Perry Hardin. (2000). "Remote Sensing /GIS Integration To Identify Potential Low-income Housing Sites." *Cities.* Vol. 17, No. 2, pg. 97-109.

Tirasawat, Penporn. (1985) "Migration in Thailand: Past and Present." Philip M. Hauser, Daniel B. Suits, and Naohiro Ogawa (Eds.). *Urbanization and Migration in Asean Development.* Tokyo, Japan: National Institute for Research Advancement, pg. 407-425.

Trinder, Dr. John. (1995). "Workshop on Automated Extraction of Man-made Objects from Aerial and Space Images." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 50, No. 5, pg. 33-34.

Tripathi, N.K., K.V.G.K. Gokhale, and M.U. Siddiqui. (2000). "Directional Morphological Image Transforms for Lineament Extraction from Remotely Sensed Images." *International Journal of Remote Sensing*. Vol. 21, No. 17, pg. 3281-3292.

Tjatera, I Wayan. (1994). *A Model for Integrating Sub-Provincial Traditional and Official Regional Planning Institutions To Achieve Sustainable Development in Bali, Indonesia*. Waterloo, Ontario: PhD Thesis, Regional Planning and Resource Development, University of Waterloo.

Ulbricht, K.A., H.S. Teotia, W.D. Heckendorff, and D.L. Civco. (1995). "International Scientific Cooperation: Application of Remote Sensing for Development Purposes." *ISPRS Journal of Photogrammetry & Remote Sensing*. Vol. 50, No. 5, pg. 31-32.

Ulbricht, K.A. and W.D. Heckendorff. (1998). "Satellite Images for Recognition of Landscape and Landuse Changes." *ISPRS Journal of Photogrammetry & Remote Sensing*. Vol. 53 (1998), pg. 235-243.

United Nations (1996). *Decision support systems for sustainable development: experience and potential.* United Nations University, Institute for Software Technology, Macau.

United Nations. (1992). "Information for Decision-Making." *Agenda 21, Chapter 40*. United Nations Conference on Environment & Development, as adopted by the Plenary in Rio de Janeiro, June 1992.

United Nations Commission on Science and Technology for Develoment (UNCSTD). (1998). *Knowledge Societies: Information Technology for Sustainable Development*. Robin Mansell and Uta When (Eds.). New York: Oxford University Press Inc.

University Consortium for Geographic Information Science (UCGIS). (1998). *GIS and Society*. http://www.geog.umn.edu/umucgis/research_priorities/GISOCIET.html (Accessed March 2000).

University Consortium for Geographic Information Science (UCGIS). (1998). *GIS and Society II*. http://www.geog.umn.edu/umucgis/research_priorities/GISandsocII.pdf (Accessed March 2000).

Urban Environmental Management Program (UEM). (2001). "Program Objectives." *Urban Environmental Management Field of Study*. http://www.uem.ait.ac.th/. Accessed October, 2001.

Vosselman, George and Jurrien de Knecht. (1995). "Road Tracing by Profile Matching and Kalman Filtering." A. Gruen, O. Kuebler, P. Agouris (Eds.). *Automatic Extraction of Man-Made Objects from Aerial and Space Images*. Basel, Switzerland: Birkhauser Verlag.

Wehr, Aloysius and Uwe Lohr. (1999). "Airborne Laser Scanning – An Introduction and Overview." *ISPRS Journal of Photogrammetry & Remote Sensing*. Vol. 54 (1999), pg. 68-82.

Weimin, Zhang. (1995). *Application of Remote Sensing and GIS to Change-Detection in the Rural-Urban Fringe Area of Bangkok, Thailand.* Thesis No. NR95-12. Space Technology Applications and Research Program, Asian Institute of Technology, Bangkok, Thailand.

Wilkinson, G.G. (1996). "A Review of Issues in the Intergration of GIS and Remote Sensing Data." *International Journal of Geographical Information Systems.* Vol. 10 No. 1, pg. 85-101.

World Commission on Environment and Development (WCED). (1987). *Our Common Future.* Oxford, England: Oxford University Press.

Xiuwan, Chen. (2002). "Using Remote Sensing and GIS to Analyze Land Cover Change and its Impacts on Regional Sustainable Development." *International Journal of Remote Sensing.* Vol. 23, No. 1, pg. 107-124.

Yeh, Anthony Gar-on and Xia Li. (2001). "Measurement and Monitoring of Urban Sprawl in a Rapidly Growing Region Using Entropy." *Photogrammetric Engineering and Remote Sensing.* Vol. 67, No. 1, pg. 83-90.

Yeh, Anthony Gar-on and Xia Li. (1998). "Sustainable Land Development Model for Rapid Growth Areas Using GIS." *International Journal of Geographical Information Science.* Vol. 12, No. 2, pg. 169-189.

Yuan, Ding, Christopher D. Elvidge, and Ross S. Lunetta. (1998). "Survey of Multispectral Methods for Land Cover Change Analysis." Ross S. Lunetta and Christopher D. Elvidge (Eds.). *Remote Sensing Change Detection: Environmental Monitoring Methods and Applications.* Ann Arbor, Michigan: Ann Arbor Press, Inc.

Zha, Daojiong. (2000). "Introduction: Globalization and Local Governments in East Asia." *East Asia: An International Quarterly.* Summer, 2000.

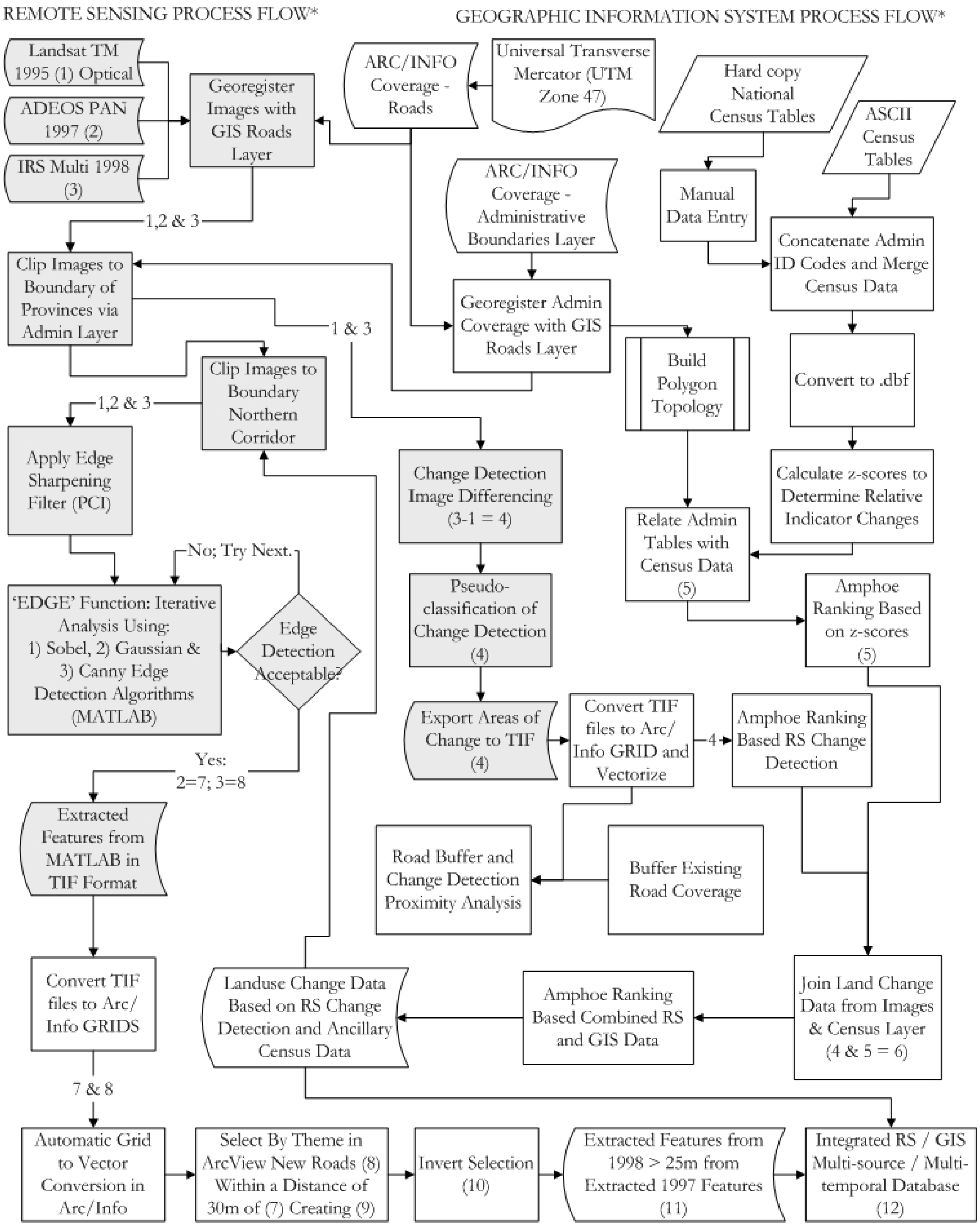
Zhang, Chunsun and Emmanuel Baltsavias. (2000). "Knowledge-Based Image Analysis for 3D Edge Extraction and Road Reconstruction." *International Archives of Photogrammetry and Remote Sensing (IAPRS).* Vol. XXIII, Amsterdam. http://www.photogrammetry.ethz.ch (Accessed March 2001).

Zhang, Chunsun, Emmanuel Baltsavias, and Armin Gruen. (2000). "Knowledge-Based Image Analysis for 3D Road Reconstruction." Paper presented to the ACRS 2000, Taipei, Dec. 3-8th, 2000. *Proceedings of the 21st Asian Conference on Remote Sensing*, pg. 100-105.

Zhang, Yun. (1999). "Optimization of Building Detection in Satellite Imagery by Combining Multispectral Classification and Texture Filtering." *ISPRS Journal of Photogrammetry & Remote Sensing.* Vol. 54 (1999), pg. 50-60.

APPENDIX I

Detailed RS and GIS Processing and Analysis Methods



* Note: All RS Analysis done using PCI Geomatica 8.0 & MATLAB 6.0; GIS work in ARC/INFO 8.1 and ArcView 3.2a

▨ Processing and Analysis in RS ☐ Processing and Analysis in GIS

APPENDIX II

Arc/Info Operational Process AML Code

```
/* Filename: mes.aml
/* Purpose:  MES Thesis - Arc/Info Automatic Coverage Generation from MATLAB
/*              Image Files Containing Extracted Binary Features from the Northern
/*              Corridor of Bangkok, Thailand
/* Author: Neil Malcolm
/* Last Modified 14/04/2002
/* You must run this AML program from ARC level

&type
&type * This program takes user input of 2 binary image files (in TIF format) exported
&type * from MATLAB, coverts them to GRIDS and then to ARC coverages using
&type * standard Arc/Info commands including 'imagegrid' and 'gridline'.

display 9999 size 1000 650

/* Input image filenames here
&type
&sv image1 = [response 'Enter the name of the first TIF image']
&type

&sv image2 = [response 'Enter the name of the second TIF image']
&type

&type * Cleaning up unnecessary files ...
&if [exist grid1 -directory] &then
  &do
    kill grid1 all
    &type
  &end

&if [exist grid2 -directory] &then
  &do
    kill grid2 all
    &type
  &end

&type
&type * Converting TIF images into GRIDS
imagegrid %image1% grid1 nearest
imagegrid %image2% grid2 nearest
&type

/* The following step is necessary because when the TIF images are
/* output from MATLAB, their binary values are reversed (ie) the background
/* has a value of 1 and the extracted features have a value of 0.
/* Therefore, the GRIDS need to be reclassified such that the background cells
/* have a value of 0 and the extracted features have a value of 1.  Without
/* this step, the GRIDLINE command with 'positive' parameter will
```

```
/* not work at required.

/* Open GRID
grid

&type * Reclassifying GRIDS to invert binary cell values using the remap.txt ascii file ...
grid_re1 = reclass(grid1,remap.txt)
grid_re2 = reclass(grid2,remap.txt)

quit
&type

/* A geo-referenced coverage is necessary to transform the ARC coverages
/* that are being created in this process because images are processed
/* and features are extracted in MATLAB, all geo-referencing is lost.
/* Therefore, when the images were exported from PCI to TIF format for
/* further analysis in MATLAB, one image was immediately brought into
/* Arc/Info so that the geo-referencing information was not lost.
/* The TICS from this coverage were used as the geo-referenced coverage.

&sv geo_cov1 = [response 'Enter the name of the Geo-referenced coverage']
&type

&type * Generating temorary process files ...
copy %geo_cov1% geo_cov1_
copy %geo_cov1% geo_cov2_
&type

&sv cover1 = [response 'Enter the name for the first final output ARC coverage']
&type

&sv cover2 = [response 'Enter the name for the second final output ARC coverage']
&type

&type * Cleaning up unnecessary files ...
&if [exist %cover1% -directory] &then
  &do
    kill %cover1% all
    &type
  &end

&if [exist %cover2% -directory] &then
  &do
    kill %cover2% all
    &type
  &end

/* Automatically convert GRIDS into ARC coverages
```

```
&type * Creating ARC coverages ...
gridline grid_re1 arc1 positive
gridline grid_re2 arc2 positive
&type

/* transform ARC coverages to Northern Corridor boundaries
&type * Transforming ARC coverages to known coordinate system ...
transform arc1 geo_cov1_
transform arc2 geo_cov2_
&type

&type * Renaming generated coverages ...
rename geo_cov1_ %cover1%
rename geo_cov2_ %cover2%
&type

&type * Building ARC topology ...
build %cover1% line
build %cover2% line
&type

/* clean up temporary files
&type * Cleaning up unnecessary files ...
kill arc1 all
kill arc2 all
kill grid1 all
kill grid2 all
kill grid_re1 all
kill grid_re2 all
&type

&type * The following ARC coverages have been created:
&type
&type %cover1%
&type
&type %cover2%
&type
&type * Both coverages will now be opened in ArcEdit for visual inspection.
&type * Also, future manual editing of the extracted features may be desirable.
&type
&sv next = [getchar '* Press ENTER key to continue']
&type

/* Visual inspection of the results provided in ArcEdit.
/*
display 9999 size 1000 650

/* Open ArcEdit
```

```
ae

/* Make Final Cover # 1 the Background cover
bc %cover1% 2
be arc

/* Make Final Cover #2 the Edit cover
ec %cover2%
de arc

draw

&pause

/* Quit ArcEdit
quit

&type
&type
&sv next = [getchar '* This program is complete, press any key to end the program']
&type
```